

Study of Declination, Inclination and Absolute Paleointensity of the Short-Term Geomagnetic Behavior (i.e. Cryptochron C2r.2r-1, ca. 2.46 ± 0.13 Ma) Recorded at the Type Section of Halawa Valley, Koo'au Volcano, Oahu, Hawaii, USA

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Abstract

A novel determination of the absolute paleointensity (P.I) of 28 flows that recorded Cryptochron C2r.2r-1 (ca. 2.46 ± 0.13 Ma) using the modified Thellier-Coe method was undertaken to understand the geomagnetic evolution of the paleofield during an excursion with the existence of less than 10 Kyr. The successful PI determinations along the 120-meter sequential erupted flows indicate that within the truly transitional/excursion portion of the record there is a conspicuous decrease of the PI values ranging from 20 μ T to low values of about 5 μ T. These values are comparable to lows similar to polarity transitions of the geomagnetic field. At the base of the sequence, the record shows oscillations of the paleofield ranging from 120 μ T and as low as ~ 10 μ T with very variable changes of the non-transitional/excursion paleofield.

Keywords

Absolute Paleointensity Determinations, Thellier-Coe, Cryptochron

1. Introduction

The study of the short-term behavior of the geomagnetic field is still one of the most relevant and important topics in geophysics today. The mechanisms by which the geomagnetic field is generated in the liquid outer core of the planet is crucial to understand the composite spectrum for the geomagnetic dipole moment and the amplitude spectrum of geomagnetic variation as a function of fre-

quency for instance (Constable & Constable, 2004; Constable & Johnson, 2005; Constable, 2007) of the so called reversals, excursions Cryptochrons, secular variation, paleosecular variation, etc. Understanding these phenomena, i.e. their origin is very important, not only because they result from very interesting dynamical processes in the core and also they may help determine the conductivity of the mantle as well as for the improvement of the time-dependent models of the generation of the Earth's magnetic field (Courtillet et al., 1988).

The discovery of a terrestrial record of a Cryptochron at Halawa Valley of the Koo'lau volcano, Oahu Hawaii triggered the study of the directional as well as the $^{40}\text{Ar}/^{39}\text{Ar}$ radiometric determination of the age of C2r.2r-1 (Cande & Kent, 1995) of 28 successive lava flow sites of a 120-m volcanic sequence (Herrero-Bervera et al., 2007).

The motivation of this study is because there is a lack of short-term geomagnetic behavior with durations less than 10^2 to 10^4 extruded by lavas. Therefore, the coupling of the latest $^{40}\text{Ar}/^{39}\text{Ar}$ determinations and the directional as well as absolute paleointensity results makes this study a very new and unique opportunity to gain an insight into how the generation of the paleofield is documented during very fast fluctuations of the Earth's magnetic field (i.e. few hundreds of years at best).

Therefore, the aim of this study is to study the third missing component of the geomagnetic vector, i.e. the absolute paleointensity determination of those 28 flows at the 120-m long Halawa type section to investigate the full vector behavior of the Cryptochron.

2. The Cryptochron Record at the Halawa Type Section

The directional (i.e. declination and inclination) record of the Cryptochron registered at the type section of Halawa valley of the Koo'lau volcano (21.3743701°N , $157.9079793^\circ\text{W}$) has been already published (Herrero-Bervera et al., 2007). A brief summary of the results indicates that the Halawa Valley is one of the very few sites characterized by a normal polarity. Twenty eight flows were sampled and between 7 - 17 magnetically and sun oriented 2.5 cm diameter cores were drilled from a 120-m thick volcanic sequence for paleomagnetic and rock magnetic properties studies (see **Figure 1**).

The alternating field (a.f.) and thermal demagnetization cleaning experiments were performed on 252 specimens in order to determine the mean declination and inclination of the 28 flows in question (**Figure 2**).

The characteristic remanent magnetization was isolated applying a.f. field between 10 to 100 mT and 300°C - 450°C pointing towards magnetite as the main mineral magnetic carrier of the 28 flows. The mean flow directions were successfully attained by averaging both the a.f. and thermal demagnetization data into a single data set per flow, (see Table 1 of (Herrero-Bervera et al., 2007)) see **Figure 3**.

Rock magnetic tests were performed to characterize the magnetic mineralogy of the 28 flows studied. The low-field vs temperature experiments (k-T) were

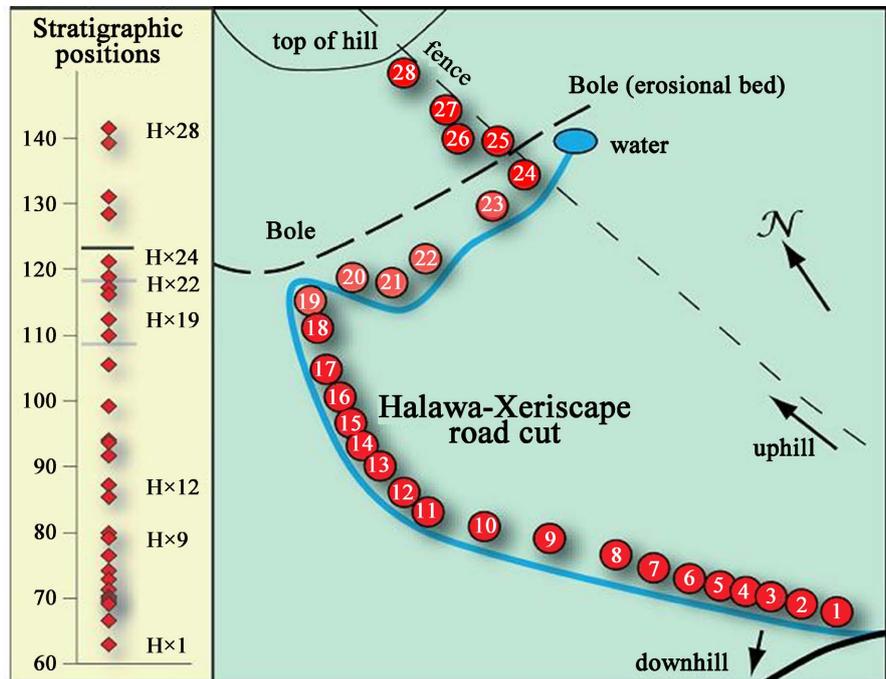


Figure 1. Stratigraphic position of the sampling sites Hx 1 to Hx 28 and their respective depths from the bottom of the section were converted and reported in meters. The Halawa site, just above the Halawa Xeriscape. The site exists along a 30-year-old road cut to a water-tank. The road incline is between 10° - 25°, and terminates 20 m below the top of the hill. The scale is 1 cm = 20 m. Modified from [Herrero-Bervera et al. \(2007\)](#).

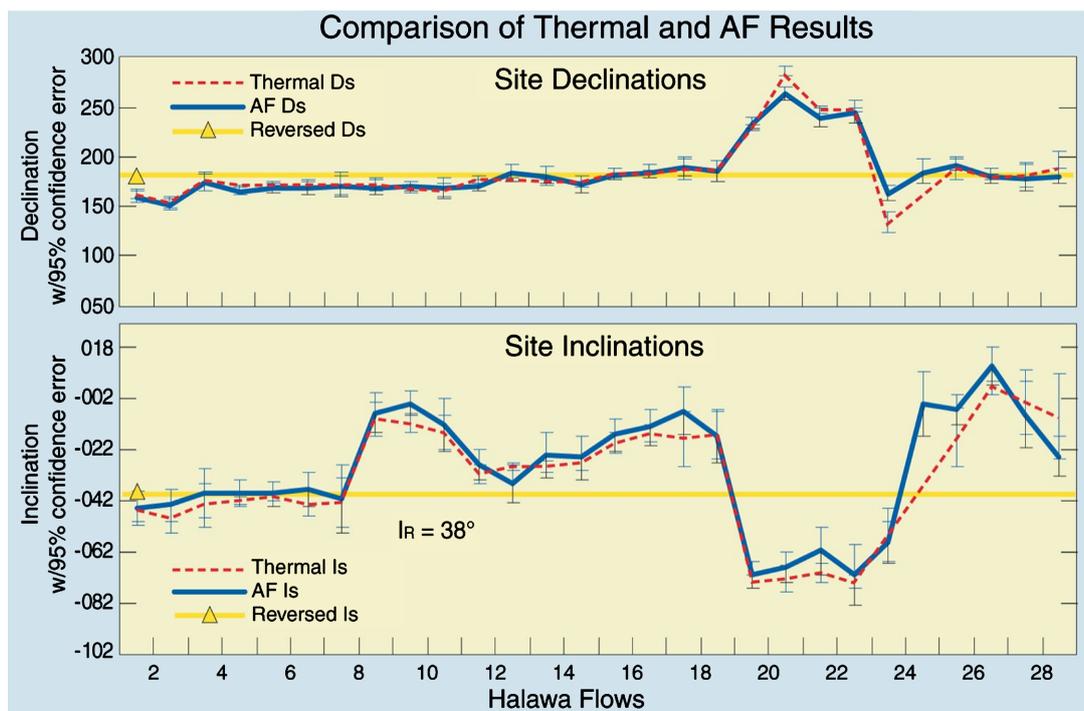


Figure 2. Plots comparing AF and thermal demagnetization results. Ds = Declinations, Is = Inclinations, IR = -38 is the mean Inclination of seven reversed lava flows. Error bars indicate the respective α_{95} . The extremely close agreement indicates a high level of confidence in our results. Taken from [Herrero-Bervera et al. \(2007\)](#).

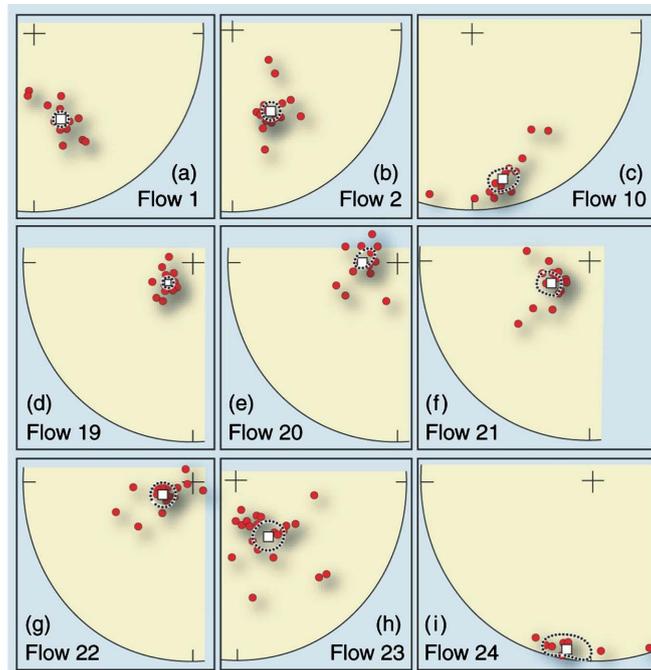


Figure 3. Selected plots of site directions. Flows 19 - 22 reflect the plotted reversing behavior. Flows 23 and 24 show the completion of an excursion. The site direction plots show the individual specimens involved in the calculation of the site means. Taken from [Herrero-Bervera et al. \(2007\)](#).

performed on forty-five specimens from at least each one of the entire set of lavas. The results of the Curie point determinations from 28 up to 700°C revealed very complex magnetic mineralogies. Three very distinct groups of magnetic minerals were identified, the first group indicated a single Curie point about 580°C showing the presence of Ti-poor magnetite. The second group displayed mainly reversible behavior with Curie points higher than 600°C attesting the occurrence of titanomagnetite. A third group showed Curie points between 300°C - 500°C pointing towards Ti-rich magnetite with additional Curie points between 550°C - 650°C with characteristic irreversible k-T curves. The overall Curie point determinations indicate without a doubt that magnetite characterizes the NRM at high temperature at high temperatures but also with small amounts of hematite (Curie point ~675°C) in some instances (**Figure 4**).

Figure 4 indicates the variety of Curie temperatures for the entire set of 28 lavas, with the predominance of Curie points between 500–600°C. Most samples show only a magnetic phase (550° - 580°C) at the end of the heating cycle, but ~20% also shows the influence of hematite with Curie points N600°C. **Figures 4(a)-(d)** display representative samples. **Figures 4(b)-(d)** display reversible samples through the heating cycle, representative of 45% of the samples analyzed. **Figure 4(b)** displays an entirely reversible, concave-down thermomagnetic curve, continuously decreasing to zero with a single Curie temperature close to 580°C, typical of low-Ti-content magnetite. **Figure 4(c)** displays a slightly higher Curie temperature indicating the presence of hematite. **Figure 4(d)** are

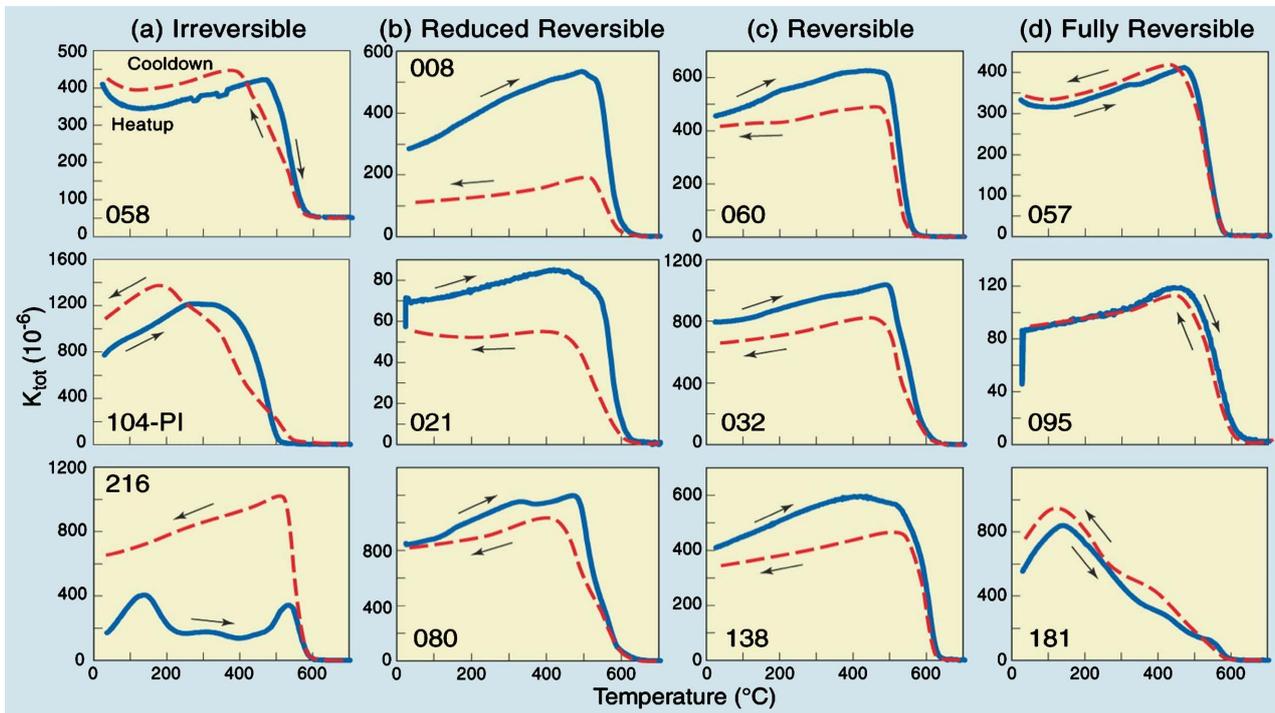


Figure 4. Low-field susceptibility vs. temperature (k-T) performed in an air atmosphere. This method is used to determine Curie points of magnetic minerals.

representative of samples with transformations indicative of various Ti-contents but still indicating only a remaining magnetite phase (550°C - 580°C) at the end of the heating cycle. Modified from [Herrero-Bervera et al. \(2007\)](#).

Induced magnetization experiments were applied to all 28 flows mainly to determine grain sizes to test the magnetic behavior of the samples upon demagnetization and eventually check the stability of magnetization of the entire set of flows. Saturation remanent magnetization (M_r), saturation magnetization (M_s), and coercive force (H_c) were calculated after removal of the paramagnetic contribution. The coercivity of remanence (H_{cr}) suggests that the NRM is carried by low-coercivity grains. The ratios of the hysteresis parameters plotted as a [Day et al. \(1977\)](#), diagram and modified according to [Dunlop \(2002\)](#) in [Figure 5](#) show that most grain sizes are scattered within the pseudo-single domain range with the exception of two which lie in the single domain range. The samples studied have an M_r/M_s ratio of approximately 0.1 to 0.5 and an H_{cr}/H_c ratio ranging from 1.2 up to 4.0 on the magnetic grain size diagram. Comparisons with theoretical mixing curves of [Dunlop \(2002\)](#) indicate that samples contain pseudosingle domain (PSD) magnetite with a small admixture of singledomain (SD) magnetite, see [Figure 5](#).

After the successful a.f. and thermal demagnetization of twenty eight flows and the isolation of the characteristic remanent magnetization (ChRM) coupled with the rock magnetic properties (i.e. k-T, magnetic granulometry tests, etc.) the directional results were plotted up in stratigraphic order from the base to the top of the volcanic sequence of the Halawa. [Figure 6](#) shows truly transitional/excursion directions between flows 19 and 22. The base of the sequence from Flows

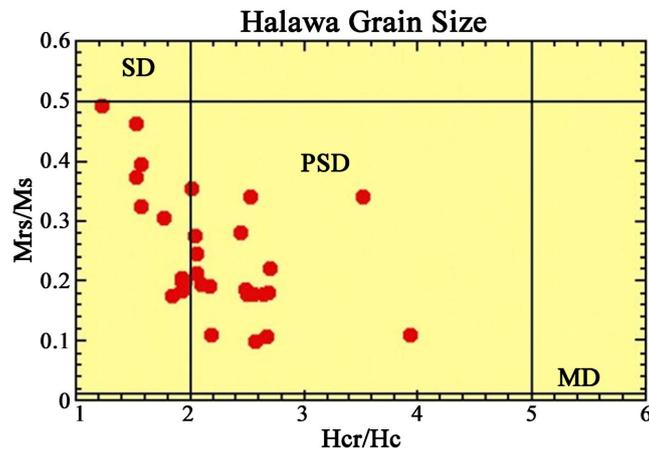


Figure 5. Plot of the hysteresis parameters, Mrs/Ms (ratio of remanent saturation moment Mrs, to saturation moment Ms) against Hcr/Hc (ratio of remanent coercive force, Hcr, to coercive force Hc). Single domain (SD), multi-domain (MD), after Day et al. (1977) and corrected according to Dunlop (2002) Grain size approximations using hysteresis parameters are consistent with single domain (SD) and pseudo-single domain (PSD) grains. However they could also represent a mixing of SD and MD particles. This methods are very useful to find out the magnetic grain sizes of carriers of magnetization of the materials under question. Taken from Herrero-Bervera et al. (2007).

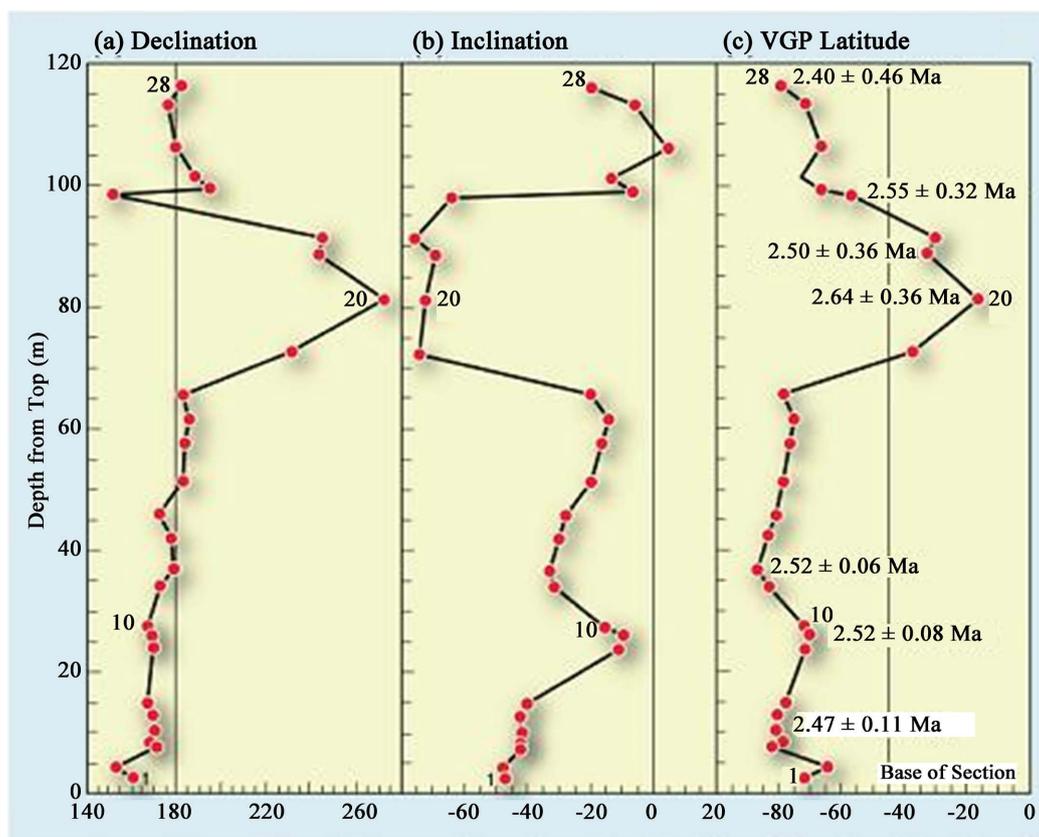


Figure 6. Shows the corresponding $^{40}\text{Ar}/^{39}\text{Ar}$ radiometric determinations of 9 individual flows. The isochrons of the nine lava flow sites are between 2.64 ± 0.23 and 2.37 ± 0.17 Ma, but these ages are indistinguishable from one another at the 95% confidence level indicating that the entire sequence of flows was most probably erupted over a period of time shorter than our best analytical precision.. The best inverse-variance weighted mean age of the nine flows studied is 2.514 ± 0.039 Ma (MSWD = 062). This age has been recalculated and published by (Singer, 2014) as 2.46 ± 0.08 Ma. This novel $^{40}\text{Ar}/^{39}\text{Ar}$ methodology is used to find out the age of the flows that recorded the fast oscillations of the paleofield.

1 to 7 correlates fairly well with the reversed geocentric axial dipole the Geocentric Axial Dipole (GAD), the site Inclination $I(s)$, is about -38° for the Halawa site, the site inclination is $I(s)$ (i.e. $I(s) = -44^\circ \pm 4^\circ$, $\alpha95 = 4^\circ$), there is a significant divergence throughout the remainder of the sequence from a fully reversed field i.e. $I(s) = -38^\circ$. The excursions were drilled in a 25 m section which, based on an average flow rate of 1000 yr and an average thickness of 2 m, would indicate a maximum duration of ~ 12 kyr, was the interpretation given by Herrero-Bervera et al. (2007), see Figure 6. These directional results have been plotted up after considering a northward motion of the plate at a rate of $0.98^\circ/\text{Ma}$ (Grip & Gordon, 1990; Herrero-Bervera & Valet, 2003).

Stratigraphic plots of (a) Declination, (b) Inclination (corrected for plate motion), and (c) latitudinal VGPs. The excursion is evident in Flows 19 through 22. GAD value for the Halawa site is $I(s) = -38^\circ$. The radiometric ages are from Flows 5, 9, 12, 19, 20, 21, 23 and 28 respectively.

In addition to the directional results, the declination and inclination values were converted into virtual geomagnetic poles (VGP) that in principle represent the apparent pole motion at the sampling site during the transitional/excursion behavior, such VGPs show clearly from flow 19 to 22 the phenomenon (i.e. excursive behavior), see Figure 7.

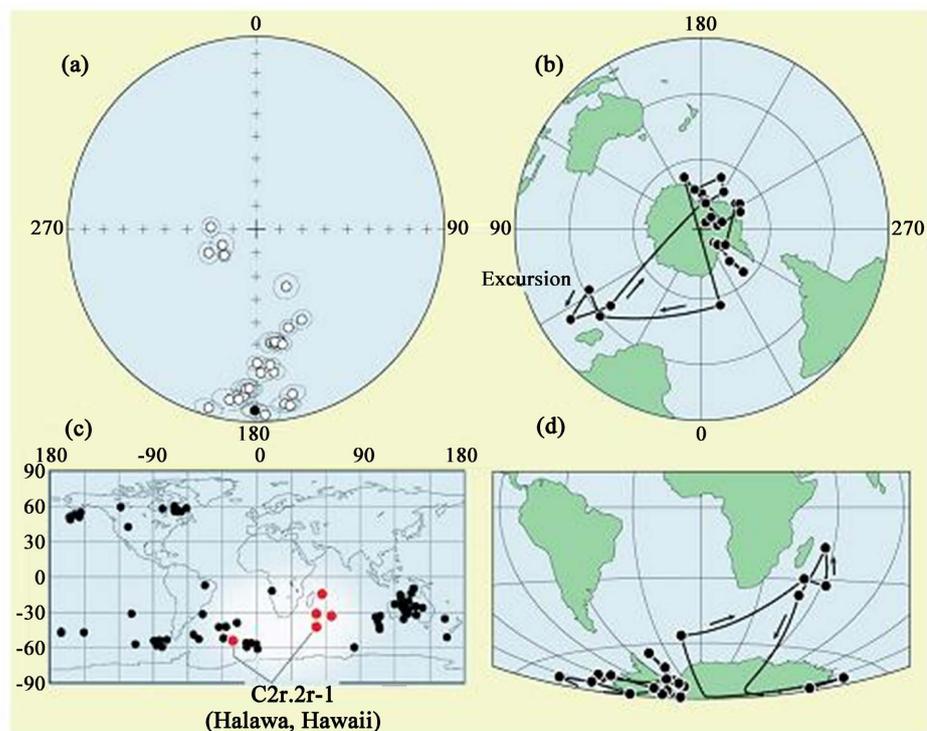


Figure 7. (a) Stereographic projection of the site-mean direction of the 28 lavas flows studied data points are shown with their 95% confidence circles. (b) Polar view of the same 28 flows studied in this paper, (c) Transitional VGPs with latitudes lower than 60° of sites located in Hawaii, Tahiti, Chile, Canaries and New Zealand. Modified from Figure 5(b) of Valet & Herrero-Bervera (2003). This behavior has been noted in studies on a number of transitions and from a number of different localities; (d) Equatorial plots (Cogne, 2003) of the VGPs. Note the VGP cluster off the coast of Madagascar.

3. The Age of the Halawa Cryptochron C2r.2r-1

The combination of the two most recent reports of the Cryptochron C2r.2r-1 from the São Gonçalo profile of 2.46 ± 0.08 Ma reported by (Holm et al., 2008); and (Knudsen et al., 2009), and the refinement of the same Cryptochron dated by (Guillou et al., 2018) obtained from the Wheeler Air Force core drilled in the Koo'alu volcano yielded $^{40}\text{Ar}/^{39}\text{Ar}$ reliable ages that allowed the authors of the study to propose an age of 2.46 ± 0.13 Ma for the magnetic anomaly that they attribute to the cryptochron C2r.2r-1 (Guillou et al., 2018), $^{40}\text{Ar}/^{39}\text{Ar}$ isochron results dated this period of low inclination between 2.52 ± 0.10 and 2.40 ± 0.17 Ma. The combination of their two most reliable ages allowed them to propose an age of 2.46 ± 0.13 Ma for the magnetic anomaly that they attribute to Cryptochron C2r.2r-1. The original date obtained by the published study of (Herrero-Bervera et al., 2007), was 2.514 ± 0.039 and later on corrected and published by (Singer, 2014) as 2.46 ± 0.08 Ma (Figure 8).

4. Absolute Paleointensity Determinations of the Halawa Cryptochron

The determination of the absolute paleointensity of the geomagnetic field from the 28 flows recorded at the Halawa valley volcanic sequence was achieved by using the modified Thellier-Coe protocol, (Coe, 1967) of the Thellier and Thellier-experiments but with a different protocol. Instead of measuring the NRM first, we preferred to apply a TRM before heating the sample in zero field (Aitken et al., 1988; Aitken, 1990; Valet et al., 1998; Herrero-Bervera & Valet, 2005, 2009; Herrero-Bervera & Acton, 2011, Herrero-Bervera et al., 2020). In this case, magnetomineralogical transformations occur in the presence of a field, resulting in a CRM (chemical remanent magnetization) component which is detected by a deviation of the NRM toward the oven field direction. Each heating step (beyond 100°C and up to 540°C) was accompanied by a pTRM check usually at the previous lower temperature step. The experiments were conducted in a Pyrox oven with a capacity of 80 samples. Heating control was carried out by three external thermocouples and accurate temperature control was monitored by three additional thermocouples located close to the samples. Cooling was performed by sliding the heating chamber away from the hot specimens. Measurements were done using a JR-5 Spinner magnetometer (i.e. for the NRM, thermal demagnetization and for the absolute paleointensity measurements) in the shielded room of the SOEST-HIGP Magnetic Materials laboratory. Each series of experiments was carried out on 27 samples positioned a few millimeters away from each other within the oven. The magnetization level of the samples was too low to expect significant interactions between adjacent samples and effectively no remagnetization was observed in the demagnetization diagrams of the NRM, except those caused by subsequent magnetomineralogical transformations in the presence of a field. Typical Arai plots are shown in Figure 9.

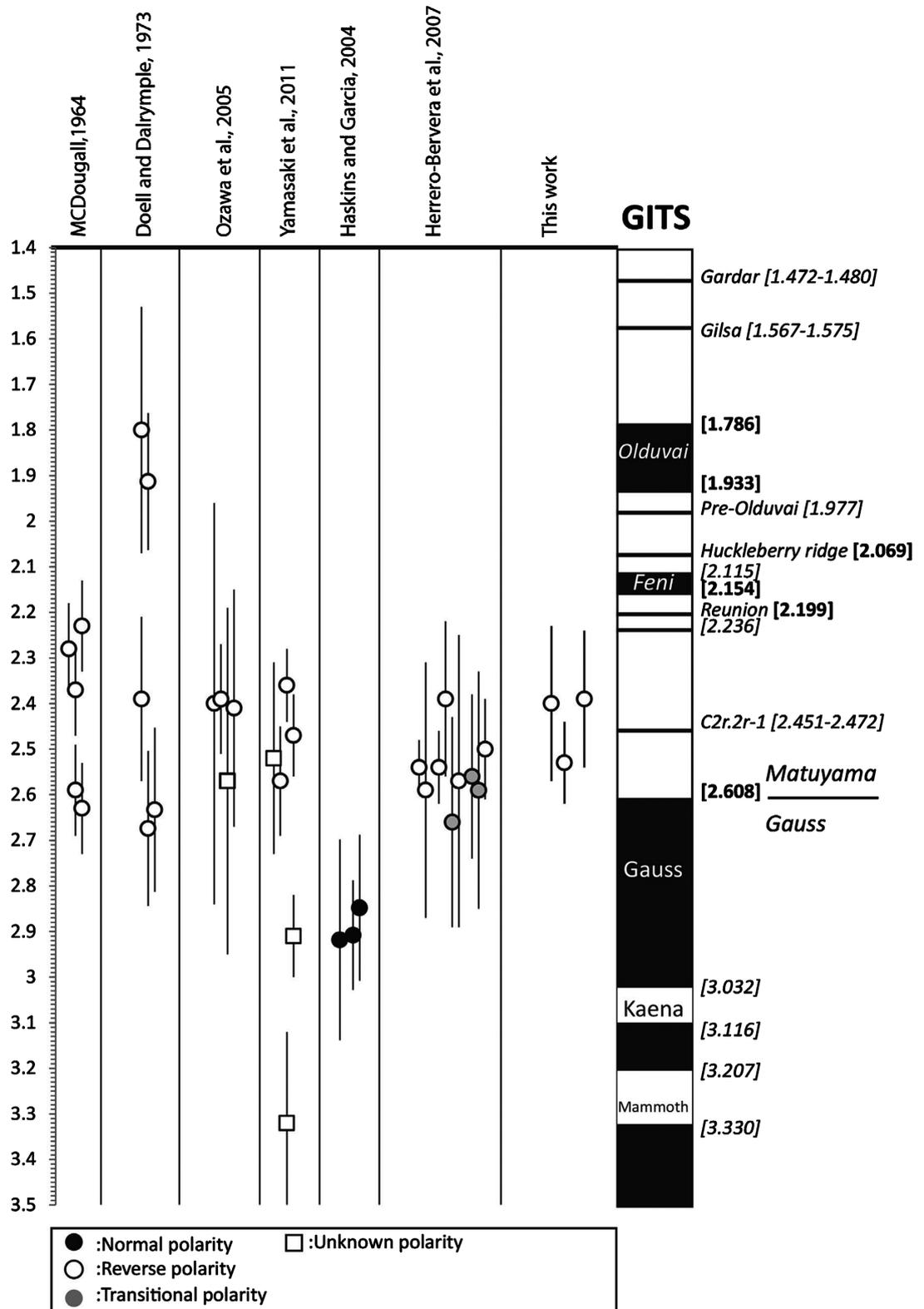


Figure 8. Comparison of published ages from the Ko’olau volcano and those obtained in the study of the Wheeler Air Force core with the geomagnetic instability timescale indicated (GITS; (Singer, 2014)). Ages in bold along the GITS are relative to FCs at 28.187 Ma, ages in italics are from astrochronology. From (Guillou et al, 2018).

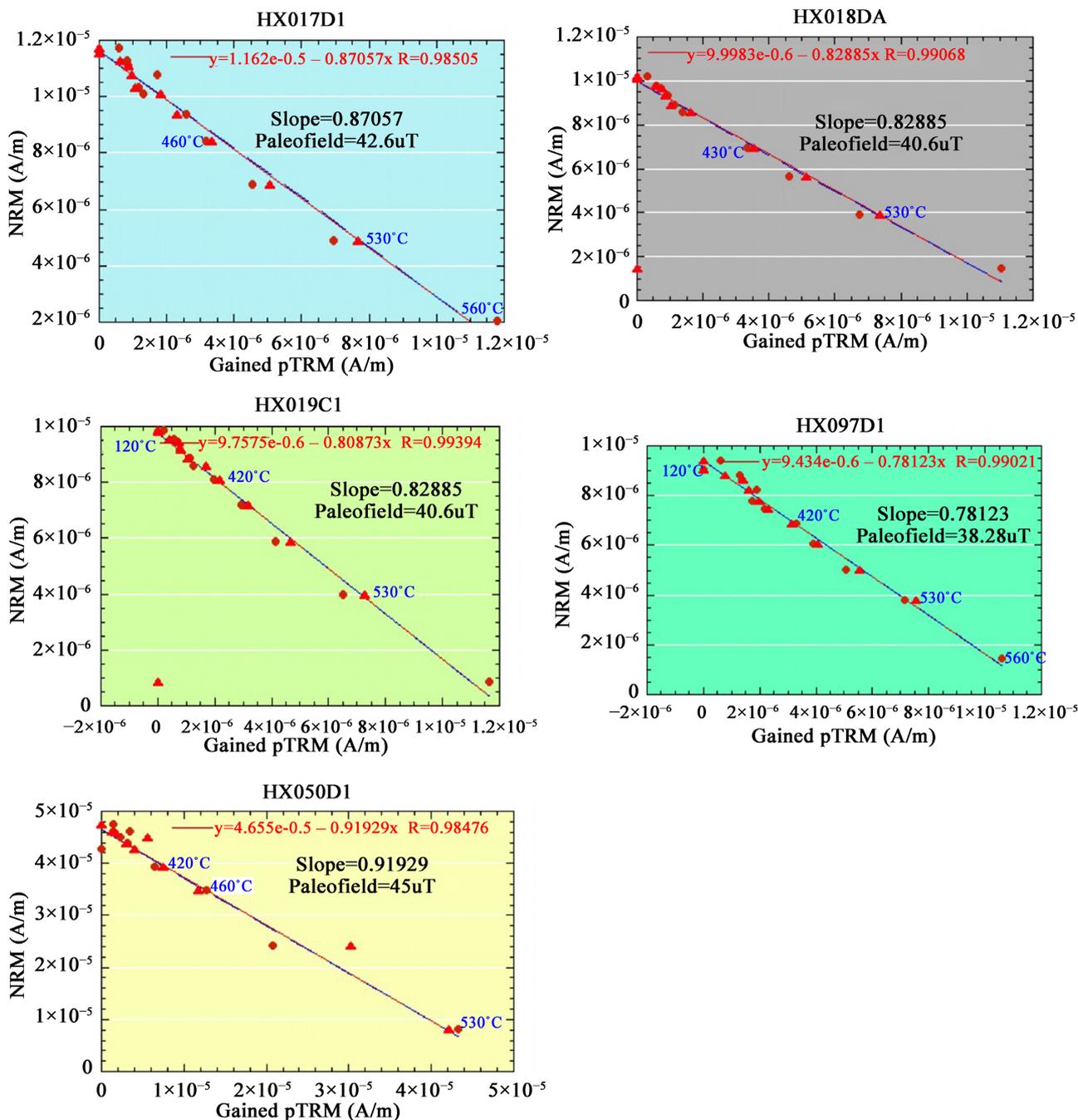


Figure 9. Typical Arai results of absolute paleointensity determinations of 5 samples from the Halawa Cryptochron using the modified Thellier-Coe method. Five typical Arai plots for Halawa specimens. Red squares represent the initial NRM-pTRM measurements, open squares are NRM-pTRM checks. Rejection was decided on the basis of the deviation of the pTRM checks (red triangles) following the criteria that have been put forward in the present study (see text). Diagrams without linear NRM-pTRM segments were rejected and thus not shown here. This modified Thellier-Coe method was selected to be used to have the best determination of the strength of the magnetic field recorded by the lava flows of the Halawa Cryptochron long volcanic sequence.

Final results of the absolute paleointensity study plotted up in stratigraphic sequence indicate that from the bottom of the section (i.e. lava flows 1 to 11) there is a high oscillation of the paleointensity (PI) values from about 100 micro-Teslas (flow 1) decreasing to as low as 9 micro-Teslas (flow 10), from that

point on the PI values increased to values as high as 110 micro-Teslas. From flow 15 (120 micro-Teslas) to 18 (~20 micro_Teslas) there is a steady decrease of the PI values that remains relatively low (i.e. from 20 micro-Teslas to 10 micro-Teslas, flow 20), then a steady increase of the PI values (i.e. flow 22 about 23 micro-Teslas). These low and relatively low values coincide well with the truly transitional/excursion flows shown on the VGP vertical diagram of **Figure 10**. From flow 22 up to flow 24 there is a sudden increase of the PI value up to ~130 micro-Teslas with a final decrease to very low PI value (i.e. flow 27) of about 10 micro-Tesla.

5. Conclusion

The conclusions of the study of the Halawa Cryptochron recorded at the type section in the Koo'ala volcano indicate that the directional results have recorded relatively fast changes of the geomagnetic field that have been previously interpreted to have a duration of about few hundred years. The rock magnetic experiments both NRM and induced magnetization tests indicate that the 28 flows studied are characterized by high magnetic stability of the directional results. The magnetic mineralogy experiments indicate dominance of magnetite, low and high Ti-magnetites as well as small portions of Hematite.

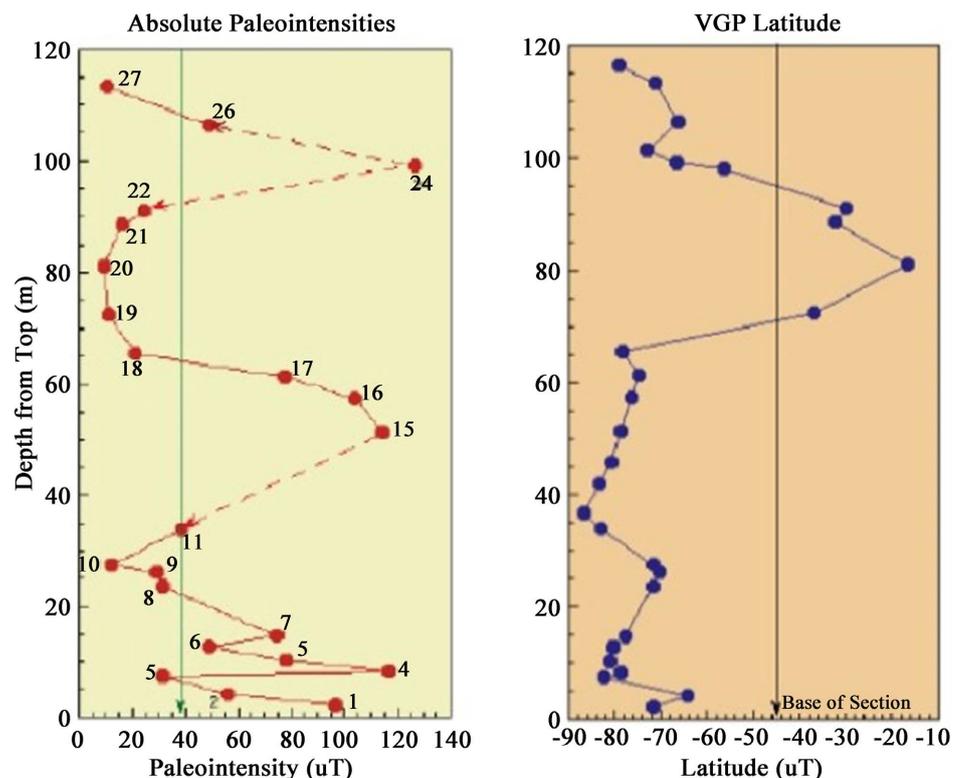


Figure 10. Absolute paleointensity stratigraphic diagram showing the sequential oscillations/variations of the paleofield during the Halawa Cryptochron, left diagram. On the right side of the plot the VGP latitude values are displayed to show the location of the truly transitional/excursion of the Cryptochron, from about 65 meters up to about 100 meters of the stratigraphic volcanic sequence.

The results of the $^{40}\text{Ar}/^{39}\text{Ar}$ experiments at the Halawa section yielded a recalculated age of 2.46 ± 0.08 Ma and a very recently obtained drilled core from the WAF base of 2.46 ± 0.13 Ma (Guillou et al., 2018). These results from the Koo' lau volcano have an excellent age correlation with studies from Cape Verde, in the Atlantic.

The successful absolute paleointensity (P.I.) results obtained from 27 flows indicate very low values ranging from about 5 - 10 micro-Teslas within the truly part of the Cryptochron as well as very high oscillations of the PI values paleo-signal outside the truly excursions/transitional zones of the 28 flow record.

The combined rock magnetic and radiometric methods yielded the best results with regards to the age of the flows that recorded the relatively fast changes of the excursion of the so called Cryptochron recorded by the Koo' lau volcano, Oahu, Hawaii.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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