

**Cretaceous-Paleogene low temperature history of the Southwestern Province, Svalbard,
revealed by (U-Th)/He thermochronometry: implications for High Arctic tectonism**

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Abstract

The High Arctic has been a complex region of collisional and extensional tectonism through the Mesozoic and Cenozoic. Svalbard, the sub-aerial exposure of the northwestern Barents Shelf, is an excellent natural laboratory investigating for High Arctic tectonism. Using apatite and zircon (U-Th)/He low-temperature thermochronometry combined with geological constraints, we resolve Cretaceous through Paleogene time-temperature histories for four regions of the Southwestern Province. Our results indicate a temperature gradient from south to north of $\sim 185^{\circ}\text{C}$ to $>200^{\circ}\text{C}$, respectively, as a consequence of sedimentary burial and elevated geothermal gradient ($\geq 45^{\circ}\text{C}/\text{km}$) from High Arctic Large Igneous Province activity. Late Cretaceous cooling affected all regions during regional exhumation related to initial rifting in the Eurasian Basin. During Eureka tectonism: 1) our models indicate a heating event (55-47 Ma) characterized by overthrusting and a lack of erosion of the West Spitsbergen Fold-and-Thrust Belt, with Central Basin sediments derived from northern Greenland, followed by 2) a subsequent cooling event (47-34 Ma) corresponding to a shift in tectonic regime from compression to dextral strike-slip kinematics; exhumation of the WSFTB coincided with strike-slip tectonics.

Résumé

Le Haut-Arctique est une région complexe ayant subi du tectonisme collisionnel et extensive pendant le Mésozoïque et Cénozoïque. La région nord-ouest du plateau Barents est exposée formant Svalbard, un excellent laboratoire naturel pour étudier le tectonisme du Haut-Arctique. Thermochronométrie par (U-Th)/He, utilisant apatites et zircons, est employée avec des contraintes géologiques pour résoudre l'histoire temps-température de quatre régions de la province du Sud-Ouest. Durant le Crétacé et Paléogène. Nos résultats montrent un gradient de température du sud au nord, de $\sim 185^{\circ}\text{C}$ à $>200^{\circ}\text{C}$ respectivement, une conséquence d'enfouissement sédimentaire et un gradient géothermique élevé ($\geq 45^{\circ}\text{C}/\text{km}$) dû à l'activité du High Arctic Large Igneous Province. Le refroidissement vers la fin du Crétacé a affecté toutes les régions. Durant l'exhumation régionale, associée avec l'initiation de la formation de rifts dans le Bassin Eurasiatique. Pendant le tectonisme Eureka: 1) nos modèles indiquent une période de réchauffement (55-47 Ma) caractérisée par des nappes de charriage et l'absence d'érosion du WSFTB et sédiments du Central Basin provenant du nord du Groenland, suivi par 2) une période de refroidissement (47-34 Ma) due à la transition d'un régime tectonique compressif à un régime coulissant dextre; l'exhumation du WSFTB a coïncidé avec une période de tectonisme à coulissage.

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Table of Contents

Cretaceous-Paleogene low temperature history of the Southwestern Province, Svalbard, revealed by (U-Th)/He thermochronometry: implications for High Arctic tectonism.....	1
Abstract.....	1
1. Introduction.....	2
2. Geological Setting.....	5
2.1 Tectonic Setting.....	5
2.1.1 Southwestern Province	5
2.1.2 Eureka Orogeny.....	7
2.1.3 High Arctic Large Igneous Province.....	9
2.2 Sedimentary Record on Svalbard	10
2.2.1 Pre-Cretaceous sedimentary record.....	11
2.2.2 Cretaceous sedimentary record.....	11
2.2.3 Paleogene sedimentary record.....	12
2.2.3.1 Central Basin	12
2.2.3.2 Forlandsundet Graben	16
3. Methodology	14
3.1 Sampling strategy and processing.....	14
4. Results	17
4.1 (U-Th)/He apatite dates	17
4.2 (U-Th)/He zircon dates.....	18
5. Discussion of apatite and zircon (U-Th)/He dates.....	19
5.1 Variability of apatite (U-Th)/He dates	20
5.2 Variability of zircon (U-Th)/He dates	20
5.3 Apatite and zircon date discrepancies	21
6. Numerical Model Constrains	23
6.1 Torellian and Caledonian Orogenies	23
6.2 Post-Caledonian	24
7. HeFTy Forward Modeling	26
7.1 Sørkapp Land	29

7.2 Wedel Jarlsberg Land.....	31
7.3 Oscar II Land.....	33
7.4 Prins Karls Forland.....	34
8. Late Mesozoic/Cenozoic Tectonothermal History of the Southwestern Province	35
8.1 Lower to Upper Cretaceous and influence of HALIP	36
8.2 Paleogene	38
8.2.1 Implications for Eureka tectonism.....	39
9. Conclusions	43
Acknowledgments	45
References	45
Figures.....	62
Tables	78

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Abstract

We apply apatite and zircon (U-Th)/He low-temperature thermochronometry to the Southwestern Province of Svalbard to investigate the shallow crustal tectonics of Svalbard and the High Arctic. We resolve Cretaceous through Paleogene time-temperature histories for four regions of the province (Sørkapp Land, SKL; Wedel Jarlsberg Land, WJL; Oscar II Land, OII; Prins Karls Forland, PKF). Zircon results follow predicted date-eU correlations for detrital samples. Results indicate peak late Cretaceous temperatures of $\sim 185^{\circ}\text{C}$ in the south (SKL, WJL), and $>200^{\circ}\text{C}$ in the north (OII) as a consequence of maximum sedimentary burial and elevated geothermal gradient ($\geq 45^{\circ}\text{C}/\text{km}$) from High Arctic Large Igneous Province activity. Late Cretaceous cooling affected all regions during regional exhumation related to initial rifting in the Eurasian Basin to the north. A subsequent heating event (recorded at WJL and OII) from 55-47 Ma is interpreted to result from tectonic burial during Eurekan compressional tectonism and development of the West Spitsbergen Fold-and-Thrust Belt (WSFTB). Erosion of the WSFTB during growth of the orogenic wedge was negligible and sediments for the Central Basin may have been derived from the Wandal Hav Mobile Belt in eastern north Greenland. Our thermal models reveal a subsequent cooling event (47-34 Ma) corresponding to a shift in tectonic regime from compression to dextral strike-slip kinematics during the Eurekan event; exhumation of the WSFTB coincided with strike-slip tectonics. Throughout Eurekan tectonism, PKF resided at temperatures $>200^{\circ}\text{C}$ and records exhumation during post-34 Ma extensional tectonism. Our

models indicate 2.5-3.5 km of exhumation in WJL and OII, and >4 km of exhumation of PKF, which is a deeper crustal level of the WSFTB than other exposures on Spitsbergen.

Keywords

(U-Th)/He thermochronology, Southwestern Province, West Spitsbergen Fold-and-Thrust Belt, Wandel Hav Mobile Belt

Key points

1. The importance of understanding and utilizing (U-Th)/He date dispersions in developing low temperature thermal histories
2. Time-temperature evolution of the Southwestern Province during the Cretaceous in response to HALIP activity, sedimentation patterns and initial rifting of the Eurasian Basin
3. Time-temperature evolution and termination of the West Spitsbergen Fold-and-Thrust Belt during the Paleogene and its relationship with Eurekan tectonism on northern Greenland

1. Introduction

We apply (U-Th)/He thermochronology to the Southwestern Province of Svalbard (**Figure 1, 2**) to evaluate its Cretaceous and Paleogene low temperature thermal history in the context of High Arctic tectonism. During this period of time, the Arctic witnessed several crustal breakup and collisional events. In the Cretaceous, arrival of the High Arctic Large Igneous Province (HALIP; **Figure 1**) is interpreted to be at c. 130 Ma based on a regional High Arctic unconformity [Maher, 2001; Galloway et al., 2016] whereas the same unconformity is considered evidence for initiation of seafloor spreading in the Amerasian Basin [Embry and Dixon, 1992; Pease et al., 2014]. Late Cretaceous emplacement of a rift-related alkaline suite is recognized at c. 85-65 Ma across the northern Canadian Arctic Islands and northern Greenland

[Tegner et al., 2011a,b; Thórarinnsson et al., 2015] possibly associated with initial rifting in the Eurasian Basin [Harland, 1997; Døssing et al., 2013a; Thórarinnsson et al., 2015].

Tectonics in the Paleogene was dominated by the Eurekan Orogeny, which resulted from movement of the Greenland microplate in response to episodic spreading of several ocean basins surrounding the microplate. Currently, the record of Eurekan tectonism is fragmented across the High Arctic, preserved on the Canadian Arctic Islands, northern Greenland and Svalbard. This spatial fragmentation has resulted in several site specific studies of the Eurekan Orogeny which in turn has led to contradictory interpretations of its tectonic evolution [Tessensohn and Piepjohn, 2000]. We examine the time-temperature history of the Eurekan Orogeny on Svalbard, and interpret the geological history with consideration of the correlative tectonic domains in northern Greenland.

On Svalbard, Eurekan tectonism is manifest as the West Spitsbergen Fold-and-Thrust Belt (WSFTB; **Figure 3**). Although the WSFTB has been interpreted to have formed during the Eocene [e.g. Maher et al., 1995; CASE Team, 2001], the kinematics are still the subject of debate. Initial investigations of the WSFTB evolution, taking into account the late Cretaceous/Paleogene plate movements, concluded that the WSFTB formed as a product of transpression along a major intracontinental shear zone, termed the De Greer Fracture Zone (DGFRZ; **Figure 3**) [e.g. Lowell, 1972; Steel et al., 1985; Harland, 1997]. However, other investigations of the WSFTB structures have pointed to a more compressional style of deformation [e.g. Dallmann et al., 1993; Lyberis and Manby, 1993; CASE Team, 2001]. Considering the location of the WSFTB adjacent to the De Greer Fracture Zone, a decoupling of stress regimes has been invoked to explain such compressive structures flanking the DGFRZ [Faleide et al., 1988; Lepvrier et al., 1992; Maher et al., 1997]. Consequently, these previous

studies can be summarized into two end-member models: 1) orthogonal compression followed by dextral strike-slip tectonism [CASE Team, 2001; Saalman and Theidig, 2002; Piepjohn et al., 2016] or 2) dominant transpressional evolution analogous to the modern day San Andreas Fault system [Braathen et al., 1995; Braathen et al., 1999; Leever et al., 2011].

On northern Greenland, Eurekan deformation is recognized as the Kap Cannon Thrust Zone (KCTZ), the Harder Fiord Fault Zone (HFFZ) and the Wandel Hav Mobile Belt (WHMB) (**Figure 3**). The KCTZ and HFFZ are characterized by orthogonal compression [von Gosen and Piepjohn, 1999; Piepjohn and von Gosen, 2001] whereas the WHMB is dominated by transpressional structures [von Gosen and Piepjohn, 2003]. Plate reconstructions of Svalbard relative to Greenland [e.g. Harland, 1969; Srivastava, 1985; Stemmerik and Håkansson, 1991; Buchan and Ernst, 2006] place the WSFTB as the along-strike continuation of the KCTZ, trending sub-parallel to the structures of the WHMB previously located in the hinterland of the WSFTB (**Figure 3**). In contrast to the WSFTB, the timing of deformation, and not the structural style, is the subject of debate for deformation in northern Greenland. An Eocene age has been proposed, coeval with the WSFTB on Svalbard [e.g. Tessensohn and Piepjohn, 2000; von Gosen and Piepjohn, 2003], and therefore contrasts arguments for late Cretaceous/Paleocene tectonism [e.g. Lyberis and Manby, 2001; Guarnieri, 2015]. When considering Svalbard and northern Greenland in a reconfigured context, Eurekan tectonism requires a uniform model of tectonic evolution across western Svalbard and northern Greenland. In order to provide a geologically accurate interpretation of the WSFTB through our thermal models, we must reconcile Eurekan Svalbard tectonics with that of northern Greenland.

Application of numerical t-T models for the Southwestern Province, combined with an understanding of the regional tectonics and sedimentation patterns, reveals Cretaceous heating

linked to sedimentary deposition and an elevated geothermal gradient, followed by c. 85-65 Ma cooling resulting from the exhumation of Svalbard during incipient rifting of the Eurasian Basin. Our data also support c. 55-47 Ma heating directly followed by cooling until c. 34 Ma, consistent with a middle Eocene change from compressional to dextral strike-slip tectonic evolution of the WSFTB. Continued cooling is observed during post-34 Ma transtensional/extensional tectonics. From these model results, we propose the WHMB acted as a sediment source region for the Central Basin from c. 55-47 Ma, supporting coeval development of Eurekan tectonism on Svalbard and northern Greenland in the Eocene. Such an interpretation invokes partitioning of deformation along pre-existing shallow crustal structures.

2. Geological Setting of Svalbard

2.1 Tectonic Setting

2.1.1 Southwestern Province

Svalbard comprises three Caledonian Basement Provinces, referred to as the Northeastern, Northwestern and Southwestern Provinces (**Figure 2**). These provinces were assembled during the Caledonian Orogeny (c. 470-420 Ma) and are differentiated in terms of their geological history, constituent rock types and metamorphic grades related to pre- and syn-Caledonian metamorphism [Gee and Tebenkov, 2004]. Our investigation focuses on the Southwestern Province which consists of pre-Carboniferous crystalline basement deformed and metamorphosed during the Caledonian Orogeny and the c. 360 Ma Ellesmerian Orogeny [Piepjohn et al., 2015]. This pre-Carboniferous basement was incorporated into the West Spitsbergen Fold-and-Thrust Belt during the c. 55-34 Ma Eurekan tectonism. The majority of the Southwestern Province is exposed along the western margin of the main island of Spitsbergen,

but also on Prins Karls Forland, an elongate north-south island separated from Spitsbergen by the Forlandsundet Graben (**Figure 2**), that opened during late Eureka tectonism [CASE Team, 2001].

The Southwestern Province was metamorphosed to greenschist facies conditions during the Caledonian Orogeny [e.g. Dallmann, 2014]; however, localities of amphibolite facies rocks within the Southwestern Province have also been identified [Maneck et al., 1998; Gee and Tebenkov, 2004; Majka et al., 2004; Majka et al., 2008; Majka et al., 2010]. In southwestern Wedel Jarlsberg Land (**Figure 4**), upper greenschist to lower amphibolite facies metavolcanics and metasediments of the Eimfjellet Formation are thrust over the amphibolite facies metasediments of the Isbjørnhamna Formation [Gee and Tebenkov, 2004]. Amphibolite facies metamorphism at this locality occurred at c. 640 Ma at peak conditions of 670°C, which corresponds to the late Cryogenian Torellian Orogeny [Majka et al., 2008; Majka et al., 2010]. This package of rocks was retrogressed during Caledonian greenschist metamorphism [Majka et al., 2004]. The southernmost portion of Sørkapp Land (**Figure 4**) also contains amphibolite facies metasediments that may correlate to the Isbjørnhamna Formation. Amphibolite facies metasediments have also been mapped on Prins Karls Forland, termed the Pinkie Unit (**Figure 4**) [Hjelle et al., 1999 and references therein]. These rocks are tectonically overlain by metasediments of Grampianfjellet Formation, which likely experienced weak Caledonian metamorphism and were displaced along the Bouréefjellet shear zone. Preliminary total-Pb monazite dating from the Bouréefjellet shear zone yields Ellesmerian ages of c. 360-370 Ma [Kośmińska et al., 2016].

2.1.2 Eurekan Orogeny on Svalbard

Eurekan deformation across the High Arctic is the result of complex tectonism related to the movement of the Greenland microplate in relation to the Laurentian and Eurasian plates [Harrison et al., 1999; CASE Team, 2001; Dallmann, 2014]. Plate motion was controlled by sea-floor spreading in the Labrador Sea and Baffin Bay to the west of Greenland and in the North Atlantic to the east of Greenland [Srivastava, 1978; Srivastava and Tapscott, 1986; Roest and Srivastava, 1989] and associated activity in the Eurasian Basin (**Figure 1**) [Srivastava, 1985]. Kilometer-scale folds, thrusts and strike-slip faults associated with Eurekan compression can be observed across the Canadian Arctic Islands, northern Greenland and Svalbard [Piepjohn et al., 2015].

On Svalbard, the Eurekan Orogeny is manifest as the West Spitsbergen Fold-and-Thrust Belt (WSFTB), an intracontinental fold-and-thrust belt, which formed during the late Paleocene/early Eocene to possibly early Oligocene [e.g. Maher et al., 1995; CASE Team, 2001; Dallmann, 2014] at the continental plate boundary between Greenland and Eurasia. The WSFTB accounts for c. 10-40 km of margin perpendicular shortening [Piepjohn et al., 2001; Saalman and Theidig, 2002] with a principal stress axis oriented perpendicular (ENE-WSW) to the trend of the structures [Manby and Lyberis, 2001a]. The WSFTB is segmented into a northern and southern region based on structural styles, separated by a dextral strike-slip tear fault located within Isfjorden (**Figure 2**) [CASE Team, 2001]. In Oscar II Land, deformation is characterized by ENE-vergent, km-scale, basement-dominated thrust sheets bounded by listric faults progressing eastward into thin-skinned decollement thrusting within the post-Caledonian cover strata [Manby and Lyberis, 2001b], classic structures for fold-and-thrust belts. The easternmost margin is characterized by emergent thrusting of post-Caledonian cover strata onto the foreland.

South of Isfjorden, the structural style is more convoluted with development of decollement structures within post-Caledonian cover strata followed by basement-involved thrusts and related folds in the cover strata thrust sheets [von Gosen and Piepjohn, 2001a]. These trends continue southwards into Wedel Jarlsberg Land. However, in some regions the broad folds are cut by east-dipping thrusts that have subsequently been folded. Several of the large-scale NNW-SSE trending fold structures continue further southwards through eastern Hornsund and into Sørkapp Land. In contrast to the northern segment, the WSFTB in the southern segments do not display emergent thrusts over the foreland as in the north; Cenozoic sediments adjacent to the eastern limit of deformation are not overthrust. Rather, the eastern limit of the fold-thrust belt is characterized by buried thrusts and decollement structures that underlie the Central Basin [CASE Team, 2001]. The structural style of the southern segment suggests the influence of pre-existing crustal blocks controlling the style and evolution of faulting [von Gosen and Piepjohn, 2001a,b], although evidence for Eurekan overprinting of older structures is also apparent in the northern segment.

Since Caledonian and Ellesmerian structures were commonly reactivated during Eurekan compression [Craddock et al., 1985; Dallmann, 1992; Piepjohn et al., 2015], it is often difficult to distinguish Eurekan structures from Caledonian/Ellesmerian structures in regions that lack post-Carboniferous cover strata. For example, total-Pb monazite dating from the Bouréefjellet shear zone on Prins Karls Forland yielded ages of c. 360-370 Ma [Kośmińska et al., 2016] yet $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite dates from the same shear zone are Eurekan [Schneider et al., unpublished data]. Except for muscovite recrystallization along foliation planes and slip surface, the Eurekan orogeny on Svalbard exhibits no apparent metamorphism.

Two slightly different models of WSFTB evolution populate the literature, either forming from orthogonal compression (c. 55-47 Ma) followed by dextral strike-slip displacement (c. 47-34 Ma) [CASE Team, 2001; Saalman and Theidig, 2002; Piepjohn et al., 2016] or a dominant transpressional evolution [Harland, 1969; Bergh and Braathen, 1995; Braathen et al., 1999; Leever et al., 2011] akin to the modern day San Andreas Fault system [Braathen et al., 1995]. Both scenarios terminate with a c. 34 Ma shift to transtensional/extensional tectonics associated with the separation of Svalbard from Greenland [e.g. Braathen et al., 1999; CASE Team, 2001; Piepjohn et al., 2016]. Blythe and Kleinspehn [1998] report apatite fission track cooling dates of the WSFTB (for samples with $>50\%$ χ^2 probability) of 55.7 ± 4.7 Ma and 39.5 ± 5.7 Ma for samples from the Kongsfjorden Basin (north of Oscar II Land), and 53.0 ± 9.2 Ma to 29.3 ± 8.8 for samples of crystalline basement from Oscar II Land and southward.

2.1.3 High Arctic Large Igneous Province

The High Arctic Large Igneous Province is present across Svalbard, Franz Josef Land, northern Greenland, the northern Canadian Arctic Islands and as the Alpha Ridge in the Amerasian Basin (**Figure 1**). The HALIP is preserved as tholeiitic dolerite intrusives and basalt flows [Maher, 2001; Buchan and Ernst, 2006; Ernst and Bleeker, 2010; Nejbert et al., 2011, Jowitt et al., 2013; Senger et al., 2014]. On Svalbard, dolerite sills within the Carboniferous to Jurassic strata are prevalent across central Spitsbergen whereas basalt flows are prominent in the eastern parts of the archipelago where they are intercalated with the Lower Cretaceous Helvetiafjellet Formation on Kong Karls Land (**Figure 2**) [Dallmann, 2014].

The HALIP is interpreted to be the result of a mantle plume that arrived to the base of the lithosphere in the early Cretaceous. The proposed location of the plume centre is the southern

portion of the Alpha Ridge (**Figure 1**) is based on convergence of dyke swarms, particularly in the Canadian Arctic and Franz Josef Land [Buchan and Ernst, 2006] and magnetic anomalies over the southern Alpha Ridge [Døssing et al., 2013a]. The HALIP lacks definitive geochronological resolution. Magnetic and stratigraphic ages of the HALIP suggest a duration spanning from 130-90 Ma [Buchan and Ernst, 2006]. This duration is generally consistent with K/Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ dates from HALIP localities across the Arctic, perhaps with two main pulses occurring at 130-120 Ma and 115-90 Ma. [Maher, 2001; Buchan and Ernst, 2006; Ernst and Bleeker, 2010; Nejbert, 2011]. The dispersion of dates for the K/Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ systems has also been interpreted as partial resetting of the chronometers for localities on Svalbard [Corfu et al., 2013]. Zircon and baddeleyite U-Pb studies on Svalbard sills and Franz Josef Land dykes yield emplacement ages of c. 125-122 Ma [Corfu et al., 2013], and ages of sills between 130-120 Ma in the Sverdrup Basin of the Canadian Arctic [Evenchick et al., 2015]. Detrital zircon U-Pb analysis of Central Basin sediments, however, reveal a range of Cretaceous zircon ages, supportive of protracted HALIP magmatism [Petersen et al., 2016].

2.2 Sedimentary record on Svalbard

Within this subsection, we present a brief summary of the sedimentary record on Svalbard, outlining key points that are essential for constructing and interpreting our thermal models. Understanding the contribution of heating from sedimentary overburden provides a means to isolate the effects of tectonic or thermal events which may have perturbed the evolution of the thermal history. Additionally, we summarize key thermochronological studies and investigate Cretaceous and Paleogene sedimentary patterns to establish and corroborate our tectonothermal interpretations.

2.2.1 Pre-Cretaceous sedimentary record

Maximum cumulative thickness of sedimentary overburden from the Carboniferous to the pre-Cretaceous is estimated to be ~4.6 km [Dallmann, 2014]. Although, during the Ellesmerian Orogeny, a series of structural highs and lows developed across Svalbard and restricted deposition of Lower Carboniferous deposits (1000 m thick) to localized fault-bounded basins. Upper Carboniferous to Lower Permian deposits (1800 m thick) covered the majority of Svalbard with the exception of the Sørkapp-Hornsund High (S-HH) [Steel and Worsley, 1984; Bergh et al. 2011], a N-S trending basement high extending across Sørkapp Land and southern Wedel Jarlsberg Land. The S-HH is unconformably overlain by Triassic sediments [von Gosen et al., 2001], reducing estimates of pre-Cretaceous maximum sedimentary overburden to ~1.6 km for parts of Sørkapp Land and southern Wedel Jarlsberg Land.

2.2.2 Cretaceous sedimentary record

In the Lower Cretaceous section, the Rurikfjellet Formation (400 m thick) is truncated by a Lower Cretaceous unconformity (c. 130 Ma) across Svalbard recording tectonically-driven, short-lived uplift of the region [Maher, 2001; Dallmann, 2014]. Unconformities of similar age are also reported on Franz Josef Land and the Sverdrup Basin in the Canadian Arctic, and have been interpreted to be the result of the onset of sea-floor spreading within the Amerasian Basin [Embry and Dixon, 1992] or associated with the arrival of the HALIP plume [Maher, 2001; Galloway et al., 2016]. Subsequent deposition of the Helvetiafjellet Formation (155 m thick) indicates marine transgression on Svalbard [Gjelberg and Steel, 1995] following exposure. The Helvetiafjellet Formation transitions upwards into the overlying Lower Cretaceous Carolinefjellet Formation (1100 m thick). Collectively, these two formations record southward

tilting of Svalbard as a result of tectonism that drove uplift of Svalbard in the early Cretaceous. Uplift of Svalbard in the late Cretaceous is also evident by an unconformity that separates the Carlinefjellet Formation from overlying Paleocene strata; Upper Cretaceous strata is absent on Svalbard [Maher, 2001; Maher et al., 2004; Dallmann, 2014]. This Upper Cretaceous unconformity is likely the result of rift-flank uplift during initiation of the Eurasian Basin [Harland, 1997; Thórarinnsson et al., 2015] and is also characterized by greater uplift in the northern regions of Svalbard [Maher et al., 2004]. Dörr et al. [2012] suggested that northern Svalbard experienced 2-3 km of exhumation in the Mesozoic (at a 20-30°C/km geothermal gradient) with the majority of exhumation occurring prior to the late Cretaceous. In addition, exhumation of the island of Bjørnøya, the southernmost island of Svalbard (**Figure 1**), also records >60°C of cooling related to exhumation during the late Cretaceous [Ritter et al., 1996]. Thus, the aerial extent of Svalbard would have been exhumed during this time if these two events are tectonically related. Exhumation in the late Cretaceous likely did not exceed ~1-2 km.

2.2.3 Paleogene sedimentary record

2.2.3.1 Central Svalbard

The Van Mijenfjorden Group, preserved across central Svalbard [Steel et al., 1985; Manum and Throndsen, 1986], comprises ~720 m Paleocene lower succession and a ~1550 m late Paleocene/early Eocene to early Oligocene upper succession [Manum and Throndsen, 1986; Helland-Hansen, 1990; Müller and Spielhagen, 1990; Grundvåg et al., 2014]. Deposition of the upper succession is a consequence of Eureka tectonism and records an eastward prograding fill of the Central Basin, the foreland basin to the WSFTB [Steel et al., 1985; Helland-Hansen, 1990; Müller and Spielhagen, 1990]. Detrital zircon analysis conducted by Petersen et al. [2016]

indicates an eastern or northeastern provenance for the lower succession and confirms a western provenance for the upper succession, a consequence of Eurekan tectonism. Thermal models from AFT data presented by Blythe and Kleinspehn [1998] demonstrate exhumation of these source terrains some time before 65 Ma for the lower succession and after 55 Ma for the upper succession, reflecting late Cretaceous exhumation of Svalbard in the east/northeast (>65 Ma), followed by Paleogene exhumation related to Eurekan tectonism in the west (<55 Ma).

2.2.3.2 Forlandsundet Graben

Paleogene deposition is also recorded in the Forlandsundet Graben, situated within the northern segment of the WSFTB (**Figure 2**). The graben has been interpreted to have initiated as a late Eocene pull-apart basin during dextral strike-slip tectonics [e.g. CASE Team, 2001] or as a piggy-back basin during transpressional thrusting [Kleinspehn and Teyssier, in press]. Eurekan structures which have been identified in Oscar II Land [CASE Team, 2001] and Prins Karls Forland [Schneider et al., unpublished data] in addition to a lack of large-scale thrusting within the Forlandsundet basin fill [CASE Team, 2001] indicate that the structures of the Forlandsundet Graben post-date Eurekan thrusting. Sediments of the Forlandsundet Graben crop out on the eastern (Oscar II Land) and western (Prins Karls Forland) margins of the graben and display depositional contacts with Caledonian basement. Sediments on the eastern margin have been constrained to a c. 38-31 Ma depositional age [Cepek, 2001; Kleinspehn and Teyssier, in press]. We are not aware of age constraints for the exposures on the western side of the basin, however, vitrinite reflectance values indicate that strata on the western side of the graben were more deeply buried than those on the east side and represent older stratigraphic levels [Kleinspehn and Teyssier, 1992 and references therein].

3. Methodology

3.1 Sampling strategy and processing

Apatite and zircon (U-Th)/He thermochronometry are powerful tools for evaluating the time-temperature (t-T) histories of shallow crustal processes [Stockli, 2005; Fitzgerald et al., 2006; Reiners and Brandon, 2006; Flowers et al., 2009; Tian et al., 2012; Guenthner et al., 2013, 2014, 2015; Powell et al., 2016]. Four regions were selected for resolving the Southwestern Province low temperature thermal history. From south to north, these regions are: southern Sørkapp Land (SKL), southern Wedel Jarlsberg Land (WJL), Oscar II Land (OII), and northern Prins Karls Forland (PKF) (**Figure 4**). Since an apparent deeper exhumation of northern Svalbard was recorded in the Cretaceous, a north-south profile of the Southwestern Province allows our study to resolve such an unroofing pattern. Additionally, our WJL, OII and PKF samples are all associated with Eurekan compressional structures compared to southern SKL which is overlain by undeformed Triassic sediments (**Figure 4**) [von Gosen et al., 2001] and therefore are probably not affected by Eurekan deformation. We sampled metagabbros/amphibolites likely of pre-Caledonian age (n: 4) for apatite, and quartzite/metasediments (n: 21) of Neoproterozoic depositional age for zircon. Detrital zircon U-Pb analysis has revealed zircon ages predominantly ranging from the Neoproterozoic to the Paleoproterozoic, with some Archean contribution [Kośmińska et al., 2015].

To conclude that (U-Th)/He dates from slowly cooled rocks possess a single closure temperature for the diffusion of ^4He is most probably misleading and an oversimplification. Instead, the system involves a partial retention zone (PRZ), defined between temperatures of 40-80°C for apatite [Farley, 2000] and 130°C-200°C for zircon [Wolfe and Stockli, 2010]. Using HeFTy [Ketcham, 2005], we employ the Radiation Damage and Annealing Model (RDAAM) for

apatite (U-Th)/He [Flowers et al., 2009] and the Zircon Radiation Damage and Annealing Model (ZRDAAM) [Guenther et al., 2013] for zircon to explore our ^4He datasets and to produce thermal models that account for the ^4He date dispersions, allowing us to interpret meaningful geological processes from a complex dataset through a 150°C window.

Apatite and zircon were separated using standard rock crushing and heavy mineral separation procedures. Selections of apatite grains were based on four major criteria: 1) absence of inclusions; 2) grain size; 3) minimal surface abrasion; and 4) grain shape. Despite our best efforts, many apatite grains possessed inclusions, which prompted us to modify our dissolution protocols to follow the zircon dissolution methods (see below). The abundance of zircon provided an effortless selection of grains. A variety of grain sizes and morphologies were selected for analysis; fractured and heavily abraded zircons were avoided. We analyzed 3-5 apatite grains per sample and 6-8 zircon grains per sample; **Table 1** presents the general details of each sample.

(U-Th)/He thermochronology was conducted at the CU TRaIL (Thermochronology Research and Instrumentation Laboratory) (U-Th)/He facility at the University of Colorado at Boulder, USA. Individual mineral grains are handpicked using a Leica M165 binocular microscope equipped with a calibrated digital camera and capable of both reflected and transmitted, polarized light. The grains are screened for quality, including crystal size, shape, and the presence of inclusions. After characterization, grains are placed into small Nb tubes that are then crimped at both ends. This Nb packet is then loaded into an ASI Alphachron He extraction and measurement line. The packet is placed in the UHV extraction line (c. 3×10^{-8} torr) and heated with a diode laser to ~800-1100°C for 5-10 min to extract the radiogenic ^4He . The degassed ^4He is then spiked with approximately 13 ncc of pure ^3He , cleaned via interaction with

two SAES getters, and analyzed on a Balzers PrismaPlus QME 220 quadrupole mass spectrometer. Degassed grains are then removed from the line, and taken to a Class 10 clean lab for dissolution. Apatite grains, still enclosed in the Nb tubes, are placed in 1.5 mL Cetac vials, spiked with a ^{235}U - ^{230}Th tracer in HNO_3 , capped, and baked in a lab oven at 80°C for 2 h. Zircon and apatite with inclusions are dissolved using Parr large capacity dissolution vessels in a multi-step acid-vapor dissolution process. Grains (including the Nb tube) are placed in Ludwig-style Savillex vials, spiked with a ^{235}U - ^{230}Th tracer, and mixed with 200 μL of Optima grade HF. The vials are then capped, stacked in a 125 mL Teflon liner, placed in a Parr dissolution vessel, and baked at 220°C for 72 h. After cooling, the vials are uncapped and dried down on a 90°C hot plate until dry. The vials then undergo a second round of acid-vapor dissolution, this time with 200 μL of Optima grade HCl in each vial that is baked at 200°C for 24 h. Vials are then dried down a second time on a hot plate. Once dry, 200 μL of a 7:1 HNO_3 :HF mixture is added to each vial, the vial is capped, and cooked on the hot plate at 90°C for 4 h. Once the minerals are dissolved, regardless of the dissolution process, they are diluted with 1 to 3 mL of doubly-deionized water, and taken to the ICP-MS lab for analysis. Mineral standards of Durango Apatite (31.5 Ma) and Fish Canyon Tuff Zircon (28.2 Ma) are routinely analyzed (degassed and dissolved) in conjunction with the samples with each run to ensure data integrity. Sample solutions, along with standards and blanks, are analyzed for U, Th, and Sm content using a Thermo Element 2 magnetic sector mass spectrometer. Once the U, Th, and Sm contents have been measured, He dates and all associated data are calculated in a custom spreadsheet made by CU TRaIL staff.

4. Results

We report AHe and ZHe dates that have been corrected for α -ejection using the methods of Farley [2002]. We plot our He dates against effective uranium (eU) content, a proxy for radiation damage which has a profound effect on ^4He retention; in apatite positive date-eU correlations are predicted [cf. Flowers et al., 2009] whereas in zircon, Gaussian correlations are predicted, commonly with a positive skew [cf. Guenthner et al., 2013, 2014; Powell et al., 2016]. A summary of important information for all AHe and ZHe samples can be found in **Table 1** and **2**, and more complete apatite and zircon (U-Th)/He data tables can be found in **Table S1** of the supplementary data.

4.1 (U-Th)/He apatite dates

The majority of the meta-igneous samples from the WSFTB did not yield apatite grains, and the samples that did provided poor quality grains. Our AHe results reveal a large dispersion in both AHe dates and eU values (**Figure 5**); AHe samples have been grouped according to dissolution method used during analysis since the two methods provided different AHe date-eU dispersion patterns. Eight single grain analyses from two samples collected from Wedel Jarlsberg Land (SP_6307, SP_6807) yield significantly different ranges in AHe dates, eU, and corresponding trends between samples. Three grains from SP_6307 (using apatite dissolution methods) yield AHe dates between 16.6 ± 3.1 Ma to 54.9 ± 4.1 Ma and eU values of 0.6-5.0 ppm with a positive date-eU trend, whereas five grains from SP_6807 provided AHe dates from 70.3 ± 4.9 Ma to 117.8 ± 7.5 Ma and eU values of 13.4-30.0 ppm with a negative date-eU trend. Five single grain analyses from an Oscar II Land sample (CB15_OII_2; dissolved using apatite dissolution methods) revealed eU values between 1.4-2.7 ppm and dates of 33.7 ± 3.4 Ma to 57.6

± 5.6 Ma (and a single older date of 160.8 ± 14.7 Ma) with a positive date-eU trend. Three single grain analyses from a sample from Prins Karls Forland (CB15_PKF_1; using zircon dissolution methods) yield eU values of 7.6-40.6 ppm and AHe dates of 16.3 ± 1.1 Ma to 66.5 ± 7.2 Ma with a positive date-eU trend. Overall, AHe dates for each of the three regions are similar with positive date-eU trends, with the exception of SP_6807 that possesses a negative date-eU trend.

4.2 (U-Th)/He zircon dates

ZHe dates have been grouped corresponding to their sample region since the scale of the Southwestern Province (100's of km) is at least one order of magnitude greater than the distances between sample locations (1-10 km) within a sample region (**Figure 4**). Our ZHe dates reveal large intra-regional date dispersions in addition to significant inter-regional differences in the ZHe date-eU correlations (**Figure 6**).

Twenty-four single grain zircon analyses of four samples collected from the southern SKL provide the oldest ZHe date population and a large dispersion between 114.0 ± 8.2 Ma to 319.9 ± 23.0 Ma with a single grain at 77.7 ± 5.7 Ma. Effective uranium values for SKL zircons show a range from 52.6-319.6 ppm. Forty-two single grain zircon analyses from six samples obtained from WJL show ZHe dates that are overall younger than SKL yet still possess a large dispersion between 42.8 ± 3.11 Ma to 140.8 ± 17.7 Ma with one younger grain of 33.6 ± 2.6 Ma and three grains with older ZHe dates at 205.1 ± 14.7 Ma, 214.5 ± 15.7 Ma and 239.7 ± 18.4 Ma. WJL zircon eU value range between 43.0-516.0 ppm, with the exception of three grains at 769.1, 826.3 and 1644.1 ppm which yielded some of the youngest ZHe dates. Twenty-three single grain zircon analyses from three samples obtained from OII yield a small range of ages between 45.1 ± 3.1 Ma to 68.4 ± 4.8 Ma that falls within the younger half of the trend of the WJL ZHe dates, but

does not contain any ZHe dates older than 68.4 ± 4.8 Ma (i.e. within the older half of the WJL ZHe date trend). Effective uranium values for OII are between 70.9-463.4 ppm with the exception of two grains at 721.1 and 897.7 ppm which have ZHe dates of 55.5 ± 3.9 Ma and 49.5 ± 3.5 Ma, respectively. In contrast to the previous samples locations, nineteen single grain zircon analyses from four samples obtained from PKF provide ZHe dates that are younger than the other sample regions and are defined by a smaller distribution from 23.8 ± 1.7 Ma to 38.5 ± 4.5 Ma, with 80% of dates between c. 29-33 Ma. Effective uranium values for PKF show a range from 154.4-388.4 ppm.

5. Discussion of apatite and zircon (U-Th)/He dates

If temperatures were insufficient to reset our grains since the Caledonian Orogeny, the most recent definitive resetting event, then AHe and ZHe dates should reflect Caledonian (c. 470-420 Ma) or potentially Ellesmerian (c. 360 Ma) cooling. Our samples exhibit AHe and ZHe dates that are significantly younger than the age of the Caledonian or Ellesmerian events suggesting that they have experienced ^4He loss since the Paleozoic. Moreover, both AHe and ZHe datasets yield large ^4He date dispersions within individual regions. Significant differences in range of ZHe date dispersion also exist between the four sample regions (**Figure 6**).

These large He date dispersions result from intrinsic (e.g. grain volume, radiation damage) and extrinsic (e.g. temperature) factors affecting the retention of radiogenic ^4He . Past studies have often neglected date dispersion in AHe and ZHe datasets, which consequently result in interpretations that are oversimplified (e.g. averaging of ages) and do not fully utilize the dataset. We aim to avoid such methods by employing RDAAM [Flowers et al., 2009] and ZRDAAM [Guenther et al., 2013], allowing us to quantify the large ^4He date dispersions to

utilize the dataset to its full potential to produce a more accurate and informative time-temperature history. To correctly model our datasets, we will first discuss potential factors for such ^4He date dispersions, both amongst and between our samples regions, as well as predicted relationships between AHe and ZHe dates.

5.1 Variability of apatite (U-Th)/He dates

Effective uranium concentrations for samples CB15_OII_2 and SP_6307 are significantly less than samples CB15_PKF_1 and SP_6807, a predicted result considering the U- and Th-rich inclusions within the latter. Additionally, samples CB15_OII_2, CB15_PKF_1, and SP_6307 follow predicted positive AHe date-eU trends with similar ranges in AHe dates. In contrast, SP_6807 provides a negative AHe date-eU with significantly older AHe dates, reflecting the older half of ZHe dates also from WJL. Almost certainly, the anomalies for this sample are due to the abundance of inclusions in these apatites (a much greater abundance than CB15_PKF_1), but we cannot confidently suggest appropriate phenomena.

5.2 Variability of zircon (U-Th)/He dates

The ZHe date variations between the four regions are likely the result of different thermal histories. Intrinsic factors of the zircon grains controlling the ZHe date distributions can be largely discounted because: 1) all zircons were obtained from Neoproterozoic quartzites and metasediments that exhibit very similar detrital zircon populations [Kośmińska et al., 2015]; 2) there are no distinct differences in ZHe date-eU correlations for samples that have only been subjected to greenschist facies metamorphism compared to samples that were subjected of amphibolite facies metamorphism and later retrogressed under greenschist facies conditions; 3)

dispersion in eU is similar between the four sample regions suggesting no significant differences in accumulated radiation damage; and 4) we do not consider grain size to be a significant factor to explain the single-grain date dispersion in our datasets. Grain volume of apatite and zircon can have a strong positive effect on AHe and ZHe dates [Reiners and Farley, 2001; Reiners et al., 2004] but our data do not show convincingly positive correlations between grain size and dates (**Figure S1** in the supplementary files). In light of the points discussed above, it is likely that the differences in ZHe dates between our four sample regions is not a product of intrinsic factors of the zircon, but rather a consequence of thermal histories unique to each sample region.

5.3 Apatite and zircon (U-Th)/He date discrepancy

With their nominal closure temperatures of ^4He diffusion from zircon and apatite, AHe dates are expected to be younger or equal to ZHe dates. Evaluating our apatite and zircon datasets reveals an antithetic relationship; some of our AHe dates for WJL, OII and PKF are older than our youngest single-grain ZHe dates. For example in the PKF sample, three grains yield AHe dates of 16.3 ± 1.1 Ma, 29.9 ± 4.8 Ma and 66.5 ± 7.2 Ma but the nineteen ZHe dates define a tight cluster between c. 29-33 Ma. Preliminary HeFTy inverse modeling of the AHe data, independent from ZHe data, reveals no permissible t-T pathways for samples SP_6307 and CB15_OII_2 that allow the large dispersion in AHe dates with the relatively narrow dispersion in eU and ESR (equivalent spherical radius). Similarly, candidate t-T histories were not successfully achieved for samples CB15_PKF_1 and SP_6807. We conclude that our AHe dataset contain spurious dates, particularly in comparison to our ZHe dataset that follow a date-eU trend as predicted in previous studies [e.g. Guenthner et al., 2013, 2014, 2015; Powell et al., 2016].

We examine possible reasons for anomalously old AHe dates. According to Vermeesch et al. [2007], grains that contain U- and Th-rich inclusions and are dissolved in HNO₃ often result in anomalously old AHe dates, whereas grains dissolved in HF should provide AHe dates which are appropriate to their cooling history, regardless of inclusions. Our anomalous AHe dates in samples SP_6307 and CB15_OII_2 could possibly be explained by U- and Th-rich inclusions, but this explanation does not apply to samples SP_6807 and CB15_PKF_1 since these samples were processed via zircon dissolution methods. Gautheron et al. [2012] discussed the effects of implantation of foreign ⁴He into the apatite crystal from nearby U- and Th-rich minerals that could markedly increase the AHe date, but given the lack of other U- and Th-rich minerals within our rocks, this seems an unlikely explanation for the majority of grains. Elemental zoning within the minerals is a potential explanation for anomalous ages, however the intracrystalline distribution of U and Th was not investigated for our apatite grains and we cannot invoke this phenomenon with much confidence. Whereas these scenarios do provide some reasoning for anomalously old AHe dates, a definite explanation remains elusive for our dataset. Nonetheless, removing AHe dates that are not admissible in the modeling with respect to ZHe dates leaves two acceptable AHe date groups within our datasets. The first AHe date group is c. 32 Ma (OII, PKF) and the second is c. 16 Ma (WJL, PKF). We therefore heavily rely on our ZHe datasets for development of our thermal models, with consideration of AHe dates that are younger than our ZHe dates into our thermal models. We acknowledge that the accuracy of our acceptable AHe dates remain speculative.

6. Numerical Model Constraints

6.1 Torellian and Caledonian orogenies

Nine of our seventeen samples have been subjected to amphibolite facies metamorphism during the Neoproterozoic Torellian Orogeny (**Table 1**) and all samples underwent Ordovician Caledonian greenschist facies metamorphism. Temperatures required for greenschist conditions (~250-450°C) would be sufficient for complete ^4He loss in our detrital Proterozoic zircon grains; therefore all models are constrained such that total ^4He loss and resetting of ZHe dates occurs during c. 420 Ma metamorphism.

Currently, ZRDAAM [Guenther et al., 2013] relies on zircon fission track (ZFT) annealing kinetics to quantify annealing kinetics of α -damage in zircon. A ZFT partial annealing zone (PAZ) of fission track damage is defined by a thermal window of 260-330°C with complete annealing of damage occurring at temperatures >330°C [Yamada et al., 2007]. However, ZFT damage annealing has been observed to be damage-dependant [Marsellos and Garver, 2010] with annealing temperatures as low as 180°C for some heavily fission-track damaged zircon grains [Garver et al., 2005]. In addition, several mechanisms responsible for annealing of α -damage have been recognized [Zhang et al., 2000; Geisler et al., 2001] and ZFT annealing kinetics may not accurately represent these mechanisms [Guenther et al., 2013]. Regardless, according to the current annealing kinetics of the model, low to medium greenschist facies temperatures should be sufficient for at least partial damage annealing, whereas samples that were metamorphosed to amphibolite facies would have experienced temperatures sufficient for complete annealing of fission track damage in zircon, and implied annealing of α -damage. Initial numerical modeling via HeFTy of our dataset with complete annealing of radiation damage during the Torellian, and partial to complete annealing during the Caledonian, does not allow for enough accumulated

radiation damage in the zircon crystals to adequately explain the single grain ZHe date dispersions evinced in our samples. We therefore include in our model a single constraint point at 420 Ma and 240°C, sufficient for complete ^4He loss and resetting of our grains. We avoid placing a broader Caledonian time constraint at 240°C to limit any radiation damage which may be annealed at this temperature according to ZRDAAM annealing kinetics. Additionally, we do not place any constraints in the model for the Torellian Orogeny resulting in complete retention of radiation damage and ^4He during this event as we cannot account for damage annealing during this event, and all ^4He is lost during Caledonian metamorphism. Other studies [e.g. Powell et al., 2016] have also invoked the need to avoid complete annealing of radiation damage for zircon which has been subjected to elevated heating conditions in order to adequately explain ZHe datasets.

6.2 Post-Caledonian

Our sample regions in SKL, and possibly WJL, reside on the Sørkapp-Hornsund High. We therefore constrain SKL and WJL at near-surface temperatures from the Carboniferous into the Triassic based on the preservation of Triassic cover which unconformably overlies our SKL sample sites [von Gosen et al., 2001]. In contrast, OII and PKF were likely buried by at least Upper Carboniferous to Permian strata allowing for the possibility of up to ~2.2 km of sedimentary cover, in addition to the Triassic and younger sedimentary cover. We constrain paleo-temperatures in the early Triassic at a maximum of 90°C, assuming a geothermal gradient of 25°C/km.

In the Cretaceous, we estimate the arrival of the HALIP plume at c. 130 Ma based on the interpretation that the Lower Cretaceous unconformity was produced in response to uplift

generated by the arrival of the plume [Maher, 2001]. Similarly, regional uplift has been interpreted from Lower Cretaceous unconformities on Franz Josef Land [Maher, 2001] and in the Sverdrup Basin of the Canadian Arctic Islands [Galloway et al., 2016] although the latter also has been used to infer the onset of seafloor spreading in the Amerasian Basin [Embry and Dixon, 1992].

Several examples of surface uplift in response to the arrival of a mantle plume exist in the geologic record [e.g. Şengör, 2001; Pik et al., 2003; Saunders et al, 2007]. Most models suggest maximum uplift on the scale of ~1 km occurs closest to the plume centre of the Large Igneous Province prior to eruption [e.g. Underhill and Partington, 1994]. This relationship is well demonstrated with the Emeishan LIP in the South China craton in which Paleozoic platform carbonates record a distinct domal pattern of uplift and are unconformably overlain by Permian flood basalts with the unconformity representing >3 m.y. [He et al., 2003; He et al., 2010; Wu et al., 2016]. The effective diameter of the Emeishan domal uplift pattern reaches ~1600 km with maximum uplift >1 km superimposed on the plume centre [He et al., 2003]. A similar pattern is also preserved with the HALIP plume arrival, interpreted to coincide with the development of the Lower Cretaceous unconformity at c. 130 Ma and subsequent first eruption phase of the HALIP from 130-120 Ma [Corfu et al., 2013; Evenchick et al., 2015]. As a result, we are confident in the interpretation that the Lower Cretaceous unconformity is a manifestation of HALIP plume arrival and not a result of seafloor spreading in the Amerasian Basin. This interpretation does not exclude the possibility that seafloor spreading in the Amerasian Basin did occur at this time as a consequence of HALIP activity [Døssing et al., 2013a], but had a negligible effect on the stratigraphic record of Svalbard.

We interpret the Upper Cretaceous unconformity on Svalbard [Maher, 2001] as the result of exhumation in response to incipient rifting in the Eurasian Basin [Harland, 1997; Thórarinnsson et al., 2015] beginning at c. 85 Ma. Evidence for such rifting in the Eurasian Basin includes the emplacement of alkaline dykes on Ellesmere Island and northern Greenland from c. 85-65 Ma [Tegner et al., 2011a,b; Thórarinnsson et al., 2015] and linear gravity anomalies interpreted to represent a late Cretaceous (c. 80 Ma) extensional structures [Døssing et al., 2013b] parallel to the dykes.

In the Paleogene, the timing of events are well-constrained whereas respective temperatures are relatively unconstrained. We model the Eurekan Orogeny from c. 55-34 Ma [Braathen et al., 1999; CASE Team, 2001; Piepjohn et al., 2016] with temperatures below greenschist facies conditions. Timing of post-Eurekan events are constrained from apatite fission track dating of the WSFTB and the sediments of the Central Basin [Blythe and Kleinspehn, 1998] and 1-D and 2-D backstripping models for Central Basin uplift [Dörr et al., 2013]. We employ the results of Blythe and Kleinspehn [1998] and Dörr et al. [2013] to constrain two post-Eurekan cooling events: the first occurring c. 34-20 Ma and the second occurring c. 10 Ma to present. The latter is coeval with a Miocene uplift event reported for northeast Greenland [Døssing et al., 2016]. Only a single thermal model is presented for the WSFTB in Blythe and Kleinspehn [1998] constraining temperatures to $50^{\circ}\text{C} \pm 15^{\circ}\text{C}$ from c. 25 Ma to 10 Ma.

7. HeFTy Forward Modeling

The development of the Radiation Damage and Annealing Model (RDAAM) for apatite [Flowers et al., 2009], and the Zircon Damage and Annealing Model (ZRDAAM) [Guenther et al., 2013] provides a means of quantifying variability within AHe and ZHe datasets. In order to

investigate potential t-T histories, we use HeFTy modeling software [Ketcham, 2005] in accordance with RDAAM [Flowers et al., 2009] and ZRDAAM [Guenther et al., 2013]. Inverse modeling of the datasets, coupled with t-T constraints derived from the independent geological information, was used for preliminary development of candidate t-T histories (**Figure S2** of the supplementary files). Grains selected for inverse modeling have a range of eU values, grain sizes and He dates that are representative of overall dataset from each sample. Typically 3-4 grains per sample are utilized for a single model. As a result, a broad range of t-T histories can be produced based on the selected grains and variation in geological constraints. As well, inverse models cannot adequately investigate unique pre-depositional histories experienced by detrital grains within a single sample. Consequently, we conduct forward modeling based on the results of the inverse models. Forward modeling allows us to define a single t-T history and compare the resulting He date-eU trends directly with our entire dataset. We are also able to investigate unique pre-depositional histories for detrital grains as different pre-depositional thermal histories of zircon within a single sample may result in date-eU trends which do not follow simple, predicted trends for the entire dataset. In order to reconcile these complexities within the ZHe dataset, we follow the methodology of Guenther et al. [2014] and Powell et al. [2016] for forward modeling, and employ the 'inheritance envelope' which encompasses a continuum of all plausible ZHe date-eU data-points for a given t-T history. In such manner we are able to explain zircon grains that have been accumulating radiation damage and ^4He for varying amounts of time prior to deposition with a single t-T history. However, unlike Guenther et al. [2014] and Powell et al. [2016], our samples do not possess inherited ^4He since all ZHe dates would have been reset during the Caledonian Orogeny, thus we only consider inherited radiation damage. To visualize this concept, we have constructed a simple hypothetical t-T history illustrating ZHe date-eU

correlations for zircon grains that have been accumulating radiation damage for varying amounts of time but have not inherited ^4He (**Figure 7**). This model presents three different detrital zircon populations, which have been accumulating radiation damage for 2000, 1500 and 1000 m.y. The model setup includes a post-depositional heating event such that all inherited radiation damage is retained but all inherited ^4He is lost from the zircon grains. Complete resetting of the ZHe dates after deposition limits the oldest ZHe date attainable by the subsequent t-T pathway. A post-depositional heating event, reaching temperatures within the ZHe PRZ, demonstrates the effects of inherited radiation damage through the different ZHe date-eU correlations for each detrital population.

Our models assessing the ZHe and AHe data follow a similar setup with the exception of the model durations of radiation damage accumulation. We choose a maximum of 2000 m.y. and a minimum of 1000 m.y. of damage accumulation, based on U-Pb detrital zircon dating from the same samples [Kośmińska et al., 2015]. Although our model constraints do not allow damage annealing of zircon grains through Torellian and Caledonian events, we cannot exclude the possibility that some grains may have been partially to fully annealed during those metamorphic episodes. To account for this, we also construct ZHe date-eU curves for 640 m.y. and 420 m.y. of damage accumulation to represent zircon grains that were annealed during the Torellian and Caledonian orogenies, respectively.

We present the 'best-fit' forward models for each of the four sample regions from the Southwestern Province. These forward models are based on initial inverse modeling for each of the datasets (**Figure S2**) and the independent geological constraints detailed above. The average zircon ESR of each of the four regions was used to produce forward models for that respective

set of samples. Average grain volumes (i.e. ESR) are as follows: SKL: 63 μm ; WJL: 46 μm ; OII: 56 μm ; PKF: 54 μm .

7.1 Sørkapp Land

Our models for Sørkapp Land (SKL; **Figure 8**) indicate maximum temperatures of $\sim 185^\circ\text{C}$ were reached in the late Cretaceous directly followed by cooling. Previous studies using apatite fission track analysis have identified a similar late Cretaceous cooling event affecting northern Svalbard [Dörr et al., 2012], on the southernmost Svalbard island of Bjørnøya [Ritter et al., 1996], and for the source terrain of the Van Mijenfjorden Group lower succession [Blythe and Kleinspehn, 1998], which is located northeast/east of Svalbard [Petersen et al., 2016]. The timing of cooling initiation at c. 85 Ma is not well constrained by the modeling. Rather, the c. 85 Ma cooling initiation is primarily based on evidence of incipient rifting of the Eurasian Basin beginning at this time [Harland, 1997; Tegner et al., 2011a,b; Døssing et al., 2013b; Thórarinnsson et al., 2015]. We interpret the late Cretaceous thermal maximum to represent maximum sedimentary burial of our Triassic-Cretaceous cover strata before initiation of rifting and subsequent exhumation of Svalbard.

The post-Cretaceous t-T history of SKL is not well resolved by our ZHe dataset; the timing of cooling in the Cenozoic is more evident in the AFT studies of Blythe and Kleinspehn [1998] and Dörr et al. [2013] yet the amounts of cooling are somewhat equivocal. Cenozoic heating cannot be ruled out, but if such heating event did occur, it was not significant enough to reach temperatures in the ZHe PRZ (130°C - 200°C).

Models that satisfy the ZHe data for SKL require paleo-temperatures of $\sim 185^\circ\text{C}$ during the late Cretaceous (**Figure 8**). Basement rocks in SKL are unconformably overlain by

undeformed, horizontally bedded Triassic sediments [von Gosen et al., 2001]. A maximum thickness of Triassic to late Cretaceous sediments has been estimated at ~3.2 km [Dallmann, 2014] based on present-day preserved sedimentary thickness, and assuming cessation of sedimentation at c. 105 Ma. With a geothermal gradient of 25°C/km, the basement would only reach paleo-temperatures in the late Cretaceous of ~80°C, which is insufficient to partially reset our ZHe dates and satisfy our model temperatures of ~185°C. Therefore an elevated geothermal gradient of ~55-60°C/km in the late Cretaceous is required to reach temperatures predicted by our models. If we account for another 1 km of sediment deposition from c. 105-85 Ma, based on accumulated thickness over time of the Helvetiafjellet and Carolinefjellet Formations that was subsequently eroded, the models reach temperatures of ~105°C at c. 85 Ma, still requiring a geothermal gradient near 45°C/km. In order to explain the model temperatures based on sedimentary overburden alone, we would require a total Triassic-Cretaceous sedimentary overburden of ~7.2 km, requiring 4.2 km of sediments which were deposited and subsequently eroded in the late Cretaceous. Based on AFT modeling, Dörr et al. [2012] suggests that ~2-3 km of sediment (with a 20-30°C/km geothermal gradient) was eroded from northern Svalbard in the Mesozoic with the majority of erosion occurring prior to the late Cretaceous. AFT models favoured by Ritter et al. [1996] also indicate that Bjørnøya (south of SKL) likely only experienced up to ~2 km of exhumation in the late Cretaceous, with a geothermal gradient of 25°C/km. Therefore it is unlikely that ~4.2 km of sediment was deposited and subsequently eroded in the late Cretaceous on SKL. We consider an additional ~1 km of sedimentary depositional between c. 105-85 Ma to be plausible, and the elevated temperatures observed in our models are likely the result of an elevated geothermal gradient of at least ~45°C/km.

To explain this elevated geothermal gradient, we consider heat flow related to advection of heat into the crust with emplacement of HALIP intrusive units. At present, few studies address crustal heat flow related to LIP emplacement; for our discussion, we consider the Paraná-Etendeka Large Igneous Province (c. 135 Ma) as an analogue to the HALIP. Hurter and Pollack [1995] model the heat flow of a single intrusive event in the Paraná Basin, Brazil. Their results suggest that advection of heat into the crust is not a long-term primary control on the temperature of the basin sediments. Whereas these models are suitable for typical LIPs which are emplaced over a short duration [Ernst and Pisarevsky, 2015], they may not apply to the HALIP as a result of the prolonged duration which could possibly account for sustained elevated heat flow. We state that the elevated geothermal gradient is most likely the result of HALIP activity advecting heat into the shallow crust. We cannot exclude the possibility that late Cretaceous rift processes in the proto-Eurasian Basin [Harland, 1997; Thórarinnsson et al., 2015] may have contributed to elevated heat flow on Svalbard in the late Cretaceous via crustal thinning. However, provided that our model records cooling during late Cretaceous rifting, we consider that the HALIP played a more significant role in elevated the geothermal gradient.

In summary, the t-T history for Sørkapp Land is characterized by a late Cretaceous ZHe partial resetting event, reaching temperatures of $\sim 185^{\circ}\text{C}$, succeeded by relatively low-temperature cooling to the present.

7.2 Wedel Jarlsberg Land

Our t-T models for Wedel Jarlsberg Land (WJL; **Figure 9**) indicate temperature conditions of $\sim 185^{\circ}\text{C}$ in the late Cretaceous, similar to SKL, and cooling to $< 130^{\circ}\text{C}$ (below the ZHe PRZ) in the latest Cretaceous/Paleocene. Similar late Cretaceous temperatures are likely

due to the Hornsund-Sørkapp High, resulting in similar crustal depths for WJL and SKL such that the basement in both regions was unconformably overlain by Triassic sediments.

In contrast to the SKL dataset, however, our dataset for WJL reveals a much younger range of ZHe dates. In order to explain these younger dates, our models require a second heating event reaching temperatures within the ZHe PRZ (175-180°C) occurring after late Cretaceous cooling. With a maximum thickness of ~560 m, deposition of the Paleocene lower Van Mijenfjorden Group is an unlikely suspect; moreover if deposition of the lower succession had a significant effect on WJL it likely would have had a similar effect on SKL as well. We infer this second heating event in WJL to result from development of the fold-thrust belt since our WJL sample region was deformed during Eurekan tectonism whereas the southern region of SKL was not directly affected [von Gosen et al., 2001].

To better understand the duration of Eurekan heating we consider two possible scenarios where subsequent cooling begins contemporaneous with a change in tectonic regime. The first cooling scenario begins at c. 47 Ma, in accord with a change in tectonic regime from compression to dextral strike-slip in the middle Eocene [Müller and Spielhagen, 1990; Saalman and Theidig, 2002; CASE Team, 2001; Piepjohn et al., 2016]. In the second scenario, cooling begins c. 34 Ma in accord with a change from a predominantly transpressional regime for the duration of the Eurekan Orogeny [Harland, 1969; Braathen et al., 1999; Leever et al., 2011] to post-Eurekan transtension/ extensional tectonics. Both scenarios can be satisfied by the ZHe data with a good fit from the numerical models (**Figure 9**). We also take into consideration our 16 Ma AHe date for WJL, as well as AFT cooling ages recorded in the WSFTB [Blythe and Kleinspehn, 1998]. In order to satisfy our 16 Ma AHe date, we require temperatures to reach ~45°C by c. 30 Ma and sustain these temperatures until c. 10 Ma. Such a model would require

average Eocene/Oligocene cooling rates of $\sim 8^{\circ}\text{C}/\text{m.y.}$ for scenario (1), and Oligocene cooling rates of $\sim 32^{\circ}\text{C}/\text{m.y.}$ for scenario (2). AFT dates reported by Blythe and Kleinspehn [1998] for the WSFTB range from 55.7 ± 4.7 Ma to 29.3 ± 8.8 Ma, and are difficult to resolve by models in which cooling commences at 34 Ma, but can be satisfied by models with cooling beginning at c. 47 Ma at rates of $\sim 8^{\circ}\text{C}/\text{m.y.}$ Incorporating AFT data from Blythe and Kleinspehn [1998] somewhat favours initiation of cooling at c. 47 Ma.

In summary, the t-T evolution for Wedel Jarlsberg Land is characterized two ZHe partial resetting events: (1) late Cretaceous temperatures similar to Sørkapp Land ($\sim 185^{\circ}\text{C}$) followed by late Cretaceous cooling, and (2) an Eocene re-heating event, reaching temperatures of $\sim 180^{\circ}\text{C}$ at c. 47 Ma.

7.3 Oscar II Land

Our models for Oscar II Land (OII; **Figure 10**) also record peak temperatures in the late Cretaceous. Unlike WJL and SKL, heating must have reached temperatures above the ZHe PRZ ($>200^{\circ}\text{C}$), effectively resetting all of our ZHe dates at this time, evinced by the lack of ZHe dates greater than 68.4 ± 4.8 Ma. In comparison to SKL and WJL, these higher temperatures for OII in the late Cretaceous likely results from the presence Upper Carboniferous and Permian strata covering OII which was absent on WJL and SKL; however variations in crustal heat flow cannot be ruled out as a factor for higher temperatures in the north of the Southwestern Province. Late Cretaceous cooling is suggested by the models, with OII having cooled below the ZHe PRZ ($<130^{\circ}\text{C}$) by the end of the Cretaceous, similar to WJL.

Modeling of the ZHe data also require Eocene heating, likely related to Eurekan burial similar to that suggested for WJL. We consider the same two scenarios as discussed above for

the initiation of this event, assuming the timing of WSFTB is broadly similar along strike from north to south. Despite the reset late Cretaceous ZHe dates from OII, our results still possess some ambiguity between the two scenarios. The inheritance envelope for a 47 Ma cooling initiation provides a tight correlation with our spread in data whereas 34 Ma cooling initiation predicts ZHe dates of <40 Ma for eU values ≥ 300 ppm. Zircon grains with such dates and eU values do not exist in our dataset. In addition, our AHe dataset provides two dates of 33.7 ± 3.4 Ma and 34.0 ± 3.9 Ma that can be modeled in conjunction with ZHe dates. To reach near-surface temperature while considering the timing of AFT cooling reported by Blythe and Kleinspehn [1998] and Dörr et al. [2013], the models require surface conditions by (1) c. 30 Ma for c. 47 Ma initiation, and (2) c. 32 Ma for c. 34 Ma initiation in order to satisfy our AHe dates. Consequently, cooling rates are $\sim 10^\circ\text{C/m.y.}$ for scenario (1), and $\sim 77^\circ\text{C/m.y.}$ for scenario (2). As is the case for WJL, AFT cooling ages reported for the WSFTB by Blythe and Kleinspehn [1998] favour a c. 47 Ma initiation of cooling. Overall, our models, in conjunction with previous thermochronology of the WSFTB, favour initiation of a cooling event initiating at c. 47 Ma. Heating at this time is also consistent with inferred Eureka compression on northern Greenland at c. 49-47 Ma on the basis of trachyte $^{40}\text{Ar}/^{39}\text{Ar}$ ages [Tegner et al., 2011a,b].

In summary, the t-T evolution for Oscar II Land is characterized by a late Cretaceous resetting of ZHe date ($>200^\circ\text{C}$) followed by late Cretaceous cooling, and an Eocene re-heating event, reaching temperatures of $\sim 175^\circ\text{C}$ at c. 47 Ma.

7.4 Prins Karls Forland

Our thermal models for Prins Karls Forland (PKF; **Figure 11**) suggest the ZHe dates of c. 29-32 Ma, regardless of eU concentrations, require heating that is greater than the ZHe PRZ

(>200°C) during the Eocene and cooling through the ZHe PRZ during the early Oligocene. We therefore lose resolution of the t-T history before the early Oligocene but infer a similar thermal evolution as the other three regions in this study; PKF likely began exhuming at c. 47 Ma in conjunction with unroofing of OII and WJL.

The AHe dates that can be modeled with our ZHe dates for PKF include 16.3 ± 1.1 Ma and 29.9 ± 4.8 Ma. The models are unable to resolve both of these dates with a single cooling history from the Oligocene to the present. Instead we examine each AHe date separately: the 16 Ma date provides a post-34 Ma cooling to ~45°C at c. 26 Ma, whereas the c. 30 Ma date requires cooling to ~20°C by c. 26 Ma. We suggest this low temperature cooling history for PKF is due to the structural setting as a horst bounded to the east by the Forlandsundet Graben and to the west by the Fram Strait. The post-Eurekan cooling event is likely associated with an extensional episode that initiated at c. 34 Ma, ending Eurekan tectonism on Svalbard. We note that this younger thermal history of PKF compared with the other areas along the western margin of Svalbard is likely a function of exposure of deeper crustal levels of the WSFTB. This is supported by higher vitrinite reflectance values of Cenozoic coals exposed on the western margin of the Forlandsundet compared to the eastern margin, demonstrating the western margin was more deeply buried and exhumed in syn- to post-Eurekan time [Kleinspehn and Teyssier, 1992 and references therein].

In summary, the t-T evolution for Prins Karls Forland can only be resolved in post-34 Ma time. Cooling from >200°C to near-surface temperatures occurs in <10 m.y.

8. Late Mesozoic/Cenozoic tectonothermal history of the Southwestern Province

Synthesizing our (U-Th)/He dates and numerical models for the Southwestern Province with records of sedimentation on Svalbard, regional geodynamics and plate reconstructions for the Cretaceous and Paleogene reveals important implications for the tectonic evolution of the High Arctic.

8.1 Lower to Upper Cretaceous and influence of the HALIP

Peak temperatures attained during the late Cretaceous for the Southwestern Province were slightly higher in the north ($>200^{\circ}\text{C}$) compared to the south (185°C). A combination of sedimentary burial beneath a Carboniferous to Cretaceous succession in the north, a relatively thinner Triassic to Cretaceous succession in the south (overlying the Hornsund-Sørkapp High) and an elevated geothermal gradient ($\sim 45^{\circ}\text{C}/\text{km}$) were likely responsible for such conditions. Both sedimentation and the geothermal gradient in the Cretaceous can be attributed to HALIP activity, thus the HALIP is a primary thermal driver for Svalbard and likely elsewhere in the High Arctic. Early rifting of the Eurasian Basin and associated alkaline volcanism [Harland, 1997; Tegner et al., 2011a,b; Thórarinnsson et al., 2015] may have also perturbed the geothermal gradient in the late Cretaceous and cannot be excluded as a possible mechanism for the elevated temperatures, although unlikely as rifting was contemporaneous with cooling recorded in our models.

Arrival of the HALIP plume (**Figure 1**), centred on the southern Alpha Ridge [Buchan and Ernst, 2006; Døssing et al., 2013a], generated broad uplift across the High Arctic manifested as Lower Cretaceous unconformities in the Sverdrup Basin of the Canadian Arctic, Franz Josef Land and Svalbard [Maher, 2001; Galloway et al., 2016]. Cretaceous sedimentary patterns after the arrival of the HALIP were a consequence of southward tilting of Svalbard resulting from

regional uplift. Sedimentation patterns of the Helvetiafjellet and Carolinefjellet formations demonstrate southward paleoflow and thickening. Further, an increase in the geothermal gradient resulted from protracted eruptive phases of the HALIP from c. 130-120 Ma [Corfu et al., 2015; Evenchick et al., 2015] and likely c. 115-90 Ma [Buchan and Ernst, 2006; Nejbert et al., 2011]. Heat input into the shallow crust would have been widely distributed across the High Arctic as dyke swarms, sill provinces, and flood basalts, advecting heat into the shallow crust, evidence of which is present across Svalbard, Franz Josef Land, the Canadian Arctic Islands and within the Amerasian Basin [Maher, 2001; Buchan and Ernst, 2006; Nejbert et al., 2011, Senger et al., 2014].

Following peak late Cretaceous temperatures, a cooling event, coinciding with the Upper Cretaceous unconformity on Svalbard, affected the entirety of the Southwestern Province likely with more cooling ($\geq 15^{\circ}\text{C}$, equating to ≥ 300 m) in the north compared to the south. This cooling event supports previous thermochronological studies indicating late Cretaceous exhumation of Svalbard [Ritter et al., 1996; Blythe and Kleinspehn, 1998; Dörr et al., 2012] and greater uplift in the northern regions [Maher et al., 2004]. Exhumation of Svalbard in the late Cretaceous was likely related to initial rift processes in the Eurasian Basin [Harland, 1997; Døssing et al., 2013a; Thórarinnsson et al., 2015] evinced by alkaline dyke swarms in northern Greenland and Ellesmere Island of the Canadian Arctic [Tegner et al., 2011a,b; Thórarinnsson et al., 2015]. In the latest Cretaceous, opening/seafloor spreading of the Labrador Sea and Baffin Bay occurred west of Greenland [Srivastava, 1978; Roest and Srivastava, 1989], coeval with these early stages of rift stages in the Eurasian Basin. Rifting in both the Eurasian Basin and Labrador Sea/Baffin Bay was likely accommodated by lateral displacement of Svalbard from Greenland along zones of crustal weakness [CASE Team, 2001].

8.2 Paleogene

No significant Paleocene thermal event is recorded in our thermal models suggesting that unroofing of Svalbard had ceased. This is supported by the deposition of the Van Mijenfjorden Group lower succession (**Figure 12**). Eocene heating (c. 55-47 Ma) is readily illustrated by our data from WJL (~180°C), OII (~185°C) and PKF (>200°C; **Figure 12**) resulting from tectonic burial via overthrusting during Eurekan tectonism. Compression along the Greenland/Svalbard margin was the result of seafloor spreading in the Labrador Sea and Baffin Bay west of Greenland [Srivastava, 1978; Roest and Srivastava, 1989] synchronous with c. 56 Ma seafloor spreading in the Eurasian Basin [Døssing et al., 2013b] and northward propagation of the North Atlantic spreading ridge [Srivastava and Tapscott, 1986]. This caused the Greenland microplate to move northeastward, independent of the Laurentia and Eurasian plates [e.g. Harrison, 1999; CASE Team, 2001]. North Atlantic spreading progressed throughout the Eocene, simultaneous with a decrease in spreading in the Labrador Sea and Baffin Bay. This modified the motion of the Greenland microplate from northeastern-directed movement to northwestern-directed movement.

Eurekan cooling elucidated in the models (**Figure 12**) coincides with the shift in tectonic regime from orthogonal compression to dextral strike-slip (c. 47-34 Ma) along the western margin of Svalbard [Harrison, 1999; CASE Team, 2001]. The change in tectonic regime terminated the tectonic burial of the Southwestern Province and initiated erosion of the WSFTB, suggested by the >1.1 km thick Aspelintoppen Formation and characterized by high sedimentation rates [Naustad, 2014], dominating the middle to late Eocene. It is also likely that

the Forlandsundet Graben separating Spitsbergen from Prins Karl Forland began to form as a pull-apart basin during strike-slip motion [CASE, 2001].

Continued cooling (post-34 Ma) highlighted by our models is the result of regional exhumation of Svalbard (**Figure 12**) during the development of the Norwegian-Greenland Sea and opening of the Fram Strait. A transtensional to extension tectonic regime affected the western margin of Svalbard during this time, related to the termination of seafloor spreading in the Labrador Sea/Baffin Bay causing the Greenland microplate to move in conjunction with the Laurentia while separating from the Eurasian plate. Cooling and denudation of the Southwestern Province through the Eocene into Oligocene was likely a combination of c. 47-34 Ma Eurekan strike-slip tectonics and post-34 Ma transtensional/extensional tectonics. The geothermal gradient on Svalbard at this time has been calculated to be $\sim 50^{\circ}\text{C}/\text{km}$ [Marshall et al., 2015], resulting in Eocene/Oligocene exhumation of $\sim 2.5\text{-}3.5$ km of the WSFTB exposed on Spitsbergen. Significant cooling and exhumation of Prins Karls Forland occurred in post-34 Ma time and is >4 km; it is likely exhumation of the region also occurred from c. 47-34 Ma. Prins Karls Forland therefore represents a deeper crustal root of the Eurekan Orogeny than the exposures on Spitsbergen.

8.2.1 Implications for Eurekan tectonism

Our models indicate that SKL and WJL resided at similar temperatures ($\sim 185^{\circ}\text{C}$) in the late Cretaceous, and given the proximity of the two sample regions, likely experienced similar amount of erosion during late Cretaceous exhumation. Preservation of Triassic sediments on SKL after regional Oligocene and Miocene regional exhumation events [Blythe and Kleinspehn, 1998; Dörr et al., 2013] suggest the majority of the 3.2 km thick Triassic-Cretaceous succession

remained over both SKL and WJL before the formation of the WSFTB. Older strata was likely present in the northern regions (OII and likely PKF) as, prior to the Eurekan Orogeny, the Cretaceous strata was significantly thinner [Maher, 2001] and more pronounced exhumation of northern Svalbard occurred after deposition of Cretaceous sediments [Maher et al., 2004]. Incorporation of the post-Caledonian cover strata for the WSFTB would have occurred during the c. 55-47 Ma compressional stage. Testaments to these relationships are still preserved as Triassic (and older) stratigraphic remnants in thrust sheets in western SKL [Tessensohn et al., 2001a; Dallmann, 2014] whereas Carboniferous and Permian strata infolded in the basement of western OII [Tessensohn et al., 2001b].

To understand the interplay between erosion and thermal evolution during tectonism, we examined predictive thermal models of fold-and-thrust belt evolution. Lock and Willett [2008] demonstrate that low-temperature thermochronometers record cooling during thrusting when syn-orogenic erosion efficiently exhumes the fold-and-thrust belt. In contrast, scenarios where erosion rates are minor, crustal thickening will result in heating due to tectonic burial [Huerta and Rodgers, 2006]. In addition, reducing slip rates along thrusts will increase the rates of heating affecting the overthrust material [Ehlers, 2005]. Through these relations between erosion and thermal evolution, we propose that the c. 55-47 Ma heating event is characterized by crustal thickening and minor erosion during growth of the orogenic wedge, whereas erosion rates significantly increased during the c. 47-34 Ma Eurekan cooling stage, outpacing thrusting and thickening.

Such interpretations for the WSFTB during the c. 55-47 Ma interval are not conducive to the traditional interpretation that the upper succession of the Van Mijenfjorden Group upper succession is derived from the WSFTB [e.g. Helland-Hansen, 1990; Müller and Spielhagen,

1990; Grundvåg et al., 2014, Petersen et al., 2016]. Additionally, detrital zircon signatures reported by Petersen et al. [2016] for the Battfjellet Formation of the Van Mijenfjorden Group upper succession indicate provenance from pre-Middle Triassic strata that cannot be reconciled with the Cretaceous to Triassic ($\pm$ Permian and Carboniferous) strata incorporated in the WSFTB at this time. We look to northern Greenland to investigate a candidate sediment source terrain during c. 55-47 Ma interval of deposition within the Central Basin. Plate reconstructions place Svalbard off the eastern north coast of Greenland [e.g. Harland, 1969; Srivastava, 1985; Stemmerik and Hakansson, 1991; Buchan and Ernst, 2006] such that the WSFTB represents the along-strike extension of the KCTZ and HFFZ (**Figure 3**). In such a reconstruction, the WHMB would be placed in the hinterland of the WSFTB (**Figure 3**). Deformed sediments within the WHMB are predominantly Middle Triassic to Upper Carboniferous [Håkansson and Stemmerik, 1989; Stemmerik et al., 1998] but younger strata are preserved within the region. Detrital zircons of the Cretaceous sediments in the WHMB [Røhr et al., 2008] reflect the detrital zircon signatures of the Battfjellet Formation [Petersen et al., 2016]. Syn-tectonic exhumation of transpressional systems is well documented in the geological record, as demonstrated by thermochronological studies examining exhumation-related cooling of structural elements of the San Andreas fault [Buscher and Spotila, 2007; Niemi et al., 2013], the Fairweather fault [McAleer et al., 2009] or the Denali fault [Riccio et al., 2014]. As a result, the WHMB appears to be a candidate sediment source for the Central Basin fill, indicating contemporaneous tectonism within WHMB and WSFTB during c. 55-47 Ma Eurekan tectonism (**Figure 12**). Tessensohn and Piepjohn [2000] and Von Gosen and Piepjohn [2003] favour syn-tectonic activity of the fault zone of northern Greenland and the WSFTB, which is supported by thermal overprinting of trachyte $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronometer in northern Greenland as a consequence of peak Eurekan

compression [Tegner et al., 2011a,b]. The tectonic conditions for such a scenario requires a decoupling of dextral transpression with the WHMB from orthogonal compression in the WSFTB [e.g. Faleide et al., 1988; Lepvrier et al., 1992; Maher et al., 1997; von Gosen and Piepjohn, 2003]. Models for such decoupling would invoke pre-existing crustal heterogeneities, evidence for which is strong in both the WSFTB [CASE Team, 2001; Piepjohn et al., 2015] and the WHMB [Håkansson and Pedersen, 1982; von Gosen and Piepjohn, 2003; Piepjohn et al., 2015].

We interpret the c. 47-34 cooling event to be a result of significant exhumation of the WSFTB, supplying sediment to the Central Basin at this time (**Figure 12**). Several studies have indicated that cooling histories can differ over the scale of 10's of km due to the structural style and/or evolution of a fold-and-thrust belt, i.e. location of footwall ramps or evolution of décollements [Robert et al., 2011; Coutand et al., 2014; McQuarrie and Ehlers, 2015]. Our ZHe datasets and modeled Eureka cooling for OII and WJL do not suggest a significant difference in timing or rates of cooling although the two regions are characterized by contrasting structural evolutions [CASE Team, 2001]. This suggests that Eureka cooling was not a consequence of compression (thrusting) of the WSFTB, but instead the result of a structural evolution that acted equally along the length of the WSFTB, i.e. dominant dextral strike-slip structures parallel to the strike of the fold-thrust belt [CASE Team, 2001; Piepjohn et al., 2016]. Strike-slip structures are dominantly concentrated on the western margin of the WSFTB [Maher et al., 1997], perhaps indicating strain localization through time as strain migrated into the De Greer Fracture Zone (**Figure 12**). Another strong indication for dextral strike-slip is the Forlandsundet Graben, most often interpreted as a pull-apart graben with defining structures post-dating Eureka thrusting [CASE Team, 2001]. Depositional contacts between the graben fill and Caledonian basement

indicate that the post-Caledonian cover must have been eroded prior to formation, thus formation of the graben would have occurred during the c. 47-34 Ma stage, supporting a dextral strike-slip period of Eurekan tectonism. Indeed, exposed sediments of the Sarsbukta Formation on the eastern margin of the graben, overlying Caledonian basement, have been constrained to a depositional age of 38-31 Ma [Cepek, 2001; Kleinspehn and Teyssier, in press].

This evolution of Eurekan tectonism on Svalbard and northern Greenland demonstrates the influence of structural styles of patterns of thermochronological data. The heating event observed from c. 55-47 Ma is a direct consequence of the decoupling of transpressive (WHMB) and orthogonal compressive (WSFTB) tectonics controlled by pre-existing crustal heterogeneities. Cooling of the WHMB transpressional zone contrasts heating recorded in the compressional zone (WSFTB) during coeval deformation events. The c. 47-34 Ma stage of tectonism records cooling of the previously active compressional zone as a result of strain localization along the De Greer Fracture Zone. Activity in the WHMB would have likely diminished during this time, reflecting the WSFTB.

9. Conclusions

We applied apatite and zircon (U-Th)/He thermochronometry to four regions along the Southwestern Province of Svalbard to understand the tectonothermal evolution of the province and implications for High Arctic tectonics. Modeling of our ZHe datasets required that a large number of zircon grains retained their α -radiation damage during Neoproterozoic and Paleozoic metamorphism, thereby suggesting a re-evaluation of zircon fission track annealing kinetics applied to annealing of α -damage and He diffusion, and that further investigations of α -damage annealing must be undertaken to refine damage annealing models.

Results from our t-T history modeling reveal an increased ($\sim 45^{\circ}\text{C}/\text{km}$) geothermal gradient in the late Cretaceous resulting from elevated heat flow related to HALIP activity. We report maximum late Cretaceous temperatures $>200^{\circ}\text{C}$ for Oscar II Land (and likely Prins Karls Forland), and $\sim 185^{\circ}\text{C}$ in Sørkapp Land and Wedel Jarlsberg Land, likely resulting from a lack of Carboniferous and Permian strata over the SKL and WJL sample regions. Late Cretaceous cooling affected all regions, with at least $\sim 15^{\circ}\text{C}$ greater cooling in Oscar II Land, possibly reflecting increased exhumation in the north. A subsequent heating event is evident in all regions along the Southwestern Province with the exception of Sørkapp Land. Our models favour this second heating event from c. 55-47 Ma reaching maximum Eocene temperatures of $\sim 180^{\circ}\text{C}$ (WJL), $\sim 185^{\circ}\text{C}$ (OII) and $>200^{\circ}\text{C}$ (PKF) at c. 47 Ma. We interpret this heating event to represent tectonic burial via overthrusting within the WSFTB during Eurekan tectonism, and little associated erosion. The sediment source for the Central Basin at this time may be the Wandel Hav Mobile Belt located in northeastern Greenland supporting contemporaneous tectonic activity in the WHMB and WSFTB in the Eocene. The c. 47-34 Ma cooling revealed by our models for Wedel Jarlsberg Land and Oscar II Land may reflect a shift from compression to dominant strike-slip tectonism inducing uplift and erosion along the entire length of the WSFTB. Post-34 Ma extensional tectonics exhumed and cooled the length of the WSFTB; however, Prins Karls Forland experienced much greater exhumation during this time compared to the west margin of Spitsbergen. In total $\sim 3\text{-}4$ km of stratigraphy was eroded from the WSFTB exposed on Spitsbergen since c. 47 Ma, compared to >4 km of stratigraphy eroded from Prins Karls Forland since c. 34 Ma. As such, Prins Karls Forland represents a deeper crustal level compared to the WSFTB exposures on the western coast of Spitsbergen.

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Figure 1. Bathymetric map of the High Arctic illustrating the spatial relationship between High Arctic continents and ocean basins (modified after Pease et al. [2014]). Svalbard is a subaerial exposure of the northwest corner of the Barents Shelf, flanked by the Eurasian Basin and Norwegian-Greenland Sea passive margins. HALIP localities are illustrated as dark grey shaded regions [Tegner et al., 2011a,b; Senger et al., 2014]. Inferred HALIP centre represented by the black star located on the southern Alpha Ridge [Buchan and Ernst, 2006; Døssing et al., 2013a]. Abbreviations: AR, Alpha Ridge; BB, Baffin Bay; CAIs, Canadian Arctic Islands; FJL, Franz Josef Land; FS, Fram Strait; LS, Labrador Sea; N-GS, Norwegian-Greenland Sea.

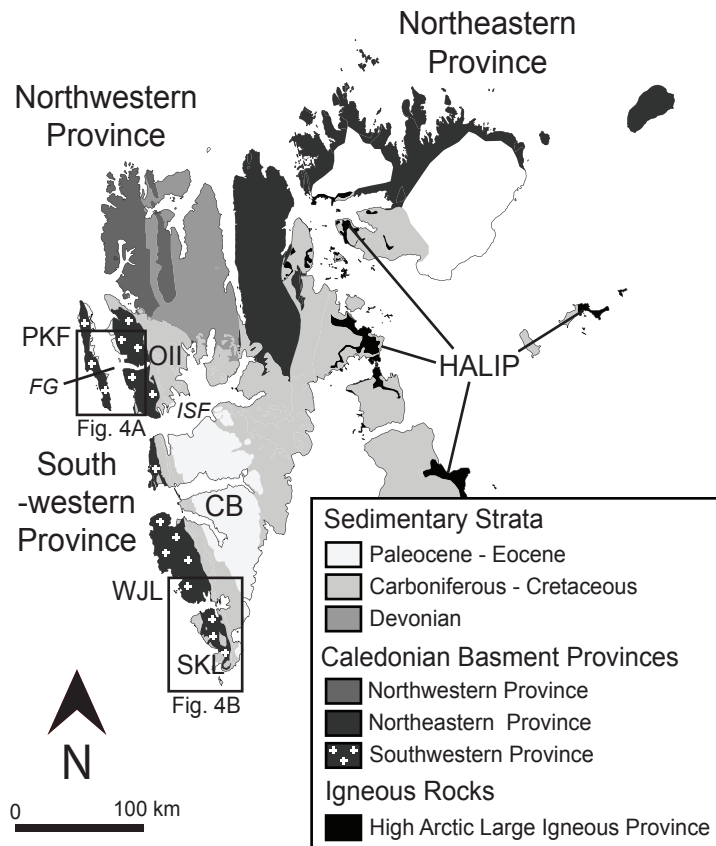


Figure 2. Simplified geological bedrock map of the Svalbard archipelago (modified after Dallmann [2014]). The Southwestern Province located along the western margin of Svalbard is primarily exposed on the main island of Spitsbergen, as well as the island of Prins Karls Forland. Manifestations of the High Arctic Large Igneous Province (e.g. sills, basalt flows) are concentrated in the eastern regions of Svalbard, but do occur on central Spitsbergen and in the Southwestern Province in lesser abundance. Locations of Figures 4a and 4b are approximated by the black boxes. Abbreviations: CB, Central Basin; HALIP, High Arctic Large Igneous Province; ISF, Isfjorden; OIL, Oscar II Land; PKF, Prins Karls Forland; SKP, Sørkapp Land; WJL, Wedel Jarlsberg Land.

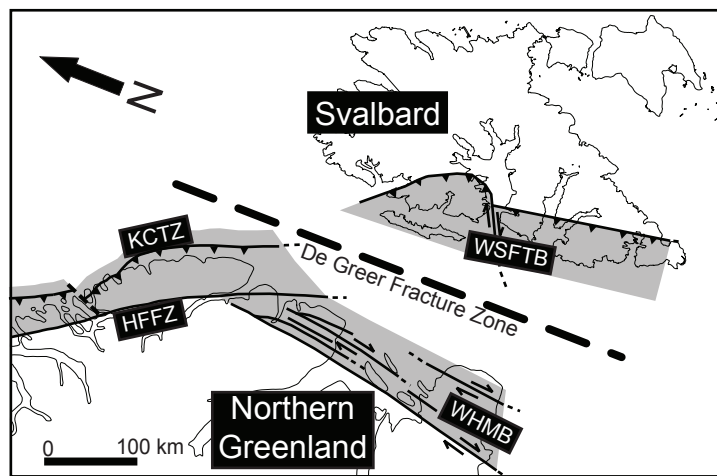


Figure 3. Simplified paleoconfiguration of Svalbard relative to northern Greenland illustrating the main Eureka tectonic domains (modified after von Gosen and Piepjohn [2003] and Piepjohn et al. [2015]). Areas of Eureka deformation are delineated by the grey shaded regions. In this configuration, the WSFTB represents the eastern along-strike continuation of the KCTZ. WSFTB structures are sub-parallel to WHMB structures. On Svalbard, the structural evolution for the WSFTB is debated as either transpressional or compressional but timing of deformation is considered to be Eocene. In contrast, on northern Greenland the structural styles are agreed to be compressional (HFFZ, KCTZ) and transpressional (WHMB), but the timing of deformation is debated to have occurred either late Cretaceous/early Paleocene or Eocene. Abbreviations: HFFZ, Harder Fiord Fault Zone; KCTZ, Kap Cannon Thrust Zone; WHMB, Wandel Hav Mobile Belt; WSFTB, West Spitsbergen Fold-and-Thrust Belt.

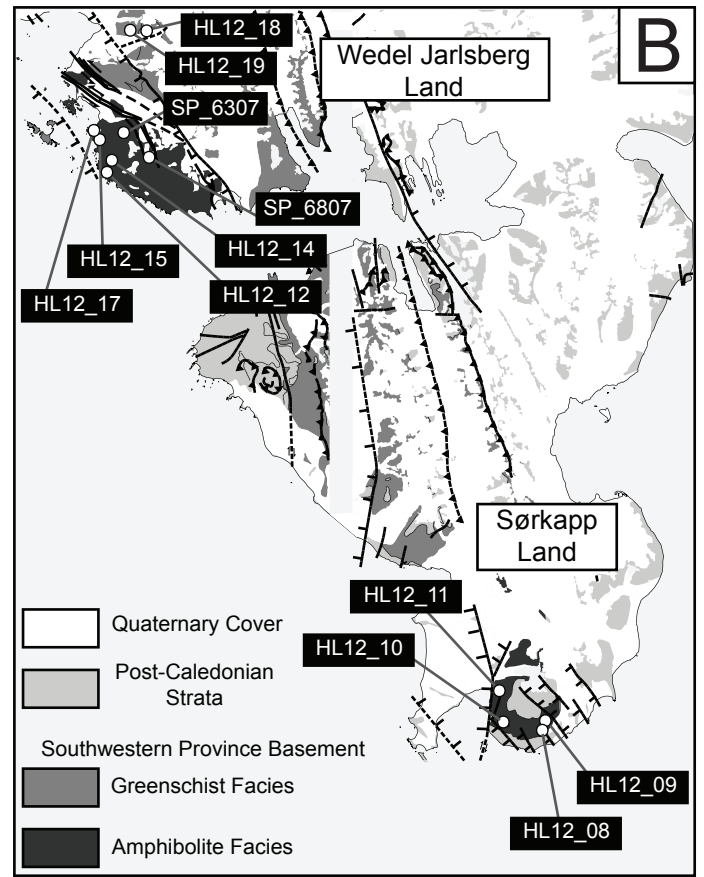
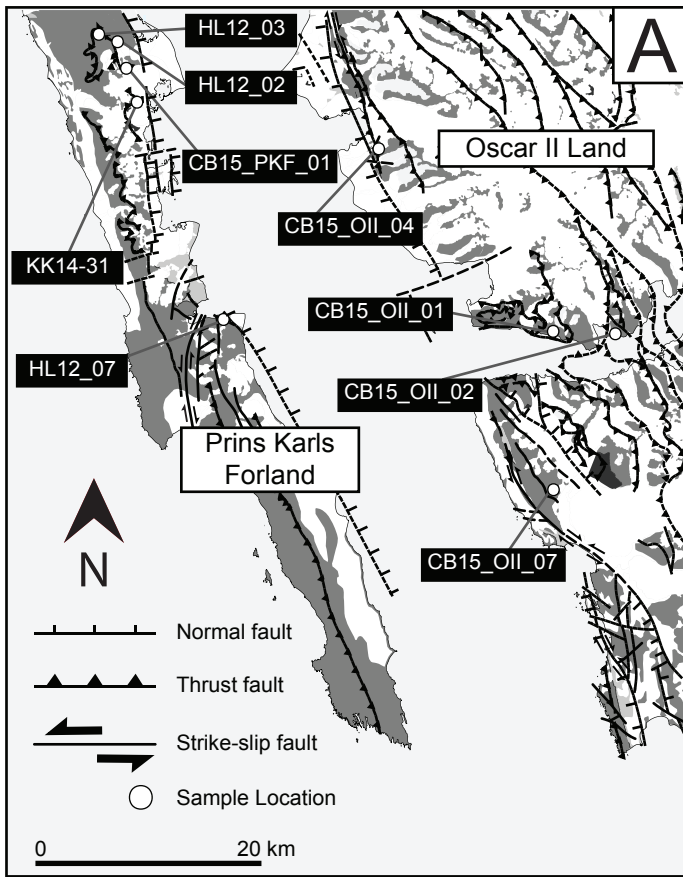


Figure 4. Simplified geological bedrock maps of regions investigated in this study: A) Prins Karls Forland and Oscar II Land; B) Wedel Jarlsberg Land and Sørkapp Land (modified after Dallmann et al. [2014]). All samples were obtained from Caledonian crystalline rock. Note the lack of compressive structures associated with our sample region in the southern Sørkapp Land; the post-Caledonian sedimentary strata overlying our sample regions are undeformed Triassic sediments.

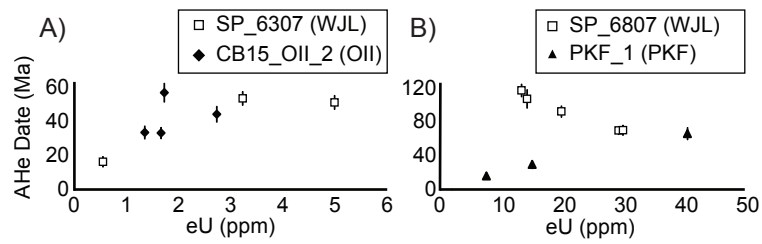


Figure 5. Apatite (U-Th)/He results in AHe date-eU space. Graphs are grouped according to dissolution method. A) Apatite grains dissolved using standard apatite HNO₃ procedures. Samples SP_6307 and CB15_OII_2 follow slight positive correlations. B) Apatite grains dissolved using zircon HF procedures. Sample CB15_PKF_1 follows slight positive correlations whereas sample SP_6807 shows a negative correlation.

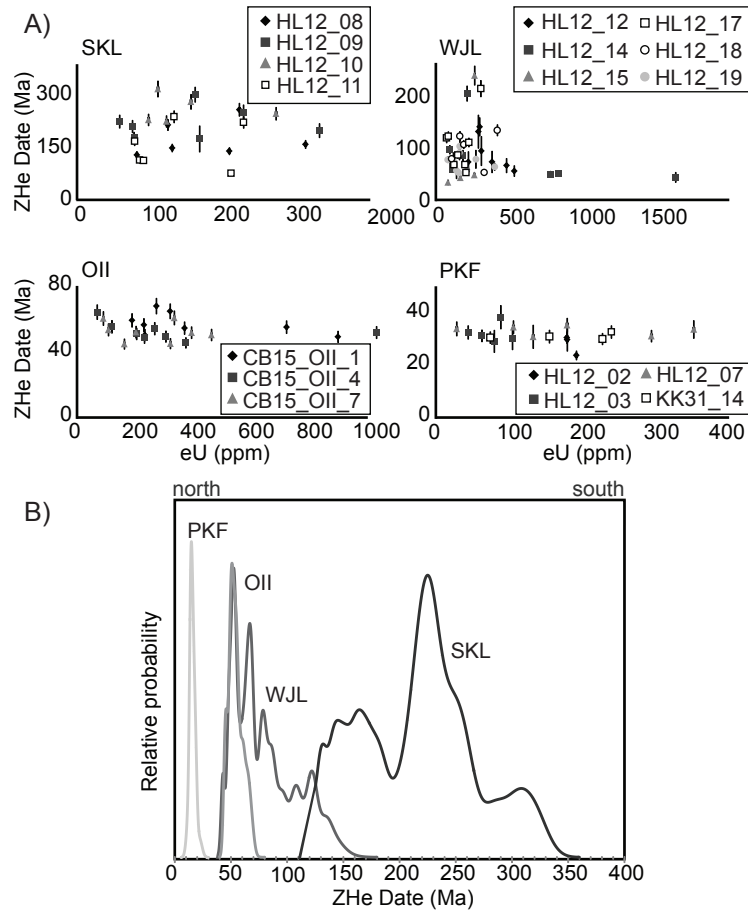


Figure 6. A) Zircon (U-Th)/He results in ZHe date-eU space, grouped according to four regions sampled in this study. SKL, n: 24; WJL, n: 42; OII, n: 23; PKF, n: 19. Individual samples are distinguished on the plots. Note the scale differences between the four graphs. B) Zircon (U-Th)/He dates plotted as probability curves. An overall younging of ZHe dates can be observed from south to north. Note that ZHe dates from Oscar II Land directly overlap with the younger portion of ZHe dates from Wedel Jarlsberg Land. Some dates present in the ZHe date-eU plots have been omitted in the probability plot to better highlight the overall trends of the four datasets (SKL, 77 Ma; WJL, 33 Ma, 205 Ma, 214 Ma, 239 Ma; PKF, 28 Ma).

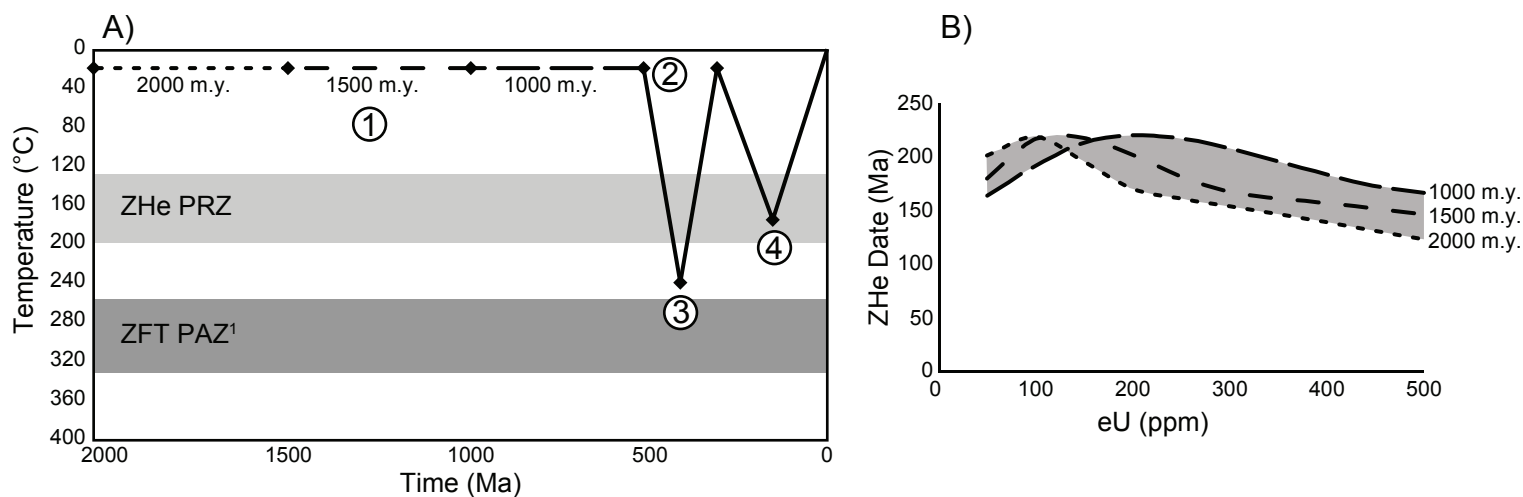


Figure 7. A) Schematic time-temperature history forward model and B) ZHe date-eU plot illustrating the effects of inherited radiation damage on ZHe date-eU correlations. We consider a single sample that contains detrital zircon grains with different pre-depositional thermal histories. Numbered steps within the model (A) are as follows: 1) Zircon grains modeled to reside at near-surface temperatures to simulate damage accumulation for 2000, 1500 or 1000 m.y. 2) Depositional age of the hypothetical sediments at 500 Ma. 3) At 400 Ma the sample is heated to a temperature of 240°C, residing above the ZHe partial retention zone (PRZ), but below the ZFT partial annealing zone (PAZ) such that only radiation damage is inherited from the various pre-depositional histories. 4) A subsequent heating event at 150 Ma reaching a temperature of 180°C within the ZHe PRZ. Individual zircon grains are partially reset during this heating event to varying degrees controlled by variations in radiation damage, demonstrated by the ZHe date-eU curves. In (B), the shaded area confined by the ZHe date-eU curves represents the area of permissible data that can be explained by the time-temperature history defined in (A). Note that maximum ZHe dates are limited by the lack of inherited ^4He . 1Kinetics of fission track damage annealing may not represent annealing of alpha damage in zircon [Guenther et al., 2013].

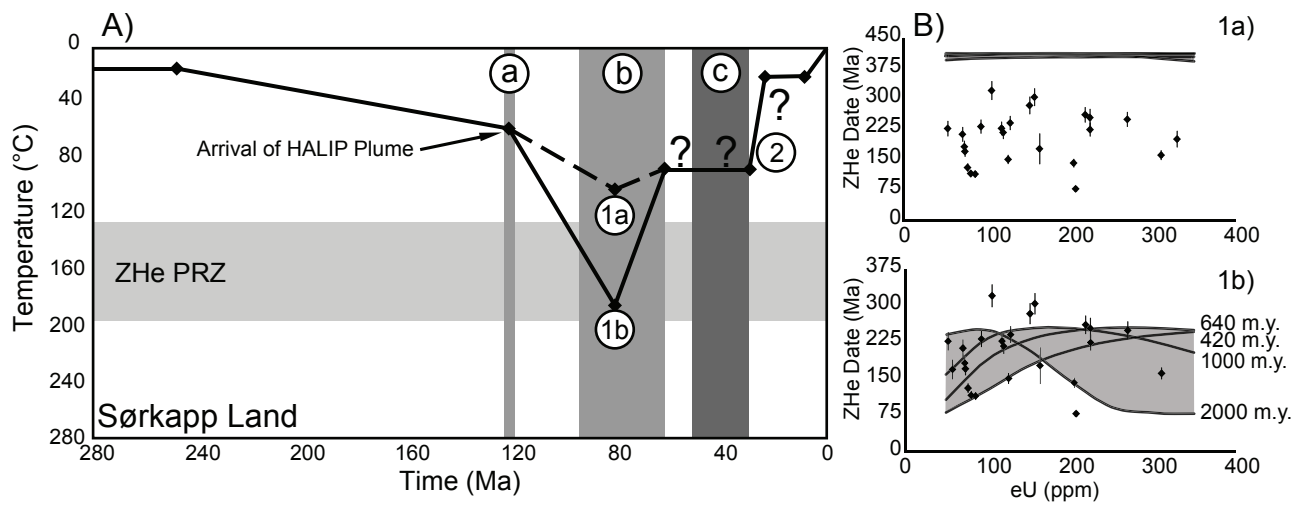


Figure 8. A) Schematic time-temperature forward model and B) associated ZHe date-eU plots for Sørkapp Land. Vertical grey bars on the t-T model indicate the amount of time represented by (a) the Lower Cretaceous unconformity, (b) the Upper Cretaceous unconformity and (c) duration of the Eurekan Orogeny. The inheritance envelope (shaded grey on date-eU plot) is defined by date-eU curves for detrital zircon grains which have been accumulating radiation damage for 420, 640, 1000 and 2000 m.y. Question marks on the t-T history model indicate poorly constrained temperatures. In this model, the Cretaceous is characterized by prolonged heating. We present two different Cretaceous t-T histories: 1a) maximum temperature of $\sim 105^{\circ}\text{C}$ at c. 85 Ma, considering maximum sedimentary overburden of ~ 4.2 km (~ 3.2 km preserved plus 1 km of erosion during late Cretaceous exhumation) with a $25^{\circ}\text{C}/\text{km}$ geothermal gradient. Such a temperature is not sufficient to reset ZHe dates as the date-eU plot records Caledonian/Ellesmerian cooling dates. In order to satisfy our ZHe dataset, the model must reach 1b) a temperature of $\sim 185^{\circ}\text{C}$ at c. 85 Ma in order to partially reset zircon grains, requiring an elevated geothermal gradient of $\geq 45^{\circ}\text{C}$. Inheritance envelopes for such resetting correlate with our ZHe dataset. Note that c. 85 Ma cooling initiation is primarily based on timing of incipient rifting in the Eurasian Basin and is not well-constrained by our models. The (2) Cenozoic history is based on timing of cooling events is based on Blythe and Kleinspehn [1998] and Dörr et al. [2013] while the temperatures are not well resolved by the modeling.

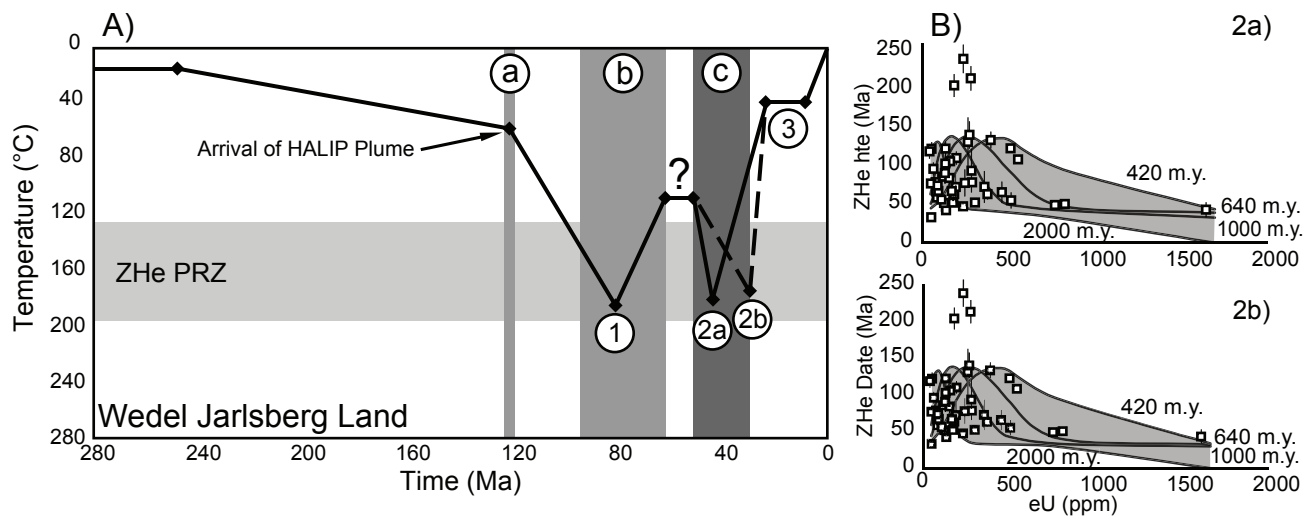


Figure 9. A) Schematic time-temperature forward model and B) associated ZHe date-eU plots for Wedel Jarlsberg Land. Vertical grey bars on the t-T model indicate the amount of time represented by (a) the Lower Cretaceous unconformity, (b) the Upper Cretaceous unconformity and (c) duration of the Eurekan Orogeny. The inheritance envelope (shaded grey on date-eU plot) is defined by date-eU curves for detrital zircon grains which have been accumulating radiation damage for 420, 640, 1000 and 2000 m.y. Question marks on the t-T history model indicate poorly constrained temperatures. In the model, the Cretaceous t-T history includes: 1) Cretaceous heating to $\sim 185^{\circ}\text{C}$ at c. 85 Ma, similar to Sørkapp Land. Note that c. 85 Ma cooling initiation is primarily based on timing of incipient rifting in the Eurasian Basin and is not well-constrained by our models. A subsequent late Cretaceous cooling event likely reached a temperature cooler than the ZHe PRZ. We present two scenarios for the Eurekan thermal history: 2a) a maximum Eurekan temperature of $\sim 180^{\circ}\text{C}$ is reached at c. 47 Ma. Cooling proceeds to temperatures of $\sim 45^{\circ}\text{C}$ at c. 30 Ma, providing AHe date of 17 Ma; 2b) a maximum Eurekan temperature of $\sim 175^{\circ}\text{C}$ is reached at c. 34 Ma. Cooling proceeds to temperatures of $\sim 45^{\circ}\text{C}$ at c. 30 Ma, providing AHe date of 17 Ma. Inheritance envelopes for both scenarios can explain our ZHe dataset.

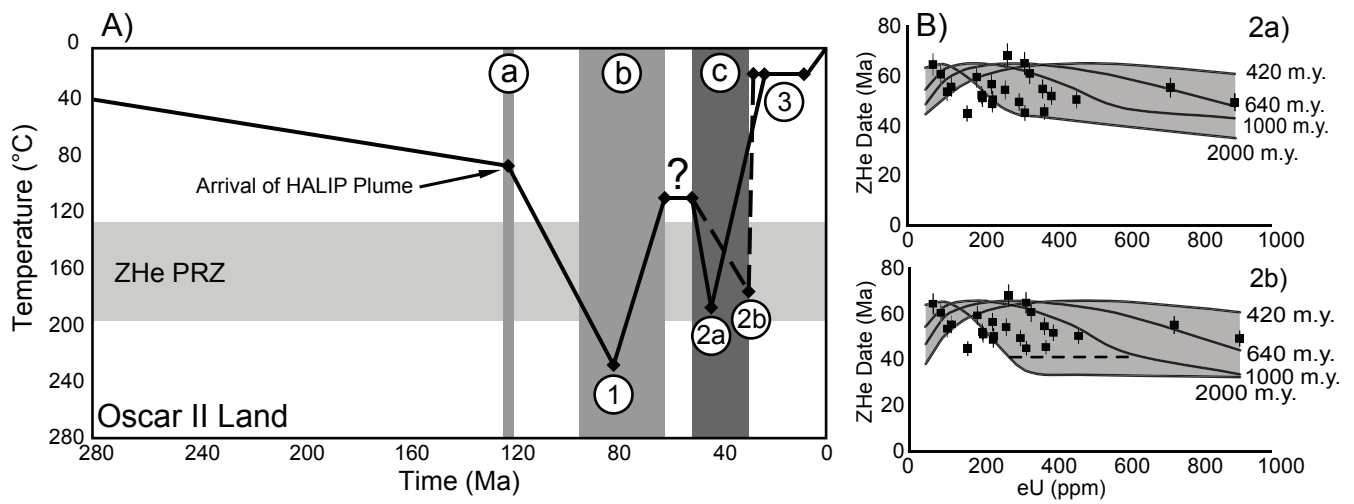


Figure 10. A) Schematic time-temperature model and B) associated ZHe date-eU plots for Oscar II Land. Vertical grey bars on the t-T model indicate the amount of time represented by (a) the Lower Cretaceous unconformity, (b) the Upper Cretaceous unconformity and (c) duration of the Eurekan Orogeny. The inheritance envelope (shaded grey on date-eU plot) is defined by date-eU curves for detrital zircon grains which have been accumulating radiation damage for 420, 640, 1000 and 2000 m.y. Question marks on the t-T history model indicate poorly constrained temperatures. In the model, the Cretaceous t-T history includes: 1) Cretaceous heating reaching a temperature that surpassed the ZHe PRZ, resetting all zircon grains. A subsequent late Cretaceous cooling event likely reached a temperature cooler than the ZHe PRZ. We present two scenarios for the Eurekan thermal history: 2a) a maximum Eurekan temperature of $\sim 185^{\circ}\text{C}$ is reached at c. 47 Ma. The system cools to $\sim 20^{\circ}\text{C}$ by c. 30 Ma, providing an AHe date of 32 Ma; 2b) a maximum Eurekan temperature of $\sim 175^{\circ}\text{C}$ is reached at c. 34 Ma. The system cools to $\sim 20^{\circ}\text{C}$ by c. 32 Ma, providing an AHe date of 30 Ma. 3) Temperatures remain at $\sim 20^{\circ}\text{C}$ until c. 10 Ma as according to Blythe and Kleinspehn [1998] and Dörr et al. [2013]. The inheritance envelope for c. 47 Ma cooling matches well with the ZHe data. The inheritance envelope for cooling initiation at c. 34 Ma cooling predicts ZHe dates of < 40 Ma for eU values 300-600 ppm (i.e. the inheritance envelope which lies below the dashed line on the ZHe date-eU plot) which do not exist within the dataset.

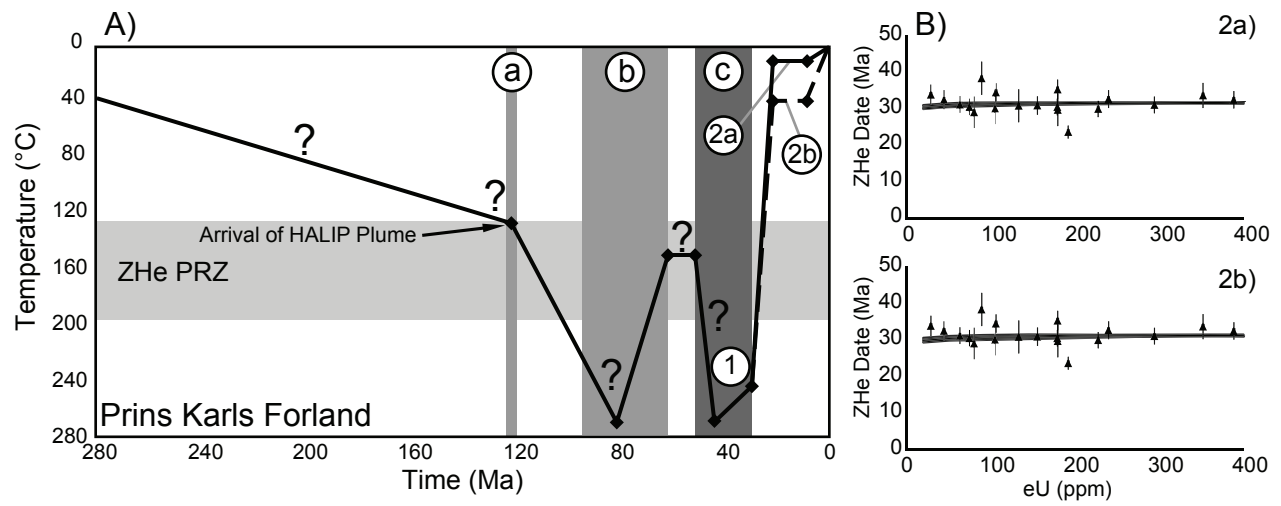


Figure 11. A) Schematic time-temperature model and B) associated ZHe date-eU plots for Prins Karls Forland. Vertical grey bars on the t-T model indicate the amount of time represented by (a) the Lower Cretaceous unconformity, (b) the Upper Cretaceous unconformity and (c) duration of the Eurekan Orogeny. The inheritance envelope (shaded grey on date-eU plot) is defined by date-eU curves for detrital zircon grains which have been accumulating radiation damage for 420, 640, 1000 and 2000 m.y. Question marks on the t-T history model indicate poorly constrained temperatures. The t-T history for PKF can only be resolved as 1) during the Eurekan Orogeny, temperatures reaching $>200^{\circ}\text{C}$ resetting all zircon grains. Eurekan thermal evolution is likely similar to OII and WJL. Rapid post-Eurekan cooling is recorded initiating from temperatures $>200^{\circ}\text{C}$, cooling to: 2a) $\sim 45^{\circ}\text{C}$ at c. 26 Ma, providing an AHe date of 17 Ma; or 2b) $\sim 20^{\circ}\text{C}$ at c. 26 Ma, providing an AHe date of 28 Ma. Date-eU curves for detrital zircon grains which have been accumulating radiation damage for 420, 640, 1000 and 2000 m.y. all define a ZHe date plateau of c. 30 Ma.

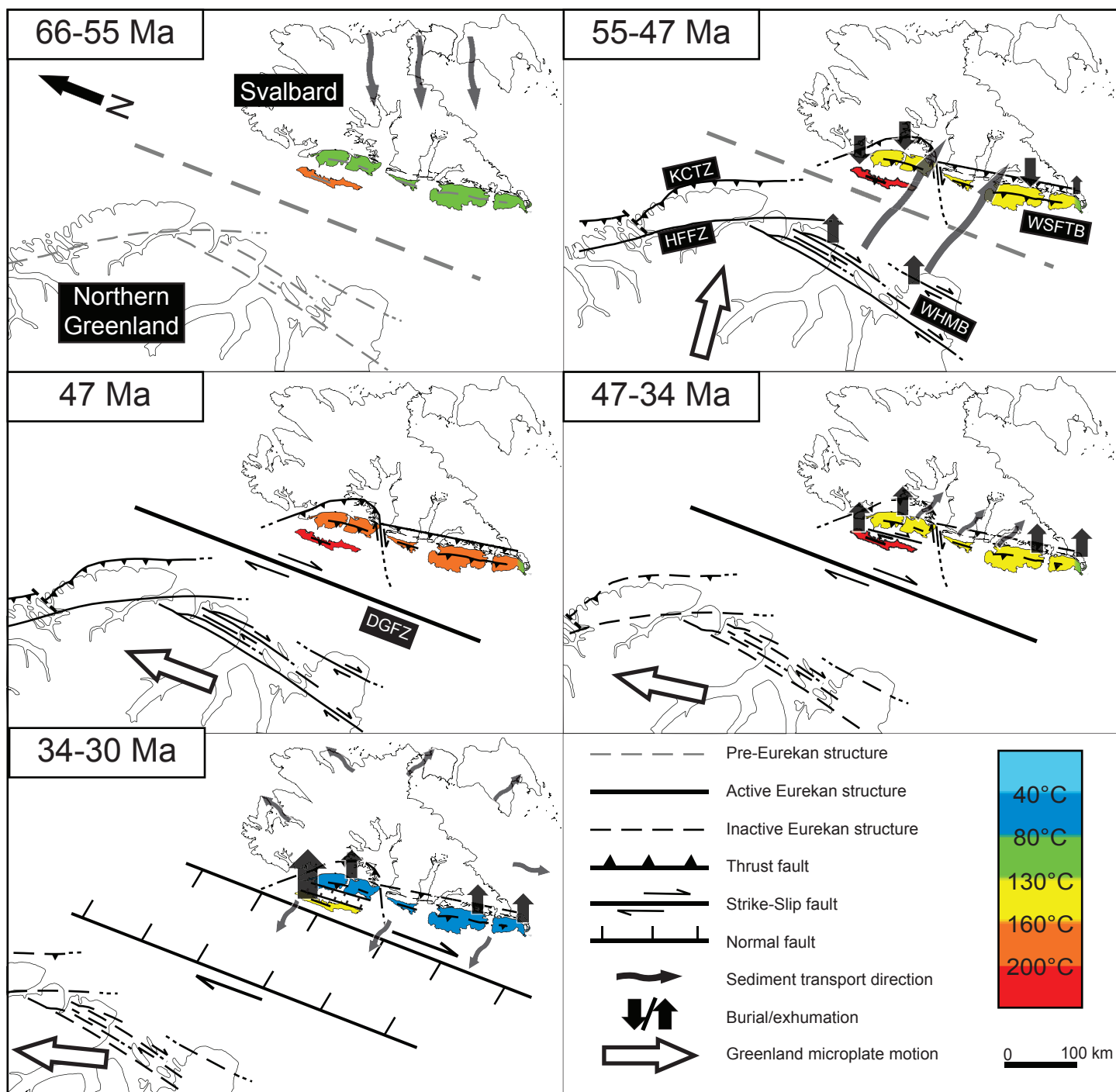


Figure 12. Synoptic diagrams depicting simplified paleo-reconfigurations of Svalbard relative to Greenland through the evolution of the Eurekan Orogeny. 65-55 Ma: Pre-Eurekan structures are located across northern Greenland and the western margin of Svalbard. North arrow indicates present-day north for Svalbard. Deposition of the Van Mijenfjorden Group lower succession derived from an eastern/northeastern source has an insignificant effect on the thermal history of the Southwestern Province. 55-47: Northeastern movement of the Greenland microplate produces Eurekan tectonism across Svalbard and northern Greenland which is characterized by a decoupling of deformation into compressional (KCTZ, HFFZ, WSFTB) and transpressional (WHMB) zones, enhanced by pre-Eurekan crustal structures. All sample regions on Svalbard, except Sørkapp Land, experience heating due to tectonic burial and crustal thickening; erosion of the WSFTB is insignificant at this time. Sediments of the Van Mijenfjorden Group upper succession may be derived from the active WHMB located in the hinterland of the WSFTB. 47 Ma: Maximum tectonic burial is attained in the WSFTB. Maximum temperatures for Oscar II Land and Wedel Jarlsberg Land are similar, whereas Prins Karls Forland reaches greater temperatures due to residence at a deeper crustal level. Plate motion of Greenland shifts towards a northwesterly direction. 47-34 Ma: The northwestern movement of the Greenland microplate, relative to Svalbard, creates a dextral strike-slip tectonic regime primarily localized in proximity to the DGFZ. Such conditions begin to form the Forlandsundet Graben as a pull-apart basin. Exhumation of the WSFTB indicates an increase in erosion, providing sediment to the Central Basin, and termination of overthrusting. Eurekan structures in northern Greenland are likely inactive during this time. 34-30 Ma: Movement of Greenland microplate in a west-northwestern direction creates a transtensional stress on the western margin of Svalbard, exhuming the Southwestern Province. Increased exhumation of Prins Karls Forland compared to Spitsbergen occurs within the first 5 m.y. of extensional tectonism due to its structural setting as a horst, flanked to the east by the Forlandsundet Graben. Abbreviations: DGFZ, De Greer Fracture Zone; HFFZ, Harder Fiord Fault Zone; KCTZ, Kap Cannon Thrust Zone; WHMB, Wandal Hav Mobile Belt; WSFTB, West Spitsbergen Fold-and-Thrust Belt.

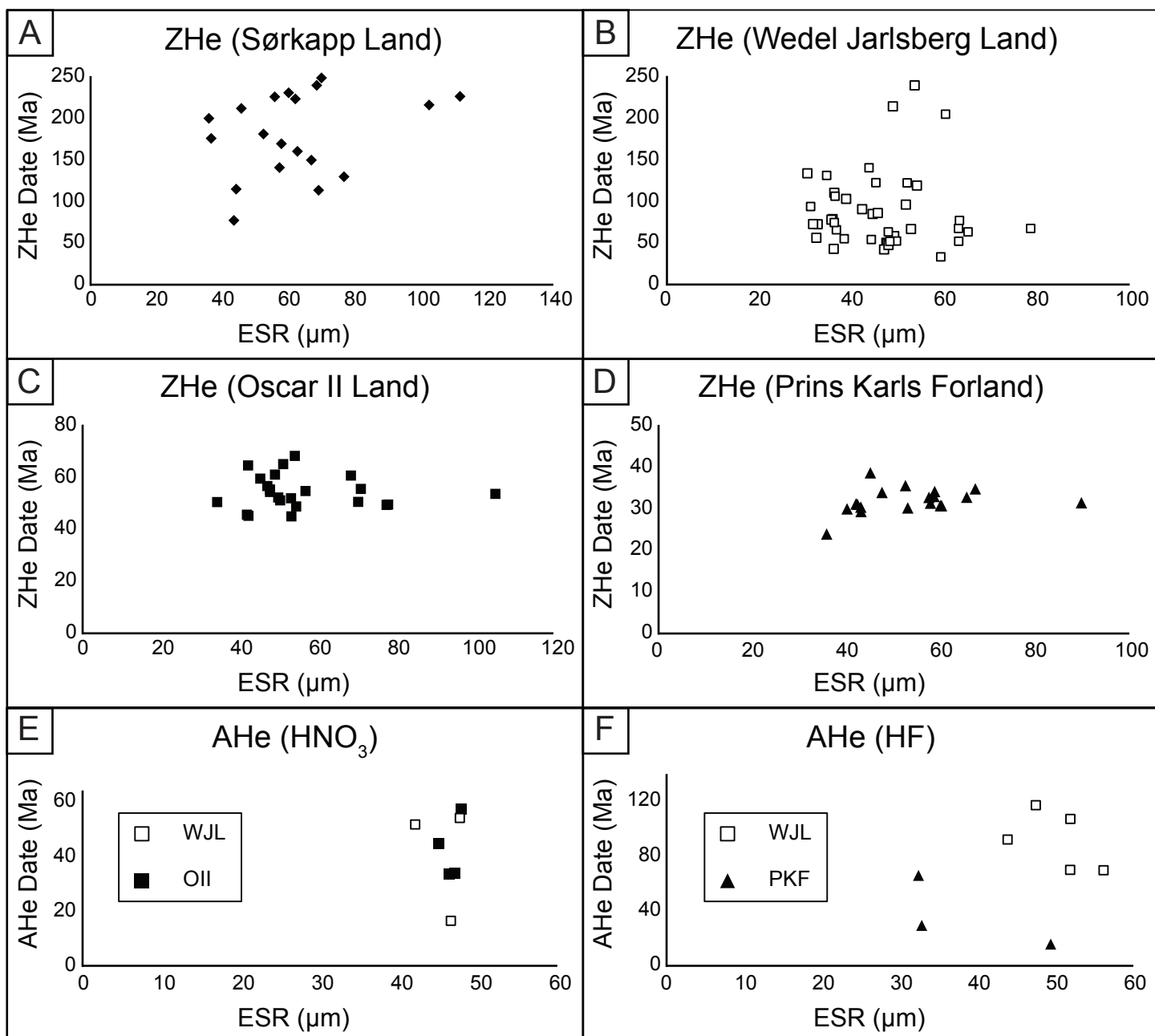


Figure S1. He date vs Equivalent Spherical Radius (ESR) graphs. A-D) ZHe date vs ESR, grouped by sample region. E-F) AHe date vs ESR, grouped by dissolution method. Sample regions are indicated in the legends below the respective graphs. No definitive positive He date vs grain size correlations are observed within either ZHe or AHe datasets.

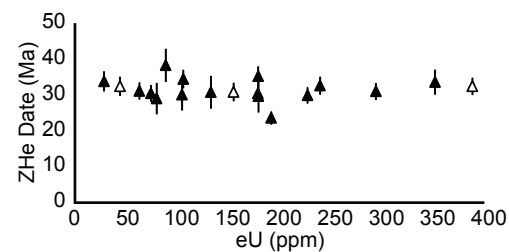
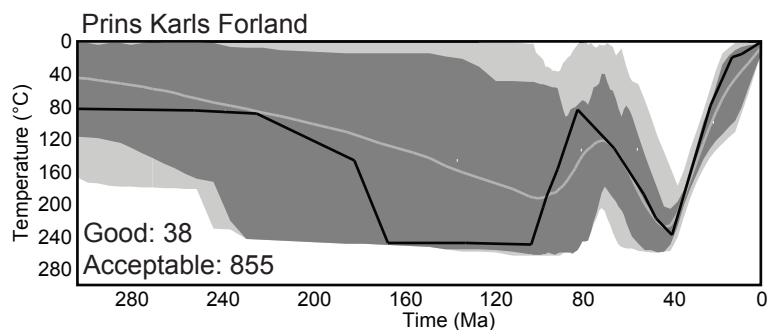
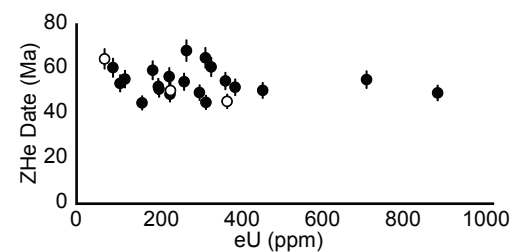
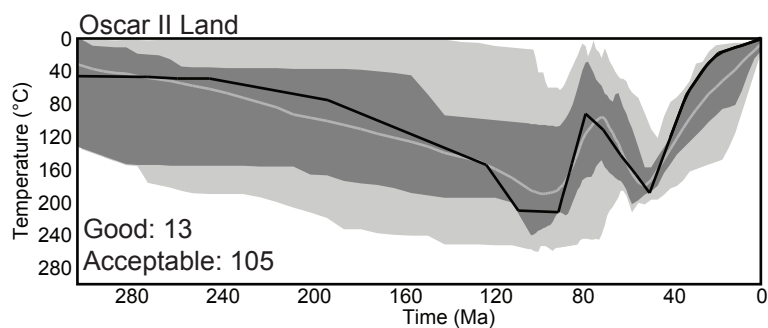
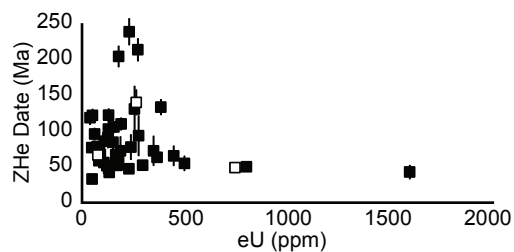
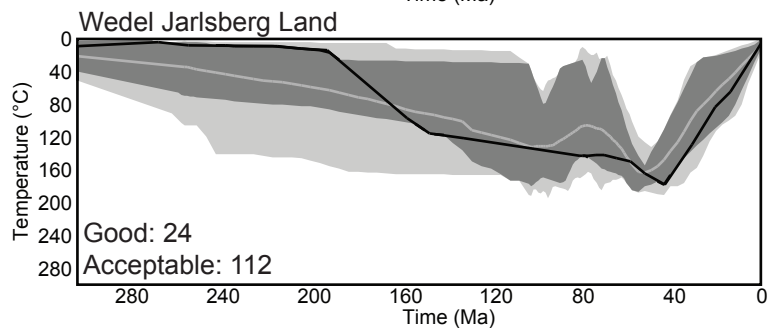
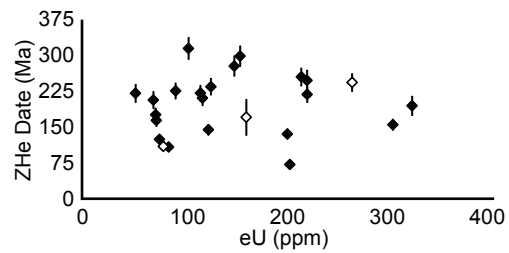
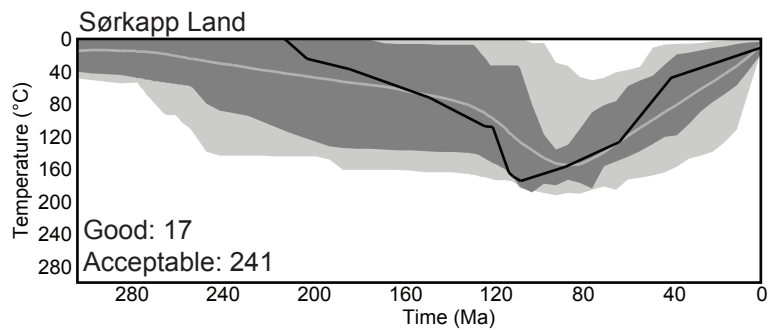


Figure S2. Example results of preliminary HeFTy inverse modeling and corresponding ZHe datasets for each model. For each inverse model, three grains were chosen from the respective ZHe dataset which represent the approximate spread in eU and ZHe date; average grain size for each dataset was input into the models. Selected and modeled grains are highlighted in white on the respective ZHe date-eU plot. For each model, 25,000 Monte Carlo simulations were run. We present pathway envelopes which constrained all possible t-T histories for each region; light grey represents acceptable-fit pathway envelope whereas the dark grey overlay represents the good-fit pathway envelope. The number of resulting good and acceptable pathways is listed on the inverse models. On each model, the sharp black line represents the best-fit t-T pathway and the smooth grey line represents the weighted mean for all acceptable and good t-T pathways. Constraints for the HeFTy models are similar to constraints described for our forward models in Section 6. All possible zircon ages are permissible for our inverse models; however, this assumes that all three zircon grains that were chosen belong to the same detrital population as inverse models do not allow for investigation of unique pre-depositional histories. The Caledonian Orogeny is constrained from c. 470-420 Ma and above $>200^{\circ}\text{C}$ (and $<450^{\circ}\text{C}$) to prevent retention of 4He but to allow the possibility for damage inheritance. The Torellian Orogeny has not been constrained for these models. For Sørkapp Land and Wedel Jarlsberg Land, models are constrained to reside at near surface temperatures ($<50^{\circ}\text{C}$) from the Ellesmerian (c. 360 Ma) to the beginning of the Triassic. Oscar II Land and Prins Karls Forland models allow for heating through the Carboniferous and Permian to account for sedimentary deposition through this time. Cretaceous and Paleogene constraints for WJL, OII and PKF are the same and allow for early Cretaceous heating constrained to $<260^{\circ}\text{C}$ in the late Cretaceous, cooling related exhumation of Svalbard (possible from 105-65 Ma, as represented by the Upper Cretaceous unconformity) and the Eurekan Orogeny from c. 55-34 Ma. Temperatures for the Eurekan Orogeny are constrained to $<260^{\circ}\text{C}$. SKL constraints are similar to the previous except no constraint for the Eurekan Orogeny is placed. Results for each region show similar t-T pathway morphologies but suggest slight variations in peak temperatures reached in the Cretaceous and Paleogene; however these differences are not well-constrained by the models as only three grains do not entirely represent each ZHe dataset, coupled with a lack of investigation into pre-depositional histories.

Table 1. Summary of geographical and geological information of samples from Southwestern Province, Svalbard

Region	Sample	Stratigraphic Unit	Rock Type	Metamorphic Facies	Mineral Dated	UTM Coordinates ¹
SKL	HL12_008	Isbjornhamna Fm.?	Quartzite	Amphbolite	Zr, n: 6	544394 m E 8500224 m N
SKL	HL12_009	Isbjornhamna Fm.?	Quartzite	Amphbolite	Zr, n: 8	544919 m E 8501149 m N
SKL	HL12_010	Isbjornhamna Fm.?	Quartzite	Amphbolite	Zr, n: 6	540439 m E 8500892 m N
SKL	HL12_011	Isbjornhamna Fm.?	Quartzite	Amphbolite	Zr, n: 6	540174 m E 8504067 m N
WJL	SP_6307		Amphibolite	Amphbolite	Ap, n: 3	504966 m E 8553030 m N
WJL	SP_6807		Amphibolite	Amphbolite	Ap, n: 5	507740 m E 8551672 m N
WJL	HL12_012	Eimfjellet Fm.	Quartzite	Amphbolite	Zr, n: 8	504562 m E 8549393 m N
WJL	HL12_014	Eimfjellet Fm.	Quartzite	Amphbolite	Zr, n: 8	506025 m E 8550315 m N
WJL	HL12_015	Eimfjellet Fm.	Quartzite	Amphbolite	Zr, n: 7	503590 m E 8552386 m N
WJL	HL12_017	Eimfjellet Fm.	Quartzite	Amphbolite	Zr, n: 8	503957 m E 8554290 m N
WJL	HL12_018	Deilegga	Quartzite	Greenschist	Zr, n: 5	506974 m E 8562653 m N
WJL	HL12_019	Sofiebogen	Quartzite	Greenschist	Zr, n: 8	506264 m E 8562606 m N
OII	CB15_OII_2		Meta-gabbro	Greenschist	Ap, n: 5	454969 m E 8718922 m N
OII	CB15_OII_1	Comfortlessbreen Grp.	Metasediment	Greenschist	Zr, n: 8	448494 m E 8719504 m N
OII	CB15_OII_4	Daudmannsodden Grp.	Metasediment	Greenschist	Zr, n: 7	433859 m E 8736666 m N
OII	CB15_OII_7	Daudmannsodden Grp.	Quartzite	Greenschist	Zr, n: 8	448753 m E 8705599 m N
PKF	CB15_PKF_1		Meta-gabbro	Greenschist	Ap, n: 4	411962 m E 8743786 m N
PKF	HL12_002	Macnairrabane Fm.	Quartzite	Greenschist	Zr, n: 3	409638 m E 8746972 m N
PKF	HL12_003	Taylorfjellet Fm.	Metasediment	Greenschist	Zr, n: 6	410777 m E 8746312 m N
PKF	HL12_007	Geike Unit	Quartzite	Greenschist	Zr, n: 7	419550 m E 8721103 m N
PKF	KK14_31	Pinkie Unit	Quartzite	Amphbolite	Zr, n: 4	412362 m E 8741557 m N

¹Zone 33 X

Table 2. Summary of apatite and zircon (U-Th)/He analyses of samples from Southwestern Province, Svalbard

Region	Sample Name	Mineral	ESR ¹ (μm)	eU ² (ppm)	Raw Date (Ma)	$\pm$ (Ma)	Ft ³	$\pm$ (%)	Corrected ⁴ Date (Ma)	$\pm$ (Ma)
SKL	HL12_08_Zr1	Zr	102.5	119.7	190.8	4.0	0.88	7.0	216.4	15.8
SKL	HL12_08_Zr2	Zr	76.8	76.6	110.1	3.0	0.85	7.0	130.2	9.8
SKL	HL12_08_Zr3	Zr	66.9	125.6	123.8	2.9	0.82	7.0	150.2	11.1
SKL	HL12_08_Zr4	Zr	57.3	204.7	112.4	2.1	0.80	7.0	141.1	10.2
SKL	HL12_08_Zr5	Zr	62.7	310.3	130.8	2.6	0.81	7.0	160.6	11.7
SKL	HL12_08_Zr6	Zr	63.9	218.6	212.5	3.7	0.82	7.0	260.3	18.8
SKL	HL12_09_Zr1	Zr	55.8	52.6	179.5	8.0	0.79	7.0	226.3	18.8
SKL	HL12_09_Zr2	Zr	36.6	163.5	122.6	2.9	0.70	21.1	176.3	37.5
SKL	HL12_09_Zr3	Zr	52.4	72.7	141.6	4.9	0.78	7.0	181.6	14.2
SKL	HL12_09_Zr4	Zr	36.9	0.2	31.3	26.9	0.68	10.0	46.4	40.1
SKL	HL12_09_Zr5	Zr	35.9	329.6	138.4	7.1	0.69	8.6	200.2	20.1
SKL	HL12_09_Zr6	Zr	45.7	70.5	159.3	7.4	0.75	7.0	212.1	17.8
SKL	HL12_09_Zr7	Zr	49.8	157.3	233.4	2.8	0.77	7.0	303.8	21.6
SKL	HL12_09_Zr8	Zr	37.2	224.4	177.0	4.5	0.70	8.0	253.1	21.3
SKL	HL12_10_Zr1	Zr	69.9	269.4	206.9	4.7	0.83	7.0	248.9	18.3
SKL	HL12_10_Zr2	Zr	119.6	105.7	287.6	4.8	0.90	7.0	320.0	23.0
SKL	HL12_10_Zr3	Zr	62.0	151.5	229.9	6.3	0.81	7.0	283.1	21.3
SKL	HL12_10_Zr4	Zr	55.6	189.5	0.0	0.0	0.79	7.0	0.1	0.0
SKL	HL12_10_Zr5	Zr	111.8	117.6	202.4	3.6	0.89	7.0	226.6	16.4
SKL	HL12_10_Zr6	Zr	60.1	92.7	186.4	3.4	0.81	7.0	231.1	16.7
SKL	HL12_11_Zr1	Zr	62.1	224.5	182.1	4.4	0.81	7.0	223.8	16.6
SKL	HL12_11_Zr2	Zr	69.1	85.9	94.5	1.5	0.83	7.0	114.0	8.2
SKL	HL12_11_Zr3	Zr	43.5	207.1	57.2	1.3	0.74	7.0	77.7	5.7
SKL	HL12_11_Zr4	Zr	68.5	128.1	198.4	3.4	0.83	7.0	240.0	17.3
SKL	HL12_11_Zr5	Zr	44.2	80.5	85.4	2.5	0.74	7.0	115.4	8.7
SKL	HL12_11_Zr6	Zr	57.9	73.5	135.5	3.8	0.80	7.0	169.8	12.8

Table 2. Cont'd

Region	Sample Name	Mineral	ESR ¹ (μm)	eU ² (ppm)	Raw Date (Ma)	$\pm$ (Ma)	Ft ³	$\pm$ (%)	Corrected ⁴ Date (Ma)	$\pm$ (Ma)
WJL	SP_6307_Ap1	Ap	47.7	3.2	38.3	1.0	0.70	7.0	54.2	4.1
WJL	SP_6307_Ap2	Ap	42.1	5.0	34.5	1.2	0.66	7.5	51.9	4.1
WJL	SP_6307_Ap3	Ap	46.6	0.6	11.1	2.0	0.66	7.0	16.6	3.1
WJL	SP_6807_Ap1	Ap	56.2	29.3	51.0	1.6	0.72	7.0	70.3	4.8
WJL	SP_6807_Ap2	Ap	47.5	13.4	78.8	1.9	0.67	7.0	117.8	7.5
WJL	SP_6807_Ap3	Ap	43.9	19.9	60.9	2.9	0.65	7.0	92.7	6.7
WJL	SP_6807_Ap4	Ap	51.9	30.0	49.2	3.3	0.69	7.0	70.6	6.1
WJL	SP_6807_Ap5	Ap	51.9	14.3	76.0	6.9	0.70	7.0	107.7	11.0
WJL	HL12_12_Zr1	Zr	44.3	181.7	40.5	0.4	0.74	10.8	54.5	5.9
WJL	HL12_12_Zr2	Zr	32.7	195.2	48.4	0.8	0.66	27.1	73.0	19.8
WJL	HL12_12_Zr3	Zr	43.7	274.4	104.2	1.0	0.74	12.5	140.8	17.7
WJL	HL12_12_Zr4	Zr	31.7	360.9	47.8	0.7	0.65	28.2	73.1	20.7
WJL	HL12_12_Zr5	Zr	36.7	462.2	46.1	0.6	0.70	20.8	66.1	13.8
WJL	HL12_12_Zr6	Zr	31.2	286.2	61.2	0.7	0.65	29.8	94.2	28.1
WJL	HL12_12_Zr7	Zr	38.4	516.0	39.4	0.8	0.71	18.5	55.6	10.3
WJL	HL12_12_Zr8	Zr	34.6	265.5	89.4	1.4	0.68	24.2	131.6	32.0
WJL	HL12_14_Zr1	Zr	60.3	185.9	165.0	2.5	0.80	7.0	205.1	14.7
WJL	HL12_14_Zr2	Zr	51.7	65.8	74.8	1.4	0.77	8.3	96.6	8.3
WJL	HL12_14_Zr3	Zr	49.3	87.1	45.4	0.6	0.77	9.0	59.2	5.4
WJL	HL12_14_Zr4	Zr	52.8	82.0	52.5	0.6	0.78	8.7	67.2	5.9
WJL	HL12_14_Zr5	Zr	47.5	826.3	38.6	0.6	0.76	10.6	50.8	5.4
WJL	HL12_14_Zr6	Zr	36.1	1644.1	30.1	0.5	0.69	22.3	43.4	9.7
WJL	HL12_14_Zr7	Zr	47.6	769.1	37.6	0.6	0.76	11.2	49.5	5.6
WJL	HL12_14_Zr8	Zr	44.5	157.4	63.5	1.1	0.75	12.1	85.2	10.4
WJL	HL12_15_Zr2	Zr	42.3	1.6	17.9	2.0	0.73	7.0	24.7	3.3
WJL	HL12_15_Zr3	Zr	47.0	138.9	31.8	0.6	0.74	7.0	42.8	3.1
WJL	HL12_15_Zr4	Zr	53.6	239.0	187.9	6.0	0.78	7.0	239.8	18.4
WJL	HL12_15_Zr5	Zr	48.0	237.2	36.3	0.6	0.76	7.0	47.9	3.5
WJL	HL12_15_Zr6	Zr	65.1	186.4	52.3	1.5	0.82	7.0	63.8	4.8
WJL	HL12_15_Zr7	Zr	59.2	53.2	27.0	0.9	0.80	7.0	33.6	2.6
WJL	HL12_17_Zr1	Zr	78.6	171.7	57.5	0.9	0.85	7.0	67.8	4.9
WJL	HL12_17_Zr2	Zr	63.1	178.8	42.6	0.7	0.81	7.0	52.6	3.8
WJL	HL12_17_Zr3	Zr	63.1	94.7	55.1	1.2	0.81	7.0	67.8	5.0
WJL	HL12_17_Zr4	Zr	45.7	121.4	64.5	0.9	0.75	7.0	86.4	6.2
WJL	HL12_17_Zr5	Zr	36.3	198.9	76.5	2.5	0.69	7.0	110.7	8.5
WJL	HL12_17_Zr6	Zr	54.1	43.0	93.7	3.6	0.78	7.0	119.4	9.5
WJL	HL12_17_Zr7	Zr	52.0	55.3	95.4	1.2	0.78	7.0	122.7	8.7
WJL	HL12_17_Zr8	Zr	48.9	282.6	162.8	3.6	0.76	7.0	214.5	15.7

Table 2. Cont'd

Region	Sample Name	Mineral	ESR ¹ (μ m)	eU ² (ppm)	Raw Date (Ma)	$\pm$ (Ma)	Ft ³	$\pm$ (%)	Corrected ⁴ Date (Ma)	$\pm$ (Ma)
OII	CB15_OII_2_Ap1	Ap	47.1	1.4	25.7	1.6	0.76	7.7	34.0	3.9
OII	CB15_OII_2_Ap2	Ap	46.3	1.7	25.6	1.3	0.76	7.3	33.7	3.4
OII	CB15_OII_2_Ap3	Ap	45.0	2.7	33.7	1.6	0.75	7.6	44.8	4.7
OII	CB15_OII_2_Ap4	Ap	49.5	2.4	124.0	5.1	0.77	7.0	160.8	14.7
OII	CB15_OII_2_Ap5	Ap	47.9	1.7	43.4	1.7	0.75	7.7	57.6	5.6
OII	CB15_OII_1_Zr1	Zr	47.9	721.1	41.8	0.4	0.75	7.0	55.5	3.9
OII	CB15_OII_1_Zr2	Zr	51.3	321.4	50.2	0.6	0.77	7.0	65.2	4.6
OII	CB15_OII_1_Zr3	Zr	56.9	370.9	43.4	0.8	0.79	7.0	54.9	3.8
OII	CB15_OII_1_Zr4	Zr	34.4	234.6	33.4	0.5	0.66	7.0	50.6	3.5
OII	CB15_OII_1_Zr5	Zr	45.4	190.4	43.9	0.5	0.74	7.0	59.6	4.2
OII	CB15_OII_1_Zr6	Zr	77.6	897.7	42.0	0.4	0.85	7.0	49.5	3.5
OII	CB15_OII_1_Zr7	Zr	54.2	274.2	53.5	0.6	0.78	7.0	68.4	4.8
OII	CB15_OII_1_Zr8	Zr	47.2	231.4	43.0	0.4	0.76	7.0	56.8	4.0
OII	CB15_OII_4_Zr1	Zr	78.0	306.6	42.1	0.6	0.85	7.0	49.7	3.5
OII	CB15_OII_4_Zr2	Zr	54.5	233.2	38.1	0.5	0.78	7.0	48.9	3.4
OII	CB15_OII_4_Zr3	Zr	42.0	375.3	33.7	0.6	0.73	7.0	45.8	3.2
OII	CB15_OII_4_Zr4	Zr	71.0	121.6	46.2	0.5	0.83	7.0	55.7	3.9
OII	CB15_OII_4_Zr5	Zr	42.3	70.9	46.6	0.7	0.72	7.0	64.7	4.5
OII	CB15_OII_4_Zr6	Zr	47.9	268.4	41.0	0.5	0.75	7.0	54.5	3.8
OII	CB15_OII_4_Zr7	Zr	50.5	206.2	39.3	0.8	0.76	7.0	51.3	3.6
OII	CB15_OII_7_Zr1	Zr	105.3	109.5	47.7	0.4	0.89	7.0	53.8	3.8
OII	CB15_OII_7_Zr2	Zr	70.3	463.4	42.2	0.4	0.83	7.0	50.7	3.5
OII	CB15_OII_7_Zr3	Zr	68.5	91.8	50.3	0.5	0.83	7.0	60.8	4.3
OII	CB15_OII_7_Zr4	Zr	50.0	204.3	39.9	0.5	0.76	7.0	52.4	3.7
OII	CB15_OII_7_Zr5	Zr	42.4	322.4	32.8	0.4	0.72	7.0	45.3	3.2
OII	CB15_OII_7_Zr6	Zr	53.2	395.0	40.6	0.4	0.78	7.0	52.1	3.6
OII	CB15_OII_7_Zr7	Zr	53.3	164.1	35.5	0.3	0.79	7.0	45.1	3.2
OII	CB15_OII_7_Zr8	Zr	49.2	335.5	47.2	0.5	0.77	7.0	61.1	4.3

Table 2. Cont'd

Region	Sample Name	Mineral	ESR ¹ (μm)	eU ² (ppm)	Raw Date (Ma)	$\pm$ (Ma)	Ft ³	$\pm$ (%)	Corrected ⁴ Date (Ma)	$\pm$ (Ma)
PKF	CB15_PKF_1_Ap1	Ap	32.5	40.6	38.3	1.0	0.57	13.1	66.5	7.2
PKF	CB15_PKF_1_Ap2	Ap	32.9	15.1	17.8	1.5	0.58	17.4	29.9	4.8
PKF	CB15_PKF_1_Ap3	Ap	49.4	7.6	11.8	0.4	0.72	7.0	16.3	1.1
PKF	CB15_PKF_1_Ap4	Ap	77.1	2.0	0.1	0.2	0.80	7.0	0.2	0.2
PKF	HL12_02_Zr1	Zr	40.1	179.6	21.5	0.3	0.72	14.7	29.9	4.4
PKF	HL12_02_Zr2	Zr	35.8	192.0	16.4	0.3	0.69	7.0	23.8	1.7
PKF	HL12_02_Zr3	Zr	60.0	179.1	24.7	0.5	0.80	7.0	30.7	2.2
PKF	HL12_03_Zr1	Zr	89.9	63.4	27.2	0.5	0.87	7.0	31.4	2.3
PKF	HL12_03_Zr2	Zr	65.5	44.5	26.8	1.0	0.82	7.0	32.7	2.6
PKF	HL12_03_Zr3	Zr	57.5	388.4	26.1	0.4	0.80	7.0	32.7	2.3
PKF	HL12_03_Zr4	Zr	43.1	105.0	22.3	0.4	0.74	14.0	30.3	4.3
PKF	HL12_03_Zr5	Zr	43.1	80.3	21.5	0.5	0.74	14.5	29.2	4.3
PKF	HL12_03_Zr6	Zr	45.1	89.2	28.6	1.1	0.74	11.1	38.5	4.5
PKF	HL12_07_Zr2	Zr	58.7	29.0	27.3	1.1	0.80	7.0	34.0	2.7
PKF	HL12_07_Zr3	Zr	67.3	106.3	28.6	0.4	0.83	7.0	34.7	2.5
PKF	HL12_07_Zr4	Zr	52.5	179.4	27.7	0.5	0.78	7.3	35.5	2.7
PKF	HL12_07_Zr5	Zr	57.8	294.2	25.0	0.4	0.80	7.0	31.3	2.3
PKF	HL12_07_Zr6	Zr	42.3	133.2	22.7	0.5	0.73	14.3	31.0	4.5
PKF	HL12_07_Zr7	Zr	47.5	351.9	25.7	0.8	0.76	9.5	33.8	3.4
PKF	KK14_31_Zr1	Zr	53.0	227.5	23.6	0.5	0.78	7.0	30.1	2.2
PKF	KK14_31_Zr2	Zr	60.2	74.7	24.7	0.5	0.80	7.0	30.7	2.2
PKF	KK14_31_Zr3	Zr	42.1	155.4	22.7	0.9	0.73	7.0	31.1	2.5
PKF	KK14_31_Zr4	Zr	58.6	239.7	26.3	0.6	0.80	7.0	32.9	2.4

¹Equivalent spherical radius²Effective uranium³alpha-ejection correction⁴Calculated by dividing raw date by alpha-ejection correction

Table S1a. Zircon (U-Th)/He analyses of samples from Sørkapp Land, Southwestern Province, Svalbard

Sample Name	Region	Mineral	length 1 (mm)	width 1 (mm)	length 2 (mm)	width 2 (mm)	Dim Mass (ug)	ESR ¹ (um)
HL12_08_Zr1	SKL	Zr	236.3	214.0	236.3	170.5	40.1	102.5
HL12_08_Zr2	SKL	Zr	201.6	151.4	201.6	123.0	17.5	76.8
HL12_08_Zr3	SKL	Zr	249.6	112.6	249.0	104.7	13.7	66.9
HL12_08_Zr4	SKL	Zr	144.0	108.3	144.0	99.6	7.2	57.3
HL12_08_Zr5	SKL	Zr	203.6	106.3	203.6	104.0	10.5	62.7
HL12_08_Zr6	SKL	Zr	227.7	112.4	232.2	97.4	11.7	63.9
HL12_09_Zr1	SKL	Zr	167.6	111.4	160.7	80.0	6.8	55.8
HL12_09_Zr2	SKL	Zr	153.6	69.4	150.1	46.7	2.3	36.6
HL12_09_Zr3	SKL	Zr	136.1	108.5	136.1	79.6	5.5	52.4
HL12_09_Zr4	SKL	Zr	163.7	65.0	162.8	50.7	2.5	36.9
HL12_09_Zr5	SKL	Zr	133.0	60.2	133.9	56.7	2.1	35.9
HL12_09_Zr6	SKL	Zr	183.3	82.6	183.3	63.7	4.5	45.7
HL12_09_Zr7	SKL	Zr	244.3	86.8	244.3	66.8	6.6	49.8
HL12_09_Zr8	SKL	Zr	136.4	66.9	123.6	54.2	2.2	37.2
HL12_10_Zr1	SKL	Zr	189.7	136.7	187.2	110.6	13.2	69.9
HL12_10_Zr2	SKL	Zr	535.6	207.4	535.0	167.2	86.3	119.6
HL12_10_Zr3	SKL	Zr	228.6	107.1	233.8	94.6	10.9	62.0
HL12_10_Zr4	SKL	Zr	199.5	105.1	207.8	76.8	7.6	55.6
HL12_10_Zr5	SKL	Zr	378.8	199.1	377.9	172.1	60.3	111.8
HL12_10_Zr6	SKL	Zr	267.5	94.8	268.5	93.6	11.1	60.1
HL12_11_Zr1	SKL	Zr	137.0	118.4	129.6	118.7	8.7	62.1
HL12_11_Zr2	SKL	Zr	156.5	131.4	150.5	129.7	12.2	69.1
HL12_11_Zr3	SKL	Zr	171.4	76.8	168.6	62.8	3.8	43.5
HL12_11_Zr4	SKL	Zr	236.2	124.6	236.2	102.0	14.0	68.5
HL12_11_Zr5	SKL	Zr	174.2	74.9	173.7	66.9	4.1	44.2
HL12_11_Zr6	SKL	Zr	155.7	127.4	155.7	77.7	7.2	57.9

¹Equivalent spherical radius

Table S1a. Continued

Sample Name	Region	Mineral	4He (nmol/g)	±	U (ppm)	±	Th (ppm)	±	Sm (ppm)	±	eU ² (ppm)
HL12_08_Zr1	SKL	Zr	125.1	0.1	94.0	0.0	109.2	1.8	2.3	4.4	119.7
HL12_08_Zr2	SKL	Zr	45.9	0.1	66.7	0.1	42.4	0.7	0.7	1.3	76.6
HL12_08_Zr3	SKL	Zr	84.7	0.1	109.8	0.1	67.3	0.8	2.3	1.7	125.6
HL12_08_Zr4	SKL	Zr	125.3	0.1	174.8	0.1	127.3	3.8	1.1	2.6	204.7
HL12_08_Zr5	SKL	Zr	221.3	0.2	290.3	0.3	85.2	2.1	1.9	1.7	310.3
HL12_08_Zr6	SKL	Zr	255.1	0.2	187.6	0.1	132.3	2.3	2.7	2.0	218.6
HL12_09_Zr1	SKL	Zr	51.7	0.0	49.3	2.4	14.4	0.7	N/A	N/A	52.6
HL12_09_Zr2	SKL	Zr	109.3	0.1	150.1	4.0	57.3	1.5	N/A	N/A	163.5
HL12_09_Zr3	SKL	Zr	56.2	0.0	64.5	2.6	34.9	1.4	3.1	0.1	72.7
HL12_09_Zr4	SKL	Zr	0.0	0.0	0.0	0.2	0.6	2.4	2.4	10.5	0.2
HL12_09_Zr5	SKL	Zr	248.8	0.2	308.2	17.4	90.9	5.2	5.5	0.3	329.6
HL12_09_Zr6	SKL	Zr	61.3	0.1	64.4	3.4	25.9	1.4	0.1	0.0	70.5
HL12_09_Zr7	SKL	Zr	202.0	0.2	137.6	1.7	84.0	1.1	0.6	0.0	157.3
HL12_09_Zr8	SKL	Zr	217.5	0.2	204.4	5.7	85.1	2.4	10.7	0.3	224.4
HL12_10_Zr1	SKL	Zr	305.9	0.2	231.8	6.3	160.1	4.4	1.5	0.0	269.4
HL12_10_Zr2	SKL	Zr	168.0	0.1	89.8	1.8	67.8	1.4	1.3	0.0	105.7
HL12_10_Zr3	SKL	Zr	191.5	0.1	138.1	4.3	57.2	1.8	0.0	0.0	151.5
HL12_10_Zr4	SKL	Zr	0.0	0.0	171.6	5.2	76.2	2.3	1.1	0.0	189.5
HL12_10_Zr5	SKL	Zr	130.6	0.1	107.5	2.1	43.1	0.9	0.2	0.0	117.6
HL12_10_Zr6	SKL	Zr	94.7	0.1	84.9	1.8	33.5	0.7	0.8	0.0	92.7
HL12_11_Zr1	SKL	Zr	223.9	0.2	219.6	5.5	20.8	0.5	2.3	0.1	224.5
HL12_11_Zr2	SKL	Zr	44.1	0.0	73.0	0.1	54.8	1.6	1.2	1.7	85.9
HL12_11_Zr3	SKL	Zr	64.3	0.0	173.0	0.1	145.0	3.1	4.2	5.3	207.1
HL12_11_Zr4	SKL	Zr	139.4	0.1	100.6	2.2	117.1	2.6	3.2	0.1	128.1
HL12_11_Zr5	SKL	Zr	37.4	0.0	66.4	2.4	59.7	2.2	4.7	0.2	80.5
HL12_11_Zr6	SKL	Zr	54.3	0.0	62.0	2.1	49.0	1.7	1.6	0.1	73.5

²Effective uranium

Table S1a. Continued

Sample Name	Region	Mineral	⁴ He (ncc)	±	U (ng)	±	Th (ng)	±	Sm (ng)	±	Th/U
HL12_08_Zr1	SKL	Zr	112.4	0.0	3.8	0.1	4.4	0.1	N/A	N/A	1.2
HL12_08_Zr2	SKL	Zr	18.0	0.0	1.2	0.0	0.7	0.0	N/A	N/A	0.6
HL12_08_Zr3	SKL	Zr	26.0	0.0	1.5	0.0	0.9	0.0	N/A	N/A	0.6
HL12_08_Zr4	SKL	Zr	20.3	0.0	1.3	0.0	0.9	0.0	N/A	N/A	0.7
HL12_08_Zr5	SKL	Zr	51.9	0.0	3.0	0.1	0.9	0.0	N/A	N/A	0.3
HL12_08_Zr6	SKL	Zr	66.9	0.1	2.2	0.0	1.5	0.0	N/A	N/A	0.7
HL12_09_Zr1	SKL	Zr	7.9	0.0	0.3	0.0	0.1	0.0	N/A	N/A	0.3
HL12_09_Zr2	SKL	Zr	5.6	0.0	0.3	0.0	0.1	0.0	N/A	N/A	0.4
HL12_09_Zr3	SKL	Zr	6.9	0.0	0.4	0.0	0.2	0.0	N/A	N/A	0.5
HL12_09_Zr4	SKL	Zr	0.0	0.0	0.0	0.0	0.0	0.0	N/A	N/A	15.7
HL12_09_Zr5	SKL	Zr	11.8	0.0	0.7	0.0	0.2	0.0	N/A	N/A	0.3
HL12_09_Zr6	SKL	Zr	6.2	0.0	0.3	0.0	0.1	0.0	N/A	N/A	0.4
HL12_09_Zr7	SKL	Zr	29.8	0.0	0.9	0.0	0.6	0.0	N/A	N/A	0.6
HL12_09_Zr8	SKL	Zr	10.7	0.0	0.4	0.0	0.2	0.0	N/A	N/A	0.4
HL12_10_Zr1	SKL	Zr	90.8	0.1	3.1	0.1	2.1	0.0	N/A	N/A	0.7
HL12_10_Zr2	SKL	Zr	325.0	0.2	7.7	0.2	5.9	0.1	N/A	N/A	0.8
HL12_10_Zr3	SKL	Zr	46.8	0.0	1.5	0.0	0.6	0.0	N/A	N/A	0.4
HL12_10_Zr4	SKL	Zr	0.0	0.0	1.3	0.0	0.6	0.0	N/A	N/A	0.4
HL12_10_Zr5	SKL	Zr	176.4	0.1	6.5	0.1	2.6	0.1	N/A	N/A	0.4
HL12_10_Zr6	SKL	Zr	23.5	0.0	0.9	0.0	0.4	0.0	N/A	N/A	0.4
HL12_11_Zr1	SKL	Zr	43.7	0.0	1.9	0.0	0.2	0.0	N/A	N/A	0.1
HL12_11_Zr2	SKL	Zr	12.0	0.0	0.9	0.0	0.7	0.0	N/A	N/A	0.8
HL12_11_Zr3	SKL	Zr	5.5	0.0	0.7	0.0	0.6	0.0	N/A	N/A	0.8
HL12_11_Zr4	SKL	Zr	43.6	0.0	1.4	0.0	1.6	0.0	N/A	N/A	1.2
HL12_11_Zr5	SKL	Zr	3.4	0.0	0.3	0.0	0.2	0.0	N/A	N/A	0.9
HL12_11_Zr6	SKL	Zr	8.7	0.0	0.4	0.0	0.4	0.0	N/A	N/A	0.8

Table S1a. Continued

Sample Name	Region	Mineral	Raw Date (Ma)	±	Ft ³	± (%)	Corrected ⁴ Date (Ma)	Full Unc. (Ma)	Analytic Unc. (Ma)
HL12_08_Zr1	SKL	Zr	190.8	4.0	0.9	7.0	216.4	15.8	4.0
HL12_08_Zr2	SKL	Zr	110.1	3.0	0.8	7.0	130.2	9.8	3.0
HL12_08_Zr3	SKL	Zr	123.8	2.9	0.8	7.0	150.2	11.1	2.9
HL12_08_Zr4	SKL	Zr	112.4	2.1	0.8	7.0	141.1	10.2	2.1
HL12_08_Zr5	SKL	Zr	130.8	2.6	0.8	7.0	160.6	11.7	2.6
HL12_08_Zr6	SKL	Zr	212.5	3.7	0.8	7.0	260.3	18.8	3.7
HL12_09_Zr1	SKL	Zr	179.5	8.0	0.8	7.0	226.3	18.8	8.0
HL12_09_Zr2	SKL	Zr	122.6	2.9	0.7	21.1	176.3	37.5	2.9
HL12_09_Zr3	SKL	Zr	141.6	4.9	0.8	7.0	181.6	14.2	4.9
HL12_09_Zr4	SKL	Zr	31.3	26.9	0.7	10.0	46.4	40.1	26.9
HL12_09_Zr5	SKL	Zr	138.4	7.1	0.7	8.6	200.2	20.1	7.1
HL12_09_Zr6	SKL	Zr	159.3	7.4	0.8	7.0	212.1	17.8	7.4
HL12_09_Zr7	SKL	Zr	233.4	2.8	0.8	7.0	303.8	21.6	2.8
HL12_09_Zr8	SKL	Zr	177.0	4.5	0.7	8.0	253.1	21.3	4.5
HL12_10_Zr1	SKL	Zr	206.9	4.7	0.8	7.0	248.9	18.3	4.7
HL12_10_Zr2	SKL	Zr	287.6	4.8	0.9	7.0	320.0	23.0	4.8
HL12_10_Zr3	SKL	Zr	229.9	6.3	0.8	7.0	283.1	21.3	6.3
HL12_10_Zr4	SKL	Zr	0.0	0.0	0.8	7.0	0.1	0.0	0.0
HL12_10_Zr5	SKL	Zr	202.4	3.6	0.9	7.0	226.6	16.4	3.6
HL12_10_Zr6	SKL	Zr	186.4	3.4	0.8	7.0	231.1	16.7	3.4
HL12_11_Zr1	SKL	Zr	182.1	4.4	0.8	7.0	223.8	16.6	4.4
HL12_11_Zr2	SKL	Zr	94.5	1.5	0.8	7.0	114.0	8.2	1.5
HL12_11_Zr3	SKL	Zr	57.2	1.3	0.7	7.0	77.7	5.7	1.3
HL12_11_Zr4	SKL	Zr	198.4	3.4	0.8	7.0	240.0	17.3	3.4
HL12_11_Zr5	SKL	Zr	85.4	2.5	0.7	7.0	115.4	8.7	2.5
HL12_11_Zr6	SKL	Zr	135.5	3.8	0.8	7.0	169.8	12.8	3.8

³ Alpha-ejection correction⁴ Calculated by dividing raw date by alpha-ejection correction

Table S1b. Apatite and zircon (U-Th)/He analyses of samples from Wedel Jarlsberg Land, Southwestern Provi

Sample Name	Region	Mineral	length 1 (mm)	width 1 (mm)	length 2 (mm)	width 2 (mm)	Dim Mass (ug)	ESR ¹ (um)
SP_6307_Ap1	WJL	Ap	116.0	92.9	116.0	98.7	2.5	47.7
SP_6307_Ap2	WJL	Ap	135.4	98.9	135.4	76.3	2.0	42.1
SP_6307_Ap3	WJL	Ap	100.3	114.9	100.3	97.2	2.4	46.6
SP_6807_Ap1	WJL	Ap	224.1	114.7	224.1	96.7	3.8	56.2
SP_6807_Ap2	WJL	Ap	175.9	105.9	175.9	82.0	2.2	47.5
SP_6807_Ap3	WJL	Ap	150.0	104.8	150.0	76.0	1.6	43.9
SP_6807_Ap4	WJL	Ap	170.1	106.2	170.1	98.9	2.5	51.9
SP_6807_Ap5	WJL	Ap	187.1	109.8	187.1	92.4	2.7	51.9
HL12_12_Zr1	WJL	Zr	133.2	72.7	137.0	78.9	3.6	44.3
HL12_12_Zr2	WJL	Zr	150.9	55.6	155.0	46.2	1.8	32.7
HL12_12_Zr3	WJL	Zr	154.0	75.9	156.0	68.0	3.7	43.7
HL12_12_Zr4	WJL	Zr	140.5	53.1	141.8	46.3	1.6	31.7
HL12_12_Zr5	WJL	Zr	150.9	62.5	151.6	54.4	2.4	36.7
HL12_12_Zr6	WJL	Zr	153.5	52.2	158.0	43.9	1.7	31.2
HL12_12_Zr7	WJL	Zr	149.6	67.5	149.2	56.0	2.6	38.4
HL12_12_Zr8	WJL	Zr	155.0	56.7	154.5	51.7	2.1	34.6
HL12_14_Zr1	WJL	Zr	145.0	120.5	145.0	101.9	8.3	60.3
HL12_14_Zr2	WJL	Zr	198.9	94.8	198.9	72.0	6.3	51.7
HL12_14_Zr3	WJL	Zr	175.1	90.8	175.1	71.0	5.2	49.3
HL12_14_Zr4	WJL	Zr	247.4	77.8	247.4	86.4	7.7	52.8
HL12_14_Zr5	WJL	Zr	186.2	77.9	186.2	74.8	5.0	47.5
HL12_14_Zr6	WJL	Zr	162.2	53.0	165.4	60.2	2.4	36.1
HL12_14_Zr7	WJL	Zr	210.8	78.6	210.8	70.9	5.5	47.6
HL12_14_Zr8	WJL	Zr	161.6	76.4	161.6	69.1	4.0	44.5

HL12_15_Zr2	WJL	Zr	200.1	66.6	202.0	64.7	4.0	42.3
HL12_15_Zr3	WJL	Zr	210.7	73.9	212.7	73.4	5.3	47.0
HL12_15_Zr4	WJL	Zr	192.0	94.2	193.3	81.4	6.9	53.6
HL12_15_Zr5	WJL	Zr	162.2	81.9	158.7	77.4	4.7	48.0
HL12_15_Zr6	WJL	Zr	165.4	120.7	166.4	114.9	10.7	65.1
HL12_15_Zr7	WJL	Zr	204.0	99.6	206.7	96.3	9.2	59.2
HL12_17_Zr1	WJL	Zr	176.1	172.1	176.1	126.5	17.8	78.6
HL12_17_Zr2	WJL	Zr	205.1	113.7	205.1	98.1	10.6	63.1
HL12_17_Zr3	WJL	Zr	149.1	115.0	148.9	119.2	9.5	63.1
HL12_17_Zr4	WJL	Zr	178.0	81.9	178.7	65.0	4.4	45.7
HL12_17_Zr5	WJL	Zr	145.6	62.2	147.5	53.8	2.3	36.3
HL12_17_Zr6	WJL	Zr	200.6	92.7	200.6	83.1	7.2	54.1
HL12_17_Zr7	WJL	Zr	193.2	95.2	193.2	73.8	6.3	52.0
HL12_17_Zr8	WJL	Zr	166.4	82.6	166.1	79.6	5.1	48.9
HL12_18_Zr1	WJL	Zr	150.1	98.5	150.1	71.5	4.9	49.7
HL12_18_Zr2	WJL	Zr	154.6	75.7	151.5	74.2	4.0	45.2
HL12_18_Zr3	WJL	Zr	116.8	51.2	116.1	47.1	1.3	30.5
HL12_18_Zr4	WJL	Zr	135.9	58.2	135.9	60.1	2.2	36.4
HL12_18_Zr5	WJL	Zr	160.9	63.6	160.9	48.8	2.3	35.9
HL12_19_Zr1	WJL	Zr	202.1	107.7	200.0	105.6	10.6	63.3
HL12_19_Zr2	WJL	Zr	210.7	80.9	210.7	71.0	5.6	48.3
HL12_19_Zr3	WJL	Zr	199.8	84.7	199.8	67.4	5.3	47.9
HL12_19_Zr4	WJL	Zr	146.2	56.3	145.2	57.2	2.2	35.6
HL12_19_Zr5	WJL	Zr	174.7	70.1	174.7	64.4	3.7	42.3
HL12_19_Zr6	WJL	Zr	143.2	63.9	143.2	52.4	2.2	36.3
HL12_19_Zr7	WJL	Zr	171.0	68.7	171.0	53.3	2.9	38.8
HL12_19_Zr8	WJL	Zr	150.2	54.7	150.5	46.2	1.8	32.4

¹Equivalent spherical radius

Table S1b. Continued

Sample Name	Region	Mineral	4He (nmol/g)	±	U (ppm)	±	Th (ppm)	±	Sm (ppm)	±	eU ² (ppm)
SP_6307_Ap1	WJL	Ap	0.7	0.0	1.7	0.1	6.4	0.1	18.7	1.0	3.2
SP_6307_Ap2	WJL	Ap	1.0	0.0	2.7	0.2	9.6	0.2	21.3	1.0	5.0
SP_6307_Ap3	WJL	Ap	0.0	0.0	0.0	0.0	2.4	0.1	0.2	0.2	0.6
SP_6807_Ap1	WJL	Ap	8.2	0.0	7.8	0.2	91.3	3.8	27.3	2.6	29.3
SP_6807_Ap2	WJL	Ap	5.7	0.0	1.7	0.2	49.8	0.9	0.0	0.0	13.4
SP_6807_Ap3	WJL	Ap	6.9	0.0	3.3	0.4	70.8	1.2	102.1	103.1	19.9
SP_6807_Ap4	WJL	Ap	8.1	0.0	2.6	0.2	116.6	8.3	36.1	71.0	30.0
SP_6807_Ap5	WJL	Ap	6.0	0.5	3.5	0.3	45.8	0.5	31.5	53.9	14.3
HL12_12_Zr1	WJL	Zr	39.8	0.0	161.9	1.6	84.3	1.5	0.0	0.0	181.7
HL12_12_Zr2	WJL	Zr	51.2	0.1	177.5	3.4	75.4	1.1	0.0	0.0	195.2
HL12_12_Zr3	WJL	Zr	155.6	0.2	248.9	2.7	108.2	1.5	0.0	0.0	274.4
HL12_12_Zr4	WJL	Zr	93.4	0.1	330.3	5.6	130.3	1.6	0.0	0.0	360.9
HL12_12_Zr5	WJL	Zr	115.3	0.1	428.3	5.9	144.2	4.2	11.3	33.6	462.2
HL12_12_Zr6	WJL	Zr	94.9	0.1	264.2	3.2	93.8	0.8	0.0	0.0	286.2
HL12_12_Zr7	WJL	Zr	110.0	0.1	500.3	11.1	66.8	1.0	0.0	0.0	516.0
HL12_12_Zr8	WJL	Zr	128.9	0.2	236.2	4.2	124.7	1.7	0.0	0.0	265.5
HL12_14_Zr1	WJL	Zr	167.8	0.1	146.5	2.8	167.9	2.1	0.7	2.6	185.9
HL12_14_Zr2	WJL	Zr	26.7	0.0	52.6	1.3	56.2	1.0	0.1	3.4	65.8
HL12_14_Zr3	WJL	Zr	21.4	0.0	79.4	1.1	32.7	0.8	0.0	0.0	87.1
HL12_14_Zr4	WJL	Zr	23.3	0.0	71.6	0.9	44.5	0.7	16.3	21.6	82.0
HL12_14_Zr5	WJL	Zr	172.5	0.2	766.7	12.3	253.6	1.7	51.7	49.5	826.3
HL12_14_Zr6	WJL	Zr	267.1	0.2	1531.2	27.0	480.5	3.9	0.0	0.0	1644.1
HL12_14_Zr7	WJL	Zr	156.5	0.1	683.4	13.2	364.8	9.1	0.1	4.0	769.1
HL12_14_Zr8	WJL	Zr	54.2	0.0	147.4	2.8	42.7	0.6	0.0	0.0	157.4

HL12_15_Zr2	WJL	Zr	0.2	0.0	1.1	0.0	2.4	0.2	0.0	0.0	1.6
HL12_15_Zr3	WJL	Zr	24.0	0.0	60.8	0.1	332.3	5.6	2.0	3.6	138.9
HL12_15_Zr4	WJL	Zr	246.0	0.3	207.6	0.2	133.5	5.1	0.8	3.8	239.0
HL12_15_Zr5	WJL	Zr	46.6	0.0	189.8	0.2	201.9	6.9	0.5	5.2	237.2
HL12_15_Zr6	WJL	Zr	52.8	0.1	155.4	0.2	132.0	2.4	0.3	2.6	186.4
HL12_15_Zr7	WJL	Zr	7.8	0.0	46.8	0.1	27.1	0.5	0.5	2.3	53.2
HL12_17_Zr1	WJL	Zr	53.5	0.1	144.3	0.1	116.9	3.8	0.3	1.1	171.7
HL12_17_Zr2	WJL	Zr	41.3	0.0	116.3	0.1	266.2	3.6	0.0	0.0	178.8
HL12_17_Zr3	WJL	Zr	28.3	0.0	74.9	0.1	84.3	1.0	0.1	1.8	94.7
HL12_17_Zr4	WJL	Zr	42.5	0.0	94.6	0.1	113.9	3.1	0.0	0.0	121.4
HL12_17_Zr5	WJL	Zr	82.5	0.1	170.1	0.2	122.4	5.5	0.6	8.8	198.9
HL12_17_Zr6	WJL	Zr	21.9	0.0	36.4	0.0	28.1	0.3	0.7	2.8	43.0
HL12_17_Zr7	WJL	Zr	28.7	0.0	48.1	0.0	30.4	1.3	0.0	0.0	55.3
HL12_17_Zr8	WJL	Zr	251.5	0.3	183.8	0.2	420.3	6.6	0.0	0.0	282.6
HL12_18_Zr1	WJL	Zr	67.2	0.1	256.6	4.8	212.6	2.0	0.4	4.3	306.5
HL12_18_Zr2	WJL	Zr	68.0	0.0	118.6	0.1	75.0	2.0	0.0	0.0	136.2
HL12_18_Zr3	WJL	Zr	186.4	0.2	378.5	0.3	81.6	2.3	0.0	0.0	397.7
HL12_18_Zr4	WJL	Zr	65.2	0.1	136.8	0.1	111.8	2.0	0.0	0.0	163.1
HL12_18_Zr5	WJL	Zr	23.2	0.0	62.3	0.1	69.7	1.6	29.6	65.4	78.7
HL12_19_Zr1	WJL	Zr	17.6	0.0	45.9	1.1	23.3	0.2	0.2	2.1	51.4
HL12_19_Zr2	WJL	Zr	27.5	0.0	115.7	2.4	50.6	0.9	0.0	0.0	127.5
HL12_19_Zr3	WJL	Zr	99.8	0.1	354.9	4.8	103.7	2.3	0.0	0.0	379.3
HL12_19_Zr4	WJL	Zr	72.3	0.1	226.7	3.6	89.3	1.2	0.0	0.0	247.7
HL12_19_Zr5	WJL	Zr	48.1	0.0	119.7	3.6	55.2	0.8	33.6	76.7	132.7
HL12_19_Zr6	WJL	Zr	25.3	0.0	82.5	2.8	33.2	0.7	0.0	0.0	90.3
HL12_19_Zr7	WJL	Zr	53.9	0.1	118.9	2.2	69.3	0.9	3.6	7.7	135.1
HL12_19_Zr8	WJL	Zr	22.6	0.0	92.7	1.8	82.3	0.3	0.8	12.1	112.1

²Effective uranium

Table S1b. Continued

Sample Name	Region	Mineral	⁴ He (ncc)	±	U (ng)	±	Th (ng)	±	Sm (ng)	±	Th/U
SP_6307_Ap1	WJL	Ap	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.7
SP_6307_Ap2	WJL	Ap	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.5
SP_6307_Ap3	WJL	Ap	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	N/A
SP_6807_Ap1	WJL	Ap	0.7	0.0	0.0	0.0	0.3	0.0	0.1	0.0	11.7
SP_6807_Ap2	WJL	Ap	0.3	0.0	0.0	0.0	0.1	0.0	0.0	0.0	29.9
SP_6807_Ap3	WJL	Ap	0.2	0.0	0.0	0.0	0.1	0.0	0.2	0.2	21.6
SP_6807_Ap4	WJL	Ap	0.5	0.0	0.0	0.0	0.3	0.0	0.1	0.2	44.7
SP_6807_Ap5	WJL	Ap	0.4	0.0	0.0	0.0	0.1	0.0	0.1	0.1	12.9
HL12_12_Zr1	WJL	Zr	3.2	0.0	0.6	0.0	0.3	0.0	N/A	N/A	0.5
HL12_12_Zr2	WJL	Zr	2.1	0.0	0.3	0.0	0.1	0.0	N/A	N/A	0.4
HL12_12_Zr3	WJL	Zr	13.0	0.0	0.9	0.0	0.4	0.0	N/A	N/A	0.4
HL12_12_Zr4	WJL	Zr	3.4	0.0	0.5	0.0	0.2	0.0	N/A	N/A	0.4
HL12_12_Zr5	WJL	Zr	6.2	0.0	1.0	0.0	0.3	0.0	N/A	N/A	0.3
HL12_12_Zr6	WJL	Zr	3.5	0.0	0.4	0.0	0.2	0.0	N/A	N/A	0.4
HL12_12_Zr7	WJL	Zr	6.5	0.0	1.3	0.0	0.2	0.0	N/A	N/A	0.1
HL12_12_Zr8	WJL	Zr	6.1	0.0	0.5	0.0	0.3	0.0	N/A	N/A	0.5
HL12_14_Zr1	WJL	Zr	31.1	0.0	1.2	0.0	1.4	0.0	N/A	N/A	1.1
HL12_14_Zr2	WJL	Zr	3.8	0.0	0.3	0.0	0.4	0.0	N/A	N/A	1.1
HL12_14_Zr3	WJL	Zr	2.5	0.0	0.4	0.0	0.2	0.0	N/A	N/A	0.4
HL12_14_Zr4	WJL	Zr	4.0	0.0	0.6	0.0	0.3	0.0	N/A	N/A	0.6
HL12_14_Zr5	WJL	Zr	19.5	0.0	3.9	0.1	1.3	0.0	N/A	N/A	0.3
HL12_14_Zr6	WJL	Zr	14.5	0.0	3.7	0.1	1.2	0.0	N/A	N/A	0.3
HL12_14_Zr7	WJL	Zr	19.2	0.0	3.7	0.1	2.0	0.0	N/A	N/A	0.5
HL12_14_Zr8	WJL	Zr	4.8	0.0	0.6	0.0	0.2	0.0	N/A	N/A	0.3

HL12_15_Zr2	WJL	Zr	0.0	0.0	0.0	0.0	0.0	0.0	N/A	N/A	2.3
HL12_15_Zr3	WJL	Zr	2.9	0.0	0.3	0.0	1.8	0.0	N/A	N/A	5.5
HL12_15_Zr4	WJL	Zr	37.9	0.0	1.4	0.1	0.9	0.0	N/A	N/A	0.6
HL12_15_Zr5	WJL	Zr	4.9	0.0	0.9	0.0	1.0	0.0	N/A	N/A	1.1
HL12_15_Zr6	WJL	Zr	12.7	0.0	1.7	0.1	1.4	0.0	N/A	N/A	0.8
HL12_15_Zr7	WJL	Zr	1.6	0.0	0.4	0.0	0.2	0.0	N/A	N/A	0.6
HL12_17_Zr1	WJL	Zr	21.4	0.0	2.6	0.0	2.1	0.1	N/A	N/A	0.8
HL12_17_Zr2	WJL	Zr	9.8	0.0	1.2	0.0	2.8	0.0	N/A	N/A	2.3
HL12_17_Zr3	WJL	Zr	6.0	0.0	0.7	0.0	0.8	0.0	N/A	N/A	1.1
HL12_17_Zr4	WJL	Zr	4.2	0.0	0.4	0.0	0.5	0.0	N/A	N/A	1.2
HL12_17_Zr5	WJL	Zr	4.2	0.0	0.4	0.0	0.3	0.0	N/A	N/A	0.7
HL12_17_Zr6	WJL	Zr	3.5	0.0	0.3	0.0	0.2	0.0	N/A	N/A	0.8
HL12_17_Zr7	WJL	Zr	4.1	0.0	0.3	0.0	0.2	0.0	N/A	N/A	0.6
HL12_17_Zr8	WJL	Zr	28.7	0.0	0.9	0.0	2.1	0.0	N/A	N/A	2.3
HL12_18_Zr1	WJL	Zr	7.4	0.0	1.3	0.0	1.0	0.0	N/A	N/A	0.8
HL12_18_Zr2	WJL	Zr	6.1	0.0	0.5	0.0	0.3	0.0	N/A	N/A	0.6
HL12_18_Zr3	WJL	Zr	5.5	0.0	0.5	0.0	0.1	0.0	N/A	N/A	0.2
HL12_18_Zr4	WJL	Zr	3.2	0.0	0.3	0.0	0.2	0.0	N/A	N/A	0.8
HL12_18_Zr5	WJL	Zr	1.2	0.0	0.1	0.0	0.2	0.0	N/A	N/A	1.1
HL12_19_Zr1	WJL	Zr	4.2	0.0	0.5	0.0	0.2	0.0	N/A	N/A	0.5
HL12_19_Zr2	WJL	Zr	3.5	0.0	0.7	0.0	0.3	0.0	N/A	N/A	0.4
HL12_19_Zr3	WJL	Zr	11.9	0.0	1.9	0.0	0.6	0.0	N/A	N/A	0.3
HL12_19_Zr4	WJL	Zr	3.5	0.0	0.5	0.0	0.2	0.0	N/A	N/A	0.4
HL12_19_Zr5	WJL	Zr	4.0	0.0	0.4	0.0	0.2	0.0	N/A	N/A	0.5
HL12_19_Zr6	WJL	Zr	1.3	0.0	0.2	0.0	0.1	0.0	N/A	N/A	0.4
HL12_19_Zr7	WJL	Zr	3.5	0.0	0.3	0.0	0.2	0.0	N/A	N/A	0.6
HL12_19_Zr8	WJL	Zr	0.9	0.0	0.2	0.0	0.1	0.0	N/A	N/A	0.9

Table S1b. Continued

Sample Name	Region	Mineral	Raw Date (Ma)	±	Ft ³	± (%)	Corrected ⁴ Date (Ma)	Full Unc. (Ma)	Analytic Unc. (Ma)
SP_6307_Ap1	WJL	Ap	38.3	1.0	0.7	7.0	54.2	4.1	1.0
SP_6307_Ap2	WJL	Ap	34.5	1.2	0.7	7.5	51.9	4.1	1.2
SP_6307_Ap3	WJL	Ap	11.1	2.0	0.7	7.0	16.6	3.1	2.0
SP_6807_Ap1	WJL	Ap	51.0	1.6	0.7	7.0	70.3	4.8	1.6
SP_6807_Ap2	WJL	Ap	78.8	1.9	0.7	7.0	117.8	7.5	1.9
SP_6807_Ap3	WJL	Ap	60.9	2.9	0.6	7.0	92.7	6.7	2.9
SP_6807_Ap4	WJL	Ap	49.2	3.3	0.7	7.0	70.6	6.1	3.3
SP_6807_Ap5	WJL	Ap	76.0	6.9	0.7	7.0	107.7	11.0	6.9
HL12_12_Zr1	WJL	Zr	40.5	0.4	0.7	10.8	54.5	5.9	0.4
HL12_12_Zr2	WJL	Zr	48.4	0.8	0.7	27.1	73.0	19.8	0.8
HL12_12_Zr3	WJL	Zr	104.2	1.0	0.7	12.5	140.8	17.7	1.0
HL12_12_Zr4	WJL	Zr	47.8	0.7	0.7	28.2	73.1	20.7	0.7
HL12_12_Zr5	WJL	Zr	46.1	0.6	0.7	20.8	66.1	13.8	0.6
HL12_12_Zr6	WJL	Zr	61.2	0.7	0.6	29.8	94.2	28.1	0.7
HL12_12_Zr7	WJL	Zr	39.4	0.8	0.7	18.5	55.6	10.3	0.8
HL12_12_Zr8	WJL	Zr	89.4	1.4	0.7	24.2	131.6	32.0	1.4
HL12_14_Zr1	WJL	Zr	165.0	2.5	0.8	7.0	205.1	14.7	2.5
HL12_14_Zr2	WJL	Zr	74.8	1.4	0.8	8.3	96.6	8.3	1.4
HL12_14_Zr3	WJL	Zr	45.4	0.6	0.8	9.0	59.2	5.4	0.6
HL12_14_Zr4	WJL	Zr	52.5	0.6	0.8	8.7	67.2	5.9	0.6
HL12_14_Zr5	WJL	Zr	38.6	0.6	0.8	10.6	50.8	5.4	0.6
HL12_14_Zr6	WJL	Zr	30.1	0.5	0.7	22.3	43.4	9.7	0.5
HL12_14_Zr7	WJL	Zr	37.6	0.6	0.8	11.2	49.5	5.6	0.6
HL12_14_Zr8	WJL	Zr	63.5	1.1	0.7	12.1	85.2	10.4	1.1

HL12_15_Zr2	WJL	Zr	17.9	2.0	0.7	7.0	24.7	3.3	2.0
HL12_15_Zr3	WJL	Zr	31.8	0.6	0.7	7.0	42.8	3.1	0.6
HL12_15_Zr4	WJL	Zr	187.9	6.0	0.8	7.0	239.8	18.4	6.0
HL12_15_Zr5	WJL	Zr	36.3	0.6	0.8	7.0	47.9	3.5	0.6
HL12_15_Zr6	WJL	Zr	52.3	1.5	0.8	7.0	63.8	4.8	1.5
HL12_15_Zr7	WJL	Zr	27.0	0.9	0.8	7.0	33.6	2.6	0.9
HL12_17_Zr1	WJL	Zr	57.5	0.9	0.8	7.0	67.8	4.9	0.9
HL12_17_Zr2	WJL	Zr	42.6	0.7	0.8	7.0	52.6	3.8	0.7
HL12_17_Zr3	WJL	Zr	55.1	1.2	0.8	7.0	67.8	5.0	1.2
HL12_17_Zr4	WJL	Zr	64.5	0.9	0.7	7.0	86.4	6.2	0.9
HL12_17_Zr5	WJL	Zr	76.5	2.5	0.7	7.0	110.7	8.5	2.5
HL12_17_Zr6	WJL	Zr	93.7	3.6	0.8	7.0	119.4	9.5	3.6
HL12_17_Zr7	WJL	Zr	95.4	1.2	0.8	7.0	122.7	8.7	1.2
HL12_17_Zr8	WJL	Zr	162.8	3.6	0.8	7.0	214.5	15.7	3.6
HL12_18_Zr1	WJL	Zr	40.5	0.6	0.8	8.0	52.8	4.3	0.6
HL12_18_Zr2	WJL	Zr	91.8	1.9	0.7	7.0	122.9	9.0	1.9
HL12_18_Zr3	WJL	Zr	86.3	3.3	0.6	7.0	134.2	10.7	3.3
HL12_18_Zr4	WJL	Zr	73.7	1.5	0.7	7.0	106.5	7.8	1.5
HL12_18_Zr5	WJL	Zr	54.3	1.5	0.7	7.0	79.2	6.0	1.5
HL12_19_Zr1	WJL	Zr	63.2	1.3	0.8	7.0	77.5	5.7	1.3
HL12_19_Zr2	WJL	Zr	39.9	0.7	0.8	10.7	52.3	5.7	0.7
HL12_19_Zr3	WJL	Zr	48.6	0.6	0.8	10.7	63.8	6.9	0.6
HL12_19_Zr4	WJL	Zr	53.9	0.8	0.7	22.2	78.3	17.4	0.8
HL12_19_Zr5	WJL	Zr	66.7	1.8	0.7	15.0	91.1	13.9	1.8
HL12_19_Zr6	WJL	Zr	51.9	1.6	0.7	21.1	74.9	15.9	1.6
HL12_19_Zr7	WJL	Zr	73.4	1.2	0.7	19.0	103.5	19.7	1.2
HL12_19_Zr8	WJL	Zr	37.2	0.6	0.7	27.5	56.6	15.6	0.6

³Alpha-ejection correction

⁴Calculated by dividing raw date by alpha-ejection correction

Table S1c. Apatite and zircon (U-Th)/He analyses of samples from Oscar II Land, Southwestern Province, Sv

Sample Name	Region	Mineral	length 1 (mm)	width 1 (mm)	length 2 (mm)	width 2 (mm)	Dim Mass (ug)	ESR ¹ (um)
CB15_OII_2_Ap1	OII	Ap	140.6	96.5	140.6	76.4	2.6	47.1
CB15_OII_2_Ap2	OII	Ap	121.6	95.3	121.6	82.9	2.3	46.3
CB15_OII_2_Ap3	OII	Ap	113.4	99.0	113.4	75.2	2.1	45.0
CB15_OII_2_Ap4	OII	Ap	146.1	99.2	146.1	84.0	2.9	49.5
CB15_OII_2_Ap5	OII	Ap	151.8	99.1	151.8	73.5	2.8	47.9
CB15_OII_1_Zr1	OII	Zr	182.2	91.9	182.2	72.1	2.9	47.9
CB15_OII_1_Zr2	OII	Zr	218.8	88.0	218.8	82.2	3.9	51.3
CB15_OII_1_Zr3	OII	Zr	144.7	115.1	144.7	95.0	3.9	56.9
CB15_OII_1_Zr4	OII	Zr	151.9	61.5	151.9	53.1	1.2	34.4
CB15_OII_1_Zr5	OII	Zr	177.6	88.0	177.6	67.6	2.6	45.4
CB15_OII_1_Zr6	OII	Zr	178.9	127.9	178.9	172.8	9.6	77.6
CB15_OII_1_Zr7	OII	Zr	166.8	106.7	166.8	85.2	3.7	54.2
CB15_OII_1_Zr8	OII	Zr	143.5	92.8	143.5	82.2	3.0	47.2
CB15_OII_4_Zr1	OII	Zr	217.1	139.8	217.1	137.7	10.2	78.0
CB15_OII_4_Zr2	OII	Zr	175.7	93.1	175.7	95.1	3.8	54.5
CB15_OII_4_Zr3	OII	Zr	159.9	66.0	159.9	71.5	2.5	42.0
CB15_OII_4_Zr4	OII	Zr	159.8	143.6	159.8	127.4	7.1	71.0
CB15_OII_4_Zr5	OII	Zr	167.8	81.0	167.8	63.3	2.1	42.3
CB15_OII_4_Zr6	OII	Zr	178.6	82.7	178.6	78.9	2.8	47.9
CB15_OII_4_Zr7	OII	Zr	151.6	108.8	151.6	75.5	3.0	50.5
CB15_OII_7_Zr1	OII	Zr	231.3	193.6	231.3	211.0	23.0	105.3
CB15_OII_7_Zr2	OII	Zr	161.1	142.6	161.1	124.4	7.0	70.3
CB15_OII_7_Zr3	OII	Zr	233.3	116.6	233.3	117.4	7.8	68.5
CB15_OII_7_Zr4	OII	Zr	215.3	89.4	215.3	77.3	3.6	50.0
CB15_OII_7_Zr5	OII	Zr	138.8	75.9	138.8	70.3	1.8	42.4
CB15_OII_7_Zr6	OII	Zr	160.1	92.1	160.1	94.2	3.4	53.2
CB15_OII_7_Zr7	OII	Zr	229.6	97.9	229.6	74.4	5.8	53.3
CB15_OII_7_Zr8	OII	Zr	171.5	85.3	171.5	81.0	3.7	49.2

¹Equivalent spherical radius

Table S1c. Continued

Sample Name	Region	Mineral	4He (nmol/g)	±	U (ppm)	±	Th (ppm)	±	Sm (ppm)	±	eU ² (ppm)
CB15_OII_2_Ap1	OII	Ap	0.4	0.0	0.7	0.2	2.6	0.1	21.5	0.8	1.4
CB15_OII_2_Ap2	OII	Ap	0.5	0.0	0.9	0.2	3.3	0.2	26.0	2.4	1.7
CB15_OII_2_Ap3	OII	Ap	1.2	0.0	1.1	0.3	7.1	0.4	28.0	1.7	2.7
CB15_OII_2_Ap4	OII	Ap	3.1	0.0	1.5	0.2	3.5	0.2	24.2	0.8	2.4
CB15_OII_2_Ap5	OII	Ap	0.8	0.0	0.8	0.1	3.9	0.1	24.2	0.9	1.7
CB15_OII_1_Zr1	OII	Zr	163.1	0.2	649.4	7.8	305.1	4.7	N/A	N/A	721.1
CB15_OII_1_Zr2	OII	Zr	87.3	0.1	288.9	3.8	138.2	2.7	N/A	N/A	321.4
CB15_OII_1_Zr3	OII	Zr	87.1	0.1	316.1	7.1	233.3	5.2	N/A	N/A	370.9
CB15_OII_1_Zr4	OII	Zr	42.3	0.1	207.4	3.2	115.4	1.5	N/A	N/A	234.6
CB15_OII_1_Zr5	OII	Zr	45.3	0.0	154.7	2.2	152.1	2.0	N/A	N/A	190.4
CB15_OII_1_Zr6	OII	Zr	203.8	0.2	808.6	9.4	379.1	4.6	N/A	N/A	897.7
CB15_OII_1_Zr7	OII	Zr	79.5	0.1	248.5	3.3	109.7	1.5	N/A	N/A	274.2
CB15_OII_1_Zr8	OII	Zr	53.8	0.1	176.1	2.2	235.2	2.8	N/A	N/A	231.4
CB15_OII_4_Zr1	OII	Zr	69.9	0.1	278.0	4.5	121.5	2.2	N/A	N/A	306.6
CB15_OII_4_Zr2	OII	Zr	48.2	0.1	184.3	3.3	208.0	1.9	N/A	N/A	233.2
CB15_OII_4_Zr3	OII	Zr	68.3	0.0	349.6	6.7	109.5	1.6	N/A	N/A	375.3
CB15_OII_4_Zr4	OII	Zr	30.5	0.0	98.6	1.3	98.0	2.0	N/A	N/A	121.6
CB15_OII_4_Zr5	OII	Zr	17.9	0.0	61.4	1.0	40.4	0.6	N/A	N/A	70.9
CB15_OII_4_Zr6	OII	Zr	59.6	0.1	231.1	3.0	158.7	2.5	N/A	N/A	268.4
CB15_OII_4_Zr7	OII	Zr	43.8	0.0	182.6	4.2	100.7	1.3	N/A	N/A	206.2
CB15_OII_7_Zr1	OII	Zr	28.3	0.0	93.7	1.0	67.2	0.8	N/A	N/A	109.5
CB15_OII_7_Zr2	OII	Zr	105.7	0.1	432.2	4.2	132.8	1.7	N/A	N/A	463.4
CB15_OII_7_Zr3	OII	Zr	25.0	0.0	82.6	0.9	39.1	0.4	N/A	N/A	91.8
CB15_OII_7_Zr4	OII	Zr	44.1	0.0	176.2	2.3	119.3	2.4	N/A	N/A	204.3
CB15_OII_7_Zr5	OII	Zr	57.1	0.1	295.2	3.5	115.8	1.0	N/A	N/A	322.4
CB15_OII_7_Zr6	OII	Zr	86.7	0.0	371.7	4.1	99.1	1.4	N/A	N/A	395.0
CB15_OII_7_Zr7	OII	Zr	31.5	0.0	146.2	1.5	75.9	1.1	N/A	N/A	164.1
CB15_OII_7_Zr8	OII	Zr	85.7	0.0	314.5	4.0	89.7	1.2	N/A	N/A	335.5

²Effective uranium

Table S1c. Continued

Sample Name	Region	Mineral	⁴ He (ncc)	±	U (ng)	±	Th (ng)	±	Sm (ng)	±	Th/U
CB15_OII_2_Ap1	OII	Ap	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	3.6
CB15_OII_2_Ap2	OII	Ap	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	3.7
CB15_OII_2_Ap3	OII	Ap	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	6.6
CB15_OII_2_Ap4	OII	Ap	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	2.3
CB15_OII_2_Ap5	OII	Ap	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	4.7
CB15_OII_1_Zr1	OII	Zr	10.7	0.0	1.9	0.0	0.9	0.0	N/A	N/A	0.5
CB15_OII_1_Zr2	OII	Zr	7.5	0.0	1.1	0.0	0.5	0.0	N/A	N/A	0.5
CB15_OII_1_Zr3	OII	Zr	7.5	0.0	1.2	0.0	0.9	0.0	N/A	N/A	0.7
CB15_OII_1_Zr4	OII	Zr	1.1	0.0	0.3	0.0	0.1	0.0	N/A	N/A	0.6
CB15_OII_1_Zr5	OII	Zr	2.6	0.0	0.4	0.0	0.4	0.0	N/A	N/A	1.0
CB15_OII_1_Zr6	OII	Zr	44.0	0.0	7.8	0.1	3.6	0.0	N/A	N/A	0.5
CB15_OII_1_Zr7	OII	Zr	6.6	0.0	0.9	0.0	0.4	0.0	N/A	N/A	0.4
CB15_OII_1_Zr8	OII	Zr	3.6	0.0	0.5	0.0	0.7	0.0	N/A	N/A	1.3
CB15_OII_4_Zr1	OII	Zr	15.9	0.0	2.8	0.0	1.2	0.0	N/A	N/A	0.4
CB15_OII_4_Zr2	OII	Zr	4.1	0.0	0.7	0.0	0.8	0.0	N/A	N/A	1.1
CB15_OII_4_Zr3	OII	Zr	3.8	0.0	0.9	0.0	0.3	0.0	N/A	N/A	0.3
CB15_OII_4_Zr4	OII	Zr	4.9	0.0	0.7	0.0	0.7	0.0	N/A	N/A	1.0
CB15_OII_4_Zr5	OII	Zr	0.8	0.0	0.1	0.0	0.1	0.0	N/A	N/A	0.7
CB15_OII_4_Zr6	OII	Zr	3.8	0.0	0.7	0.0	0.5	0.0	N/A	N/A	0.7
CB15_OII_4_Zr7	OII	Zr	3.0	0.0	0.6	0.0	0.3	0.0	N/A	N/A	0.6
CB15_OII_7_Zr1	OII	Zr	14.6	0.0	2.2	0.0	1.5	0.0	N/A	N/A	0.7
CB15_OII_7_Zr2	OII	Zr	16.5	0.0	3.0	0.0	0.9	0.0	N/A	N/A	0.3
CB15_OII_7_Zr3	OII	Zr	4.4	0.0	0.6	0.0	0.3	0.0	N/A	N/A	0.5
CB15_OII_7_Zr4	OII	Zr	3.6	0.0	0.6	0.0	0.4	0.0	N/A	N/A	0.7
CB15_OII_7_Zr5	OII	Zr	2.3	0.0	0.5	0.0	0.2	0.0	N/A	N/A	0.4
CB15_OII_7_Zr6	OII	Zr	6.6	0.0	1.3	0.0	0.3	0.0	N/A	N/A	0.3
CB15_OII_7_Zr7	OII	Zr	4.1	0.0	0.8	0.0	0.4	0.0	N/A	N/A	0.5
CB15_OII_7_Zr8	OII	Zr	7.2	0.0	1.2	0.0	0.3	0.0	N/A	N/A	0.3

Table S1c. Continued

Sample Name	Region	Mineral	Raw Date (Ma)	±	Ft ³	± (%)	Corrected ⁴ Date (Ma)	Full Unc. (Ma)	Analytic Unc. (Ma)
CB15_OII_2_Ap1	OII	Ap	25.7	1.6	0.8	7.7	34.0	3.9	1.6
CB15_OII_2_Ap2	OII	Ap	25.6	1.3	0.8	7.3	33.7	3.4	1.3
CB15_OII_2_Ap3	OII	Ap	33.7	1.6	0.8	7.6	44.8	4.7	1.6
CB15_OII_2_Ap4	OII	Ap	124.0	5.1	0.8	7.0	160.8	14.7	5.1
CB15_OII_2_Ap5	OII	Ap	43.4	1.7	0.8	7.7	57.6	5.6	1.7
CB15_OII_1_Zr1	OII	Zr	41.8	0.4	0.8	7.0	55.5	3.9	0.4
CB15_OII_1_Zr2	OII	Zr	50.2	0.6	0.8	7.0	65.2	4.6	0.6
CB15_OII_1_Zr3	OII	Zr	43.4	0.8	0.8	7.0	54.9	3.8	0.8
CB15_OII_1_Zr4	OII	Zr	33.4	0.5	0.7	7.0	50.6	3.5	0.5
CB15_OII_1_Zr5	OII	Zr	43.9	0.5	0.7	7.0	59.6	4.2	0.5
CB15_OII_1_Zr6	OII	Zr	42.0	0.4	0.8	7.0	49.5	3.5	0.4
CB15_OII_1_Zr7	OII	Zr	53.5	0.6	0.8	7.0	68.4	4.8	0.6
CB15_OII_1_Zr8	OII	Zr	43.0	0.4	0.8	7.0	56.8	4.0	0.4
CB15_OII_4_Zr1	OII	Zr	42.1	0.6	0.8	7.0	49.7	3.5	0.6
CB15_OII_4_Zr2	OII	Zr	38.1	0.5	0.8	7.0	48.9	3.4	0.5
CB15_OII_4_Zr3	OII	Zr	33.7	0.6	0.7	7.0	45.8	3.2	0.6
CB15_OII_4_Zr4	OII	Zr	46.2	0.5	0.8	7.0	55.7	3.9	0.5
CB15_OII_4_Zr5	OII	Zr	46.6	0.7	0.7	7.0	64.7	4.5	0.7
CB15_OII_4_Zr6	OII	Zr	41.0	0.5	0.8	7.0	54.5	3.8	0.5
CB15_OII_4_Zr7	OII	Zr	39.3	0.8	0.8	7.0	51.3	3.6	0.8
CB15_OII_7_Zr1	OII	Zr	47.7	0.4	0.9	7.0	53.8	3.8	0.4
CB15_OII_7_Zr2	OII	Zr	42.2	0.4	0.8	7.0	50.7	3.5	0.4
CB15_OII_7_Zr3	OII	Zr	50.3	0.5	0.8	7.0	60.8	4.3	0.5
CB15_OII_7_Zr4	OII	Zr	39.9	0.5	0.8	7.0	52.4	3.7	0.5
CB15_OII_7_Zr5	OII	Zr	32.8	0.4	0.7	7.0	45.3	3.2	0.4
CB15_OII_7_Zr6	OII	Zr	40.6	0.4	0.8	7.0	52.1	3.6	0.4
CB15_OII_7_Zr7	OII	Zr	35.5	0.3	0.8	7.0	45.1	3.2	0.3
CB15_OII_7_Zr8	OII	Zr	47.2	0.5	0.8	7.0	61.1	4.3	0.5

³Alpha-ejection correction⁴Calculated by dividing raw date by alpha-ejection correction

Table S1d. Apatite and zircon (U-Th)/He analyses of samples from Prins Karls Forland, Southwestern Provinc

Sample Name	Region	Mineral	length 1 (mm)	width 1 (mm)	length 2 (mm)	width 2 (mm)	Dim Mass (ug)	ESR ¹ (um)
CB15_PKF_1_Ap1	PKF	Ap	96.5	77.8	96.5	63.8	0.6	32.5
CB15_PKF_1_Ap2	PKF	Ap	142.2	72.8	142.2	54.0	0.8	32.9
CB15_PKF_1_Ap3	PKF	Ap	173.5	116.1	173.5	85.3	2.3	49.4
CB15_PKF_1_Ap4	PKF	Ap	289.6	183.8	289.6	128.4	9.3	77.1
HL12_02_Zr1	PKF	Zr	127.6	75.8	125.1	59.6	2.7	40.1
HL12_02_Zr2	PKF	Zr	167.4	69.0	167.4	42.4	2.3	35.8
HL12_02_Zr3	PKF	Zr	162.1	106.7	162.3	105.5	8.5	60.0
HL12_03_Zr1	PKF	Zr	204.3	203.3	204.3	135.8	26.2	89.9
HL12_03_Zr2	PKF	Zr	216.2	108.5	213.5	110.4	12.0	65.5
HL12_03_Zr3	PKF	Zr	185.3	108.4	184.5	84.9	7.9	57.5
HL12_03_Zr4	PKF	Zr	171.1	72.5	171.1	65.5	3.8	43.1
HL12_03_Zr5	PKF	Zr	183.3	63.0	182.5	73.3	3.9	43.1
HL12_03_Zr6	PKF	Zr	151.3	83.0	150.5	67.0	3.9	45.1
HL12_07_Zr2	PKF	Zr	175.0	107.8	172.0	93.9	8.2	58.7
HL12_07_Zr3	PKF	Zr	181.0	118.2	181.8	120.6	12.0	67.3
HL12_07_Zr4	PKF	Zr	162.8	90.4	162.3	88.0	6.0	52.5
HL12_07_Zr5	PKF	Zr	223.5	96.9	218.3	89.5	8.9	57.8
HL12_07_Zr6	PKF	Zr	160.8	72.2	167.9	64.7	3.6	42.3
HL12_07_Zr7	PKF	Zr	158.3	86.9	158.2	71.6	4.6	47.5
KK14_31_Zr1	PKF	Zr	185.0	75.0	188.2	99.7	6.5	53.0
KK14_31_Zr2	PKF	Zr	167.4	101.8	169.0	109.2	8.7	60.2
KK14_31_Zr3	PKF	Zr	181.9	73.3	179.8	59.3	3.7	42.1
KK14_31_Zr4	PKF	Zr	162.8	102.7	166.8	103.0	8.1	58.6

¹Equivalent spherical radius

Table S1d. Continued

Sample Name	Region	Mineral	4He (nmol/g)	±	U (ppm)	±	Th (ppm)	±	Sm (ppm)	±	eU ² (ppm)
CB15_PKF_1_Ap1	PKF	Ap	8.4	0.0	31.3	1.0	39.7	0.5	5.0	13.2	40.6
CB15_PKF_1_Ap2	PKF	Ap	1.5	0.0	13.9	0.3	5.3	0.1	96.6	148.4	15.1
CB15_PKF_1_Ap3	PKF	Ap	0.5	0.0	7.0	0.2	2.7	0.0	34.3	1.8	7.6
CB15_PKF_1_Ap4	PKF	Ap	0.0	0.0	0.4	0.1	6.6	0.1	5.3	15.0	2.0
HL12_02_Zr1	PKF	Zr	20.9	0.0	167.7	2.9	50.2	2.1	0.0	0.0	179.6
HL12_02_Zr2	PKF	Zr	17.0	0.0	174.8	0.3	73.4	0.6	29.7	44.0	192.0
HL12_02_Zr3	PKF	Zr	23.9	0.0	149.8	0.2	124.5	3.5	2.3	2.7	179.1
HL12_03_Zr1	PKF	Zr	9.3	0.0	53.1	1.3	43.7	1.1	N/A	N/A	63.4
HL12_03_Zr2	PKF	Zr	6.4	0.0	37.7	1.7	29.0	1.3	N/A	N/A	44.5
HL12_03_Zr3	PKF	Zr	54.7	0.0	353.9	6.0	146.5	2.5	N/A	N/A	388.4
HL12_03_Zr4	PKF	Zr	12.6	0.0	91.8	1.9	56.5	1.2	N/A	N/A	105.0
HL12_03_Zr5	PKF	Zr	9.3	0.0	72.2	2.0	34.5	1.0	N/A	N/A	80.3
HL12_03_Zr6	PKF	Zr	13.8	0.0	64.1	3.4	106.5	5.6	N/A	N/A	89.2
HL12_07_Zr2	PKF	Zr	4.3	0.0	25.4	1.2	15.0	0.7	N/A	N/A	29.0
HL12_07_Zr3	PKF	Zr	16.5	0.0	95.1	1.7	47.4	0.8	N/A	N/A	106.3
HL12_07_Zr4	PKF	Zr	26.8	0.0	160.5	3.5	80.3	1.7	N/A	N/A	179.4
HL12_07_Zr5	PKF	Zr	39.7	0.0	275.4	5.3	80.0	1.6	N/A	N/A	294.2
HL12_07_Zr6	PKF	Zr	16.3	0.0	123.8	3.0	39.8	1.0	N/A	N/A	133.2
HL12_07_Zr7	PKF	Zr	48.8	0.0	318.3	11.9	143.0	5.4	N/A	N/A	351.9
KK14_31_Zr1	PKF	Zr	29.0	0.0	216.6	4.6	46.5	1.0	0.2	0.0	227.5
KK14_31_Zr2	PKF	Zr	10.0	0.0	59.5	1.5	64.6	1.7	0.0	0.0	74.7
KK14_31_Zr3	PKF	Zr	19.1	0.1	144.6	6.2	45.8	2.0	2.3	0.1	155.4
KK14_31_Zr4	PKF	Zr	34.1	0.0	203.3	5.6	155.1	4.3	0.6	0.0	239.7

²Effective uranium

Table S1d. Continued

Sample Name	Region	Mineral	⁴ He (ncc)	±	U (ng)	±	Th (ng)	±	Sm (ng)	±	Th/U
CB15_PKF_1_Ap1	PKF	Ap	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3
CB15_PKF_1_Ap2	PKF	Ap	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.4
CB15_PKF_1_Ap3	PKF	Ap	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.4
CB15_PKF_1_Ap4	PKF	Ap	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	16.3
HL12_02_Zr1	PKF	Zr	1.2	0.0	0.4	0.0	0.1	0.0	N/A	N/A	0.3
HL12_02_Zr2	PKF	Zr	0.9	0.0	0.4	0.0	0.2	0.0	N/A	N/A	0.4
HL12_02_Zr3	PKF	Zr	4.5	0.0	1.3	0.0	1.1	0.0	N/A	N/A	0.8
HL12_03_Zr1	PKF	Zr	5.5	0.0	1.4	0.0	1.1	0.0	N/A	N/A	0.8
HL12_03_Zr2	PKF	Zr	1.7	0.0	0.5	0.0	0.3	0.0	N/A	N/A	0.8
HL12_03_Zr3	PKF	Zr	9.7	0.0	2.8	0.0	1.2	0.0	N/A	N/A	0.4
HL12_03_Zr4	PKF	Zr	1.1	0.0	0.3	0.0	0.2	0.0	N/A	N/A	0.6
HL12_03_Zr5	PKF	Zr	0.8	0.0	0.3	0.0	0.1	0.0	N/A	N/A	0.5
HL12_03_Zr6	PKF	Zr	1.2	0.0	0.3	0.0	0.4	0.0	N/A	N/A	1.7
HL12_07_Zr2	PKF	Zr	0.8	0.0	0.2	0.0	0.1	0.0	N/A	N/A	0.6
HL12_07_Zr3	PKF	Zr	4.4	0.0	1.1	0.0	0.6	0.0	N/A	N/A	0.5
HL12_07_Zr4	PKF	Zr	3.6	0.0	1.0	0.0	0.5	0.0	N/A	N/A	0.5
HL12_07_Zr5	PKF	Zr	7.9	0.0	2.5	0.0	0.7	0.0	N/A	N/A	0.3
HL12_07_Zr6	PKF	Zr	1.3	0.0	0.4	0.0	0.1	0.0	N/A	N/A	0.3
HL12_07_Zr7	PKF	Zr	5.0	0.0	1.5	0.1	0.7	0.0	N/A	N/A	0.4
KK14_31_Zr1	PKF	Zr	4.2	0.0	1.4	0.0	0.3	0.0	N/A	N/A	0.2
KK14_31_Zr2	PKF	Zr	1.9	0.0	0.5	0.0	0.6	0.0	N/A	N/A	1.1
KK14_31_Zr3	PKF	Zr	1.6	0.0	0.5	0.0	0.2	0.0	N/A	N/A	0.3
KK14_31_Zr4	PKF	Zr	6.2	0.0	1.6	0.0	1.3	0.1	N/A	N/A	0.8

Table S1d. Continued

Sample Name	Region	Mineral	Raw Date (Ma)	±	Ft ³	± (%)	Corrected ⁴ Date (Ma)	Full Unc. (Ma)	Analytic Unc. (Ma)
CB15_PKF_1_Ap1	PKF	Ap	38.3	1.0	0.6	13.1	66.5	7.2	1.0
CB15_PKF_1_Ap2	PKF	Ap	17.8	1.5	0.6	17.4	29.9	4.8	1.5
CB15_PKF_1_Ap3	PKF	Ap	11.8	0.4	0.7	7.0	16.3	1.1	0.4
CB15_PKF_1_Ap4	PKF	Ap	0.1	0.2	0.8	7.0	0.2	0.2	0.2
HL12_02_Zr1	PKF	Zr	21.5	0.3	0.7	14.7	29.9	4.4	0.3
HL12_02_Zr2	PKF	Zr	16.4	0.3	0.7	7.0	23.8	1.7	0.3
HL12_02_Zr3	PKF	Zr	24.7	0.5	0.8	7.0	30.7	2.2	0.5
HL12_03_Zr1	PKF	Zr	27.2	0.5	0.9	7.0	31.4	2.3	0.5
HL12_03_Zr2	PKF	Zr	26.8	1.0	0.8	7.0	32.7	2.6	1.0
HL12_03_Zr3	PKF	Zr	26.1	0.4	0.8	7.0	32.7	2.3	0.4
HL12_03_Zr4	PKF	Zr	22.3	0.4	0.7	14.0	30.3	4.3	0.4
HL12_03_Zr5	PKF	Zr	21.5	0.5	0.7	14.5	29.2	4.3	0.5
HL12_03_Zr6	PKF	Zr	28.6	1.1	0.7	11.1	38.5	4.5	1.1
HL12_07_Zr2	PKF	Zr	27.3	1.1	0.8	7.0	34.0	2.7	1.1
HL12_07_Zr3	PKF	Zr	28.6	0.4	0.8	7.0	34.7	2.5	0.4
HL12_07_Zr4	PKF	Zr	27.7	0.5	0.8	7.3	35.5	2.7	0.5
HL12_07_Zr5	PKF	Zr	25.0	0.4	0.8	7.0	31.3	2.3	0.4
HL12_07_Zr6	PKF	Zr	22.7	0.5	0.7	14.3	31.0	4.5	0.5
HL12_07_Zr7	PKF	Zr	25.7	0.8	0.8	9.5	33.8	3.4	0.8
KK14_31_Zr1	PKF	Zr	23.6	0.5	0.8	7.0	30.1	2.2	0.5
KK14_31_Zr2	PKF	Zr	24.7	0.5	0.8	7.0	30.7	2.2	0.5
KK14_31_Zr3	PKF	Zr	22.7	0.9	0.7	7.0	31.1	2.5	0.9
KK14_31_Zr4	PKF	Zr	26.3	0.6	0.8	7.0	32.9	2.4	0.6

³Alpha-ejection correction⁴Calculated by dividing raw date by alpha-ejection correction