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Identification of the short-lived Santa Rosa geomagnetic excursion in lavas on Floreana Island (Galapagos) by $^{40}Ar/^{39}Ar$ geochronology

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ABSTRACT

A set of closely related basaltic lava flows (supersite GA-X) on Floreana Island in the Galapagos Archipelago has a published record of an excursional or transitional direction (virtual geomagnetic pole located at 153.1°E, 54.2°S with α_{95} = 5.0°) and a geomagnetic field strength (1.1 × 10^{22} Am^2) that is only ~14% of the strength of the modern magnetic field (7.8 × 10^{22} Am^2). The very large age uncertainty of previous dating of a lava flow (G43) from this set, however, has prevented placing this event in the geomagnetic polarity time scale. Here we report highly reproducible and precise $^{40}Ar/^{39}Ar$ ages on the lava flow that indicate that the distinct geomagnetic excursion is 925.7 ± 4.6 ka (2σ; n = 6; mean square of weighted deviates = 1.23). This shows that this dramatic weakening of the geomagnetic field is associated with the Santa Rosa Excursion instead of the Matuyama-Brunhes polarity reversal. Our high-precision $^{40}Ar/^{39}Ar$ ages for Floreana provide evidence for the global significance of the Santa Rosa Excursion.

INTRODUCTION

Large geomagnetic field disruptions, known as excursions, are characterized by reduced field strengths and intermediate magnetic pole locations and have occurred stochastically through geologic time. Understanding such anomalous geomagnetic behavior is important for further refining the geomagnetic polarity time scale (Berggren et al., 1995; Channell et al., 2002; Singer, 2014) as well as for unraveling the complexities of the geodynamo, which controls the stability of Earth's magnetic field (Merrill et al., 1996). The age, duration, global distribution, magnitude, and mechanism of geomagnetic field excursions, however, remain poorly understood.

Existing age constraints suggest that the Santa Rosa Excursion (SRE) occurred between 935 ka and 920 ka (Singer, 2014). It has only been identified in the Santa Rosa rhyolite dome (SRRD) in New Mexico (USA) (Doell and Dalrymple, 1966) and in sediment cores from the Philippine Sea (Horng et al., 2002) and the Iceland Basin (Channell et al., 2002). The limited manifestation of this excursion in geological records may result from variable regional changes in the geomagnetic field at the time. Alternatively, the SRE was extremely short lived, and is thus difficult to recognize elsewhere, especially in sporadic volcanic successions and low-sedimentation-rate sedimentary sequences. Here we identify a new low-latitude record of the SRE based on our dating of a basaltic lava flow from Floreana Island in the Galapagos Archipelago that was reported (Wang and Kent, 2013) to be characterized by an extremely low geomagnetic field intensity and transitional field directions.

Geomagnetic Excursion on Floreana Island

Cox and Dalrymple (1966) examined the paleomagnetism and geochronology of basaltic lava flows from Floreana Island. Of the nine sampled sites, five (G37–G41) were assigned to the Brunhes normal polarity chron and four (G42–G45) were assigned to the Matuyama reverse polarity chron. Initial K-Ar ages on one of these lava flows (site G43) yielded a mean age of 720 ± 400 ka (Cox and Dalrymple, 1966). Subsequent studies determined that some of these flows have intermediate virtual geomagnetic poles (VGPs) indicating a possible transitional behavior of the geomagnetic field (Rochette et al., 1997; Gromme et al., 2010; Kent et al., 2010). Gromme et al. (2010) reprocessed the samples collected by Cox and Dalrymple (1966) and reported tabulated results using a blanket cleaning method (generally alternating fields at 10 mT) from a total of 186 sites from 16 Galapagos Islands, including Floreana. Two of the original four reverse-polarity sites (G44 and G45) were now characterized as having intermediate VGPs and, in conjunction with the nearby reverse polarity sites (G42 and G43), were interpreted as possibly associated with the Matuyama-Brunhes polarity transition (Gromme et al., 2010). In Kent et al. (2010) progressive thermal demagnetization was used to study more than 400 specimens remaining from the Rochette et al. (1997) sample collection, and a grand average of 4 Floreana sites (GA78, GA79, GA84, and GA85) with closely grouped intermediate VGPs (153.1°E, 54.2°S, α_{95} = 5.0°, n = 4) was reported. Wang and Kent (2013) analyzed multiple specimens from these four sites, collectively referred to as GA-X, using three standard Thellier methods as well as a new multidomain correction method, yielding a paleoinstensity of 4.23 ± 1.29 μT (2σ, n = 11) that is only ~14% of the modern-day geomagnetic field strength. Finding concordant paleointensity lows and excursional directions in four separate lava flows makes it likely that four similar-age eruptions were sampled and that the paleomagnetic results are unlikely to be secondary artifacts (e.g., lighting strike). The combination of intermediate directions with very low paleointensities in the four GA-X sites is consistent with a record of either a polarity transition or an excursion.

METHODS AND RESULTS

We resampled Floreana lava flow GA79 (1.273°S, 90.488°W) from Rochette et al. (1997) and Kent et al. (2010) that corresponds to site G44 from Cox and Dalrymple (1966) in order to obtain new $^{40}Ar/^{39}Ar$ ages. We verified that we resampled site GA79 by reobtaining a paleomagnetic direction from this set of newly collected samples, resulting in an inclination/declination of –30.5°/215.7° (n = 42, α_{95} = 4.8°) that corresponds to an intermediate VGP located at 151.3°E, 50.6°S, nearly identical with the VGP (153.1°E, 54.2°S) for supersite GA-X as reported in Kent et al. (2010). Lava flow GA79 is vertically stratified and varies between 5 and 7 m in thickness. It consists of a dense, holocrystalline, nonvesicular basalt at its base, grading upward into a finer grained, oxidized, highly vesicular basalt; the upper ~1.25 m has a red frothy appearance. In order to test how $^{40}Ar/^{39}Ar$ age spectra, plateau ages, and mean square of weighted deviates (MSWD) statistics vary depending on the physical volcanology of lava flow GA79, we collected 9 samples from 3 vertical flow sections, each spaced ~4 m apart. We distinguish layer A, which represents the least-altered, holocrystalline and nonvesicular base of the flow, layer B, which represents an intermediately altered and vesicular section, and layer C, which represents the frothy fine-grained altered top of the flow. A thin soil horizon overlies the flow in the sampling area, indicating that we have captured the full height and top boundary of the flow.

We selected six samples from lava flow GA79 for $^{40}Ar/^{39}Ar$ geochronology (three from layer A, two from layer B, and one from layer C) that were crushed and sieved to a grain size between 106 and 180 μm to avoid the inclusion of phenocrysts and potential xenocrysts. Predominantly crystalline groundmass phases were separated and analyzed in order to directly determine the eruption age of the lava flow and to avoid magmatic crystal residence bias (e.g., Hora et al., 2010) and/or excess ^{40}Ar issues (McDougall and Harrison, 1999). The groundmass was magnetically separated from the mineral phases and acid leached following previously defined methods (Koppers et al., 2011). The pure groundmass was then hand-picked under a binocular microscope to remove any remaining alteration and/or adhering pieces of the coarser mineral phases.

When possible, groundmass splits of 15 and 25 mg were analyzed from each sample (Table DR1 and analytical data in the GSA Data Repository[1]) using a multicollector ARGUS-VI mass spectrometer at Oregon State University (USA) outfitted with 5 10^{12} Ω Faraday collectors and an ion-counting CuBe electron multiplier. The ages and uncertainty estimates include corrections for baselines, blanks, irradiation production ratios, radioactive decay, mass fractionation, and the multiplier/Faraday collector calibration on Ar isotope mass 36. Ages were calculated using ArArCALC v2.7.0 (Koppers, 2002) with a Fish Canyon Tuff (FCT) sanidine age of 28.201 ± 0.046 Ma (2σ; Kuiper et al., 2008) and a corrected decay constant of 5.530 ± 0.097 × 10^{-10} yr^{-1} (2σ) as reported by Min et al. (2000). Reproducibility of Alder Creek AC-2 sanidine analyses is excellent, with mean ages of 1176.3 ± 3.9 ka and 1184.0 ± 3.9 ka (internal error, 2σ; MSWD = 5.68; n = 132/143) against the FCT sanidine ages of 28.02 Ma of Renne et al. (1998) and 28.201 Ma of Kuiper et al. (2008), respectively.

The three GA79 intraflow layers measured gave slightly different ages that are statistically distinguishable, given the high precision achievable by using ARGUS-VI multicollector mass spectrometry. We suggest that these small age variations are a function of alteration and oxidation, which is greatest in the upper frothy and finer grained (more glassy) part, whereas the base layer (layer A) is less susceptible due to its higher groundmass crystallinity (a function of slower cooling near the base). Consequently, we define our age using layer A samples (see the Data Repository for layers B and C). Three separate samples from layer A (44-Ar-2, 44-Ar-3, 44-Ar-5) were measured twice and produced concordant ages within the 1σ and 2σ confidence intervals (Fig. 1). Their age spectra exhibit long plateaus (46%–71%) characterized by radiogenic ^{40}Ar components >50% and 2σ uncertainties <1.4% that range between 11.8 and 9.3 ka (for 15 mg splits) and 10.2 and 7.9 ka (for 25 mg splits). The low-temperature higher apparent ages are readily explained by $^{39}Ar[k]$ recoil (e.g., Koppers et al., 2004) and can be related to some remaining submicroscopic alteration in the groundmass samples, even after careful acid leaching and hand-picking. However, the age plateaus show no scatter beyond what is expected from analytical scatter alone, as implied by low MSWDs ranging from 0.7 to 1.4 (n = 5) and 2.4 (n = 1). We conclude that the layer A holocrystalline groundmasses fulfill our quality criteria and display no significant recoil effects in the age plateaus within quoted 2σ uncertainty bounds. Because all 6 layer A groundmass analyses are extremely reproducible, even at 1σ confidence levels, their overall average age provides us with an eruption age of 925.7 ± 4.6 ka (internal error including the uncertainty on the J-curve, 2σ, n = 6) for lava flow GA79, corresponding to a total of 99 incremental heating steps and yielding a satisfactorily low MSWD of 1.23. The external error on this age is 21.4 ka (2σ), which includes the error on the decay constant and age of the FCT standard. The combined layer A analyses also yield a concordant inverse isochron age (930.7 ± 6.4 ka) with an intercept of 291.3 ± 3.8 (slightly below the atmospheric value of 295.5) and a concordant ideogram age (925.7 ± 3.2 ka), reinforcing the high-quality layer A analyses.

DISCUSSION

Age of the Santa Rosa Excursion

Chronological and paleomagnetic studies of the SRRD (Santa Rosa Dome I) in New Mexico began as early as 1966 (Doell and Dalrymple, 1966). For ease of comparison to these previous studies, we have recalibrated all $^{40}Ar/^{39}Ar$ ages to the FCT sanidine age of 28.201 Ma (Kuiper et al., 2008) and the Min et al. (2000) decay constants, and we report all ages with an uncertainty of 2σ. Intermediate VGPs recorded in the SRRD were first dated to 922 ± 56 ka using K-Ar methodology and initially interpreted as recording the termination of the Jaramillo normal polarity chron (Doell and Dalrymple, 1966; Doell et al., 1968). Using $^{40}Ar/^{39}Ar$ total fusion analysis of single sanidine crystals, Spell and Harrison (1993) reanalyzed this flow to provide an inverse isochron age of 925 ± 8 ka. Izett and Obradovich (1994) also used total fusion analyses of single sanidine crystals to provide an age of 938 ± 34 ka for the SRRD, which they tentatively distinguished from the Jaramillo reversal. Singer et al. (1999) first confirmed an older age for the termination of the Jaramillo and then took the mean of all previously published Santa Rosa ages, obtaining an age of 922 ± 12 ka, confirming that the SRRD was significantly younger than the termination of the Jaramillo and must have formed during a distinct geomagnetic excursion. This newly discovered event was named the Santa Rosa Excursion after the location of the only published terrestrial record of the event known at the time. Subsequent work by Singer and Brown (2002) obtained an age of 942 ± 8 ka. A third attempt to date the SRRD resulted in a younger age of 932 ± 5.4 ka (Singer, 2014). All sanidine ages from SRRD are affected by the

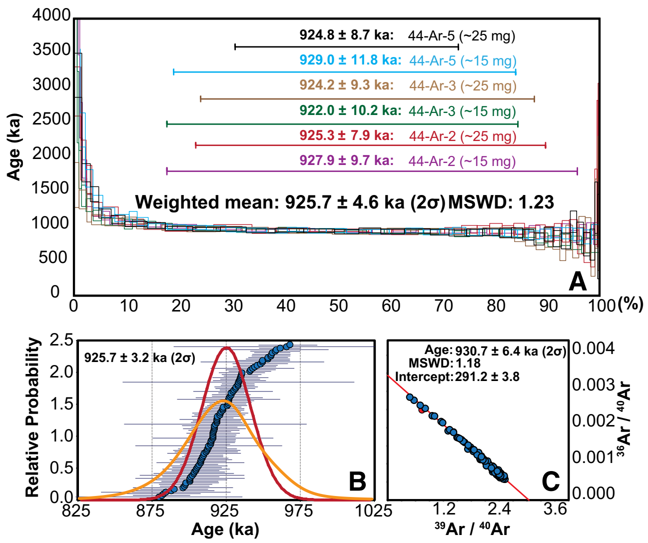

Figure 1. The $^{40}Ar/^{39}Ar$ age results for the layer A basalts samples. A: Stacked $^{40}Ar/^{39}Ar$ incremental heating plateau. Ages for the individual samples and splits are indicated along with the weight of sample analyzed. MSWD—mean square of weighted deviates. B: Ideogram of all selected incremental heating steps. The red line represents a normal distribution curve and the orange line represents a probability density curve based on the results. C: Inverse isochron for all selected incremental heating steps (blue circles). Red circle represents the total fusion value for all combined steps.

[1]GSA Data Repository item 2016118, figures and descriptions of all sample analyses and paleomagnetic data, and all $^{40}Ar/^{39}Ar$ analytical data, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

presence of (minor) excess ^{40}Ar, as revealed in elevated $^{40}Ar/^{36}Ar$ trapped argon signatures and characteristic saddle-shaped incremental heating spectra for single sanidine crystals (Singer and Brown, 2002). Therefore, these sanidine ages are likely somewhat older than the SRRD eruption age and thus overestimate the timing of the SRE.

The SRE was also recorded as a large directional change in a sediment core (MD972143) from the Philippine Sea (Horng et al., 2002) and as a directional change that appears to be related to a prominent decrease in relative geomagnetic paleointensity (RPI) in Ocean Drilling Program (ODP) cores at Sites 983 and 984 from the Iceland Basin (Channell et al., 2002). The astrochronologic age for the SRE recorded in core MD972143 is 920 ± 2 ka (Marine Isotope Stage 23-24; Horng et al., 2002). The higher sedimentation rates and corresponding higher resolution of ODP cores 983 and 984 provide an age of ca. 932 ka (top of Marine Isotope Stage 25) with a duration of 3 k.y. for the SRE (Channell et al., 2002). A stack of multiple astronomically tuned sedimentary archives of RPI (PISO-1500) suggests that the SRE is a global feature associated with a virtual axial dipole moment (VADM) low at 926 ka (Channell et al., 2009). We regard the astrochronology of the global paleointensity stack PISO-1500 as providing the most reliable target age estimate of the SRE.

Our new $^{40}Ar/^{39}Ar$ ages suggest that the intermediate directions and very low absolute paleointensities in lava flows from supersite GA-X on Floreana Island (Wang and Kent, 2013) are associated with the SRE. We derived the most consistent and reliable age spectra from the groundmasses sampled at the base of lava flow GA79 that give an average age of 925.7 ± 4.6 ka (Fig. 1). As expected for the dating of holocrystalline groundmass samples, which reflect the eruption ages of the lava flows and are not affected by any residence time in a magma chamber, there is no significant sign of excess ^{40}Ar in the presented data, explaining our lower eruption age compared to the sanidine ages of the SRRD (Singer and Brown, 2002; Singer, 2014). Our age is in excellent agreement with the 926 ka age for the paleomagnetic minimum in the global PISO-1500 stack (Channell et al., 2009) (Fig. 2).

Santa Rosa Excursion as a Short-Lived Global Geomagnetic Excursion

The close agreement of our new high-precision age for the Floreana lava flow with ages from high-latitude ODP Sites 983 and 984, as well as with the terrestrial SRRD in New Mexico, shows the global extent of the SRE, whereas VGPs and relative intensity data from ODP cores 983 and 984 suggest a reduction and recovery of the field within ~3 k.y. (Channell et al., 2002). These observations are validated in the basaltic lava flows on Floreana, which record

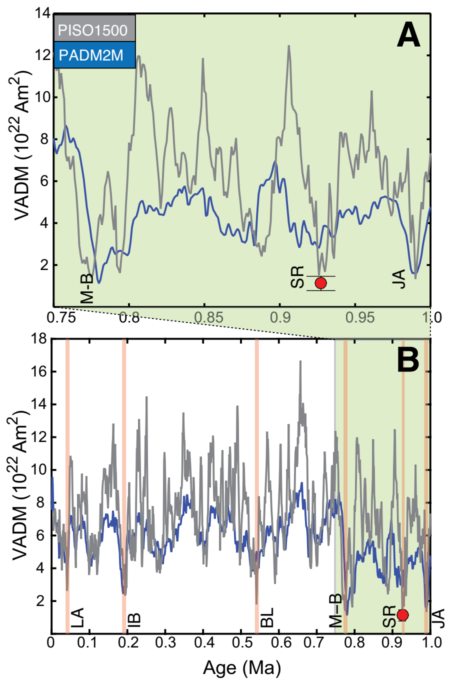

Figure 2. The paleomagnetic axial dipole moment (PADM; comparable to virtual axial dipole moment, VADM) for 0–2 Ma (PADM2M stack of Ziegler et al., 2011) is shown as a blue line. The paleointensity stack PISO-1500 of Channell et al. (2009) is shown as a gray line. The VADM for Floreana (Galapagos Islands) lava supersite GA-X from Wang and Kent (2013) is shown with a red circle. The error for the Floreana lavas represents the measured error on the paleomagnetic intensity as well as the error on the age. A: Axis showing the age range of 1–0.75 Ma. B: VADM variation during the past 1 m.y. Some major paleointensity lows are highlighted in pink; LA—Laschamp, IB—Iceland Basin, BL—Big Lost, M-B—Matuyama-Brunhes, SR—Santa Rosa, JA—end of Jaramillo.

a VADM value of 1.1 ± 0.3 × 10^{22} Am^2 (Fig. 2) that is as low as during any paleomagnetic reversal (e.g., Channell et al., 2009; Ziegler et al., 2011). During this time interval, the SRE resulted in the single lowest VADM value for all recognized and defined excursional events. The PADM2M (PADM, paleomagnetic axial dipole moment; Ziegler et al., 2011) stack for the past 2 Ma displays a mean VADM of 5.32 × 10^{22} Am^2 compared to the mean (1.35 × 10^{22} Am^2) of the lowest intensities during polarity reversals that closely corresponds to the Santa Rosa VADM value of 1.1 ± 0.3 × 10^{22} Am^2. Our new data demonstrate that geomagnetic field excursions can result in field strength lows similar to known reversals; they further suggest that changes within the geodynamo can generate a global field strength reduction equal to an ~86% loss of the present-day field strength (7.8 × 10^{22} Am^2; Korte and Constable, 2005) in a time interval as short as 3 k.y.

Of the multiple excursions identified thus far, only a few have been studied in detail and even fewer have been confirmed as global events. The most widely studied geomagnetic excursion is known as the Laschamp excursion (Bonhommet and Zahringer, 1969; Roperch et al., 1988; Gubbins, 1999), which occurred at 41.2 ± 1.6 ka, extended over only 1500 yr, and had a VADM minimum of 1.2 ± 0.1 × 10^{22} Am^2 (Laj et al., 2014), comparable in field strength reduction to the SRE record on Floreana. These two events indicate that excursions may have similar dynamics in terms of duration and minimum field strength independent of whether they occur within a normal polarity chron (e.g., Laschamp) or a reverse polarity chron (e.g., SRE).

CONCLUSIONS

We define a new $^{40}Ar/^{39}Ar$ age of 925.7 ± 4.6 ka (2σ) for the SRE that is recorded in lavas on Floreana Island in the Galapagos Archipelago. Our data illustrate a dramatic change in VGP and geomagnetic field strength during a similar time interval recorded in two volcanic and three sedimentary archives, identifying a global extent for the excursion. The published record from Floreana Island suggests an 86% reduction in absolute field intensity in the equatorial region. The PISO-1500 stack illustrates a significant relative field strength reduction at the time (Channell et al., 2009) and the data from high-resolution ODP Sites 983 and 984 indicate a directional excursion lasting a few millennia that was synchronous with this event (Channell et al., 2002). Taken together, the sedimentary records and igneous rock data are convincing evidence of global field behavior that deviated markedly from an axial geocentric dipole. These data suggest that the SRE was both a significant and short-lived geomagnetic anomaly, illustrating the potential for the geodynamo to dramatically alter the geomagnetic field in a few millennia. The global extent and short duration (sediment records) and the dramatic decrease in field intensity (igneous rock data) of this excursion should thus place important constraints on models of the geodynamo. The equatorial record suggests that the dramatic reduction in field strength likely results in larger changes in the in situ production rates of cosmogenic nuclides at lower latitudes, as a function of the changing dipole moment and colatitude terms in the cut-off rigidity equation (Elsasser, 1957). This underscores the importance of further work to constrain the relationship between low-latitude field strength changes and the associated changes to in situ cosmogenic nuclide production rates.

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