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Insights into the age of the Mono Lake Excursion and magmatic crystal residence time from (U-Th)/He and ^{230}Th dating of volcanic allanite

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ABSTRACT

We present new data for the age of the Mono Lake Excursion at its type locality. Using the (U-Th)/He system on allanite, we dated Wilson Creek Ash 15 (Lajoie, 1968) to 38.7 ± 1.2 ka (2 SE). The new age for this ash supports the hypothesis (Kent et al., 2002; Zimmerman et al., 2006) that the Mono Lake Excursion is coincident with, and probably the same event as, the Laschamp Geomagnetic Excursion (40.4 ± 2 ka), an event that shares similar magnetic characteristics with the excursion identified at Mono Lake. We also estimate an allanite magma residence time of slightly less than 30 ka based on ^{230}Th/^{238}U disequilibrium and the (U-Th)/He-based eruption age.

1. Introduction

Mono Lake is a closed-basin lake in the western Great Basin, east of the Sierra Nevada in California. The ancient lake sediments of the Mono Basin contain important regional climate records (Benson et al., 1990, 1997, 1998; Bursik and Gillespie, 1993; Davis, 1999; Graham and Hughes, 2007; Lajoie, 1968; Reheis et al., 2002; Russell, 1889; Stine, 1987, 1990a, 1990b; Zimmerman et al., 2006, 2011a, 2011b) that can be dated in a relative sense by correlation of the volcanic ashes that occur throughout the basin. The Upper Pleistocene Wilson Creek Formation (WCF), first mapped by Lajoie (1968), comprises unconsolidated lake sediments punctuated by eighteen rhyolitic ashes and one basaltic ash that have been numbered and bundled into marker sequences. These ashes can be identified with confidence simply based upon outcrop appearance and stratigraphic order.

While these ashes provide closely spaced relative age constraints for climate records from the last glacial period in the Mono Basin, absolute ages are difficult to obtain due to the youth of the ashes and geochemical complications in Mono Lake. Low in situ produced daughter product concentrations and uncertainty about initial compositions and secular equilibrium pose challenges for most radiometric dating systems in such juvenile materials. While ^{14}C dating is frequently used for materials younger than ~50 ka, several unique problems such as a large and almost certainly time-varying dead carbon reservoir and extreme carbonate chemistry plague radiocarbon dating attempts in this hypersaline alkaline lake (Benson et al., 1990; Cassata et al., 2010; Kent et al., 2002; Zimmerman et al., 2006). ^{40}Ar/^{39}Ar dating of several WCF ashes suffers from significant variability due to inheritance and high uncertainties in the results (Cassata et al., 2010; Chen et al., 1996; Kent et al., 2002; Zimmerman et al., 2006). In this work, we present new (U-Th)/He eruption age data for allanites from the ash associated with the prominent magnetic excursion known as the Mono Lake Excursion (Liddicoat and Coe, 1979; Lund et al., 1988) at its type locality and also present U–Th disequilibrium data that bears on the allanite crystal residence time in the magma chamber.

2. Geologic background

2.1. The age of Ash 15 in the Wilson Creek Formation

One of the most intriguing WCF ashes is Ash 15 (Lajoie, 1968), which bisects a geomagnetic excursion first identified by Denham and Cox (1971), who were in search of expressions of the Laschamp Excursion. Because the excursion appeared to lack the negative inclinations characteristic of the Laschamp Excursion, and because existing age estimates led them to think this excursion was too old to be

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the Laschamp, Denham and Cox (1971) concluded that the Laschamp Excursion was not present in the section, and that they had identified a previously unknown excursion. Liddicoat and Coe (1979) better characterized this event and named it the Mono Lake Excursion.

In the following decades, the age of the Laschamp Excursion was refined to 40.4 ± 2 ka (Guillou et al., 2004). Many authors now believe that the Mono Lake Excursion must be younger than this, at ~32–34 ka, based on a carbonate radiocarbon timescale and correlation to a contemporaneous geomagnetic excursion present in some marine records (Benson et al., 1998, 2003; Cassata et al., 2010; Laj et al., 2004).

New dating efforts have substantially revised the timescale of the Wilson Creek Formation (Benson et al., 1998, 2003; Cassata et al., 2010; Kent et al., 2002; Zimmerman et al., 2006). Carbonate U–Th disequilibrium dating of cross cutting calcite indicates that the formation extends to at least 49 ka (Xianfeng Wang, unpublished ^{238}U–^{230}Th measurement, personal communication), and it almost certainly extends to greater than 60 ka (Cassata et al., 2010; Kent et al., 2002; Zimmerman et al., 2006). It is clear that the two geomagnetic excursions observed between 30 and 45 ka in some marine records (Laj et al., 2004) fall within the time span of the apparently continuous high-resolution sediment record at Mono Lake.

Liddicoat and Coe (1979) demonstrated the presence of negative inclinations in the event at Mono Lake, casting doubt on the original evidence that precluded the event in Mono Lake from being the Laschamp. One possibility is that the Mono Lake Excursion is in fact the Laschamp Excursion, as suggested by Kent et al. based on the constraints that radiocarbon ages represent minimum depositional ages and that the $^{40}Ar/^{39}Ar$ sanidine ages represent maximum depositional ages (Kent et al., 2002).

Zimmerman et al. (2006) created a timescale for the WCF based on a correlation of the paleomagnetic record in the sediments to the GLOPIS stack (Laj et al., 2004). In this timescale, Ash 15 falls at 39.8 ka, overlapping the Laschamp Excursion at its type locality. Ash 15 is about 20 cm above the paleointensity low in the Mono Lake record, which has an average sedimentation rate of ~20 cm/ka (Zimmerman et al., 2006). Models that place the excursion preserved in the Mono Lake sediments near 34 ka and fit the Laschamp to another feature in the paleointensity record either directly violate concordant radiocarbon and $^{40}Ar/^{39}Ar$ ages higher in the core, imply large fluctuations in sedimentation rates that are not correlated with any known tectonic, volcanic, or climatic events (Zimmerman et al., 2006), or produce significant mismatch of the paleointensity patterns at the key interval of interest (Cassata et al., 2010). Attempts to constrain the entirety of the Wilson Creek Formation to the time period after the Laschamp (e.g., Model B in Cassata et al., 2010) are unable to produce a feasible paleomagnetic correlation and imply even larger fluctuations in sedimentation rate. Cassata et al. (2010) force the paleomagnetic intensity minimum in the Mono Lake record to correspond to a 34 ka minimum in the GLOPIS record and argue that the low sedimentation rates implied before 34 ka would not have captured the Laschamp. However this line of reasoning demands independent evidence for such a sedimentation rate change, which is currently lacking.

Even when excursions and reversals are well expressed globally, single paleomagnetic records are fragmented due to inconsistent sedimentation and may not preserve such short duration events (Coe et al., 2004). The difficulty of resolving short events in a single paleomagnetic record and the uncertainties in correlation pointed out by Cassata et al. (2010) demand a direct date for the excursion.

2.2. (U-Th)/He dating of juvenile materials

Dating of young volcanic samples using the (U-Th)/He system can be undertaken on uranium- and thorium-rich minerals that quantitatively retain helium, such as zircon, monazite, xenotime, sphene, allanite, and garnet. For example, Aciego et al. (2003) dated garnets from the 79 AD eruption of Mount Vesuvius, and Farley et al. (2002) dated apatite and zircon from the 330 ka Rangitawa tephra. Davidson et al. (2004) demonstrated the application of the (U-Th)/He chronometer to young volcanic rocks that cannot be easily dated using the $^{40}Ar/^{39}Ar$ technique. Application of this method to samples with such young crystallization ages requires potentially uncertain uranium–thorium disequilibrium corrections that must be measured or modeled. Thus in many cases the precision of the radiocarbon and $^{40}Ar/^{39}Ar$ systems is superior. However, lack of appropriate material, contamination, inheritance, and other problems sometimes favor use of the (U-Th)/He technique. Ash 15, which cannot be reliably dated using more established techniques (Cassata et al., 2010; Zimmerman et al., 2006), is one such case.

Allanite ($(Ca,REE)_2Al_2Fe_2Si_3O_{12}OH$) is an epidote group mineral common in Ash 15. It typically carries high concentrations of thorium, in this case up to 1 wt.% (Table 1), making it an appealing choice for dating of very young samples. Previous (U-Th)/He dating of allanite is very limited: Wolf (1997) dated a sample from the Peninsular Ranges batholith and concluded this phase has a He closure temperature > 100 °C. Ash 15 is an unwelded tephra deposit, indicating that pumice lapilli cooled to very low temperatures during ascent and fall, a geologically instantaneous event. The deposit was never deeply buried or heated, so the observation of Wolf (1997) is sufficient to ensure quantitative retention of He in the allanite beginning immediately after eruption and deposition.

2.3. Magmatic crystal residence time from ^{238}U–^{230}Th disequilibrium

Disequilibrium in the actinide decay chains at the time of eruption violates the assumption of secular equilibrium that underlies standard helium dating, and can lead to erroneous ages in young samples due to the different decay rates of different isotopes of U and Th (Farley et al., 2002). Isotopic disequilibrium must therefore be measured in order to date young samples. Because U and Th are retained after crystallization in minerals such as allanite (Vazquez and Reid, 2004) and zircon (e.g., Crowley et al., 2007; Schmitt et al., 2003), this disequilibrium can also be used as a crystallization chronometer. The ratio of the current excess of a given isotope that is out of equilibrium (^{230}Th in this study) to the initial excess at the time of crystallization, which can be inferred based on the observed partitioning of more stable isotopes of the same element, is a function of the time since crystallization. In conjunction with an eruption chronometer such as a (U-Th)/He age, this allows the calculation of a residence time in the magma for the crystal.

3. (U-Th)/He and ^{230}Th dating methods

3.1. Sampling and allanite separation

We collected Ash 15 at the South Shore outcrop (37°59′11″N, 118°54′44″W) on the southeast shore of modern Mono Lake. After removing the ~50 cm weathered layer of the outcrop, we removed clean samples of the ash with a spackling knife. We took the sample from the uppermost coarse layer of the 24 cm unconsolidated ash bed, which has distinctive layering (See Supplementary Fig. 1). We washed the sample in a 63 μm sieve and processed the coarse fraction first through lithium heteropolytungstate (ρ = 2.85) and then methylene iodide (ρ = 3.32). We then removed ferromagnetic minerals from the high density fraction with a hand magnet and handpicked the remaining material for allanite. We selected allanite grains for large size, physical integrity, and the presence of glass adhering to the edges of the crystals. Fig. 1 shows a representative grain, which is approximately 450 × 275 μm. Because allanite is almost opaque, it is not possible to avoid inclusion-bearing crystals, but the large