RESEARCH METHODS VOLCANICA

Using paleomagnetism to determine the heating effect of lava flows on underlying substrates

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Abstract

The extent to which heat from lava flows passes into underlying and adjacent materials has significant implications for volcanic hazard studies. Here we demonstrate how paleomagnetism can be used as a tool to determine the heating effects of lava flows in the pre-existing substrates over which they flow. Samples from soils taken beneath lava flows from Rangitoto and Puketutu eruptive centres (Auckland Volcanic Field, Aotearoa New Zealand) and a human-made berm beneath the June 27th Lava Flow (2014–2015; Kīlauea Volcano, Hawaii, USA) were subjected to progressive thermal demagnetization to assess the strength and stability of their remanent magnetizations. The temperature and depth to which these soils display a strong coherent magnetization represents the extent to which they were remagnetized (and therefore heated) by the overlying flow. Results suggest heating to at least 570 °C at depths of up to 21 cm below the substrate-flow contact. This information is valuable for constraining and validating heat transfer models, which can be used to assess the lava flows' subterranean thermal hazard. Among many uses, this is vital for emergency management planning for buried infrastructure networks traversing regions that could be exposed to effusive volcanic activity. Further afield, in astrobiology, it might find application in determining the thickness of a substrate layer heated sufficiently by a lava flow to kill living organisms.

Keywords: Lava flow; Paleomagnetism; Temperature; Auckland Volcanic Field; Kīlauea;

1 Introduction

Lava flows from effusive volcanic eruptions can reach temperatures up to 1200 °C [Kilburn 2015]. As a flow spreads, heat redistributes itself within the lava by conductive and convective processes. It can also conduct into the underlying or adjacent substrates resulting in the heating of this material to high temperatures and be lost through exposed surfaces, mainly by convection and radiation [Patrick 2004; Harris and Rowland 2015]. The extent of substrate heating depends not only on the thermal properties, including initial temperature, of both substrate and lava, but also on other characteristics of the lava flow, such as its thickness, flow rate, and particularly the duration of the event [e.g. Reilly 1958; Rumpf et al. 2013; Tsang et al. 2020]. While other properties of the substrate, such as its water saturation, and the ambient environment, such as the air temperature, affect the extent of heating, they appear to be less influential [Tsang et al. 2019].

Direct measurements of the temperature of layers underlying active lava flows are extremely rare [Keszthelyi 1995], while experimental measurements thus far have been recorded only over short timescales and have typically focused on the lava flows themselves rather than the underlying materials [Edwards et al. 2013], though recently experiments have begun to investigate the materials beneath flows [Tsang et al. 2019]. As such, modeling techniques may be a more accessible way to understand the heat transfer process into underlying substrates. These models can be developed and their calibration improved using proxy measurements of the temperature beneath lava flows (e.g. palynomorphs) [Baker et al. 2015]. Understanding the depth and temperature to which heat from the lava flow extends into adjacent substrates is also important for mitigating volcanic hazards as buried infrastructure such as water pipes and electrical cables are susceptible to high temperatures [Tsang et al. 2020]. Heat from lava flows can also sterilize adjacent soils creating an ecological "dead zone" within the heated area [Blong 1984; Rumpf 2014; Baker et al. 2015].

In this study, we use an adaptation of the classic paleomagnetic "baked contact" test [Everitt and Clegg 1962; Buchan 2007; Tauxe et al. 2018] to understand the temperature to which lava flows can heat adjacent materials and the depth to which significant heat penetrates. This method has been used sparingly in the past. Audunsson and Levi [1988] conducted a paleomagnetic study on basement rock beneath a lava flow to determine heat transfer into adjacent rock. Tsang et al. [2019] analyzed samples from soils below a Hawaiian lava flow to determine the depth to which heat extended from a lava flow, however the use of alternating field demagnetization precluded precise estimation

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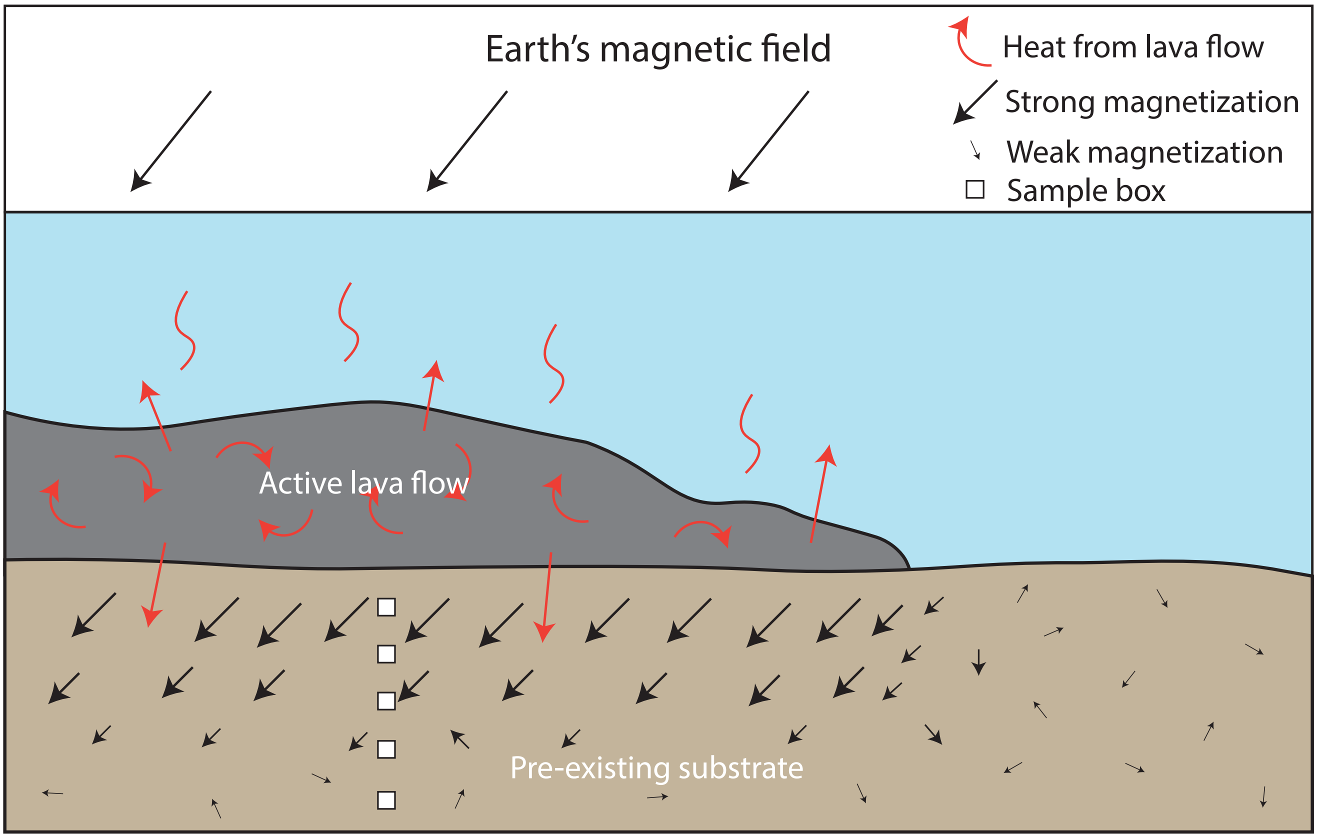

Figure 1: Schematic of lava flow heat transfer and magnetization of adjacent substrates. Red arrows demonstrate the transfer of heat within the lava flow and into adjacent materials. Black arrows demonstrate strong and weak magnetization resulting from reheating of underlying soil by the lava flow. Boxes demonstrate sampling method of taking paleomagnetic box samples at regular intervals of increasing depth beneath the flow.

of temperatures. Here we consolidate and thermally demagnetize samples taken from beneath lava flows to obtain data relating to the maximum temperature reached by the material.

1.1 Thermoremanent magnetization of lava flow contacts

Lava flows and other volcanic materials typically contain magnetite or other ferri- or ferromagnetic minerals (hereafter referred to as "magnetic" minerals). When these volcanic deposits cool from above the Curie temperatures of their magnetic minerals—usually between 500 and 700 °C—to ambient temperature, the rock gains a strong thermoremanent magnetization (TRM) in the direction of the surrounding magnetic field at the time [e.g. Tauxe et al. 2018]. By contrast, although soils, clays, and anthropogenic deposits in volcanic areas may also contain magnetic minerals, the orientations of the grain magnetic moments are usually close to random due to the physically-reworked nature of the deposit; this results in—at best—only a weak overall remanent magnetization. Sediments deposited in water or air may carry a detrital remanent magnetization (DRM) but, compared with a TRM, this is generally weak [e.g. Evans and Heller 2003].

The process of acquiring a TRM during cooling takes place *every time* a rock or deposit cools from a high temperature, meaning that rocks or deposits will gain a new magnetization if they are reheated and cool again to ambient temperature [Tauxe et al. 2018]. If heated above the Curie temperature of the constituent magnetic minerals then remagnetization is complete; if heated to a lower temperature then remagnetization is only partial, with the higher "blocking temperature" component of the original magnetization being retained. This principle is commonly used in the paleomagnetic baked contact test when comparing magnetization directions in baked country rock that has been heated by a dike to the magnetization of the intrusion itself [Buchan 2007] and also in determining the emplacement temperature of clast or matrix material in pyroclastic flows [Hoblitt and Kellogg 1979]. However, the principle can be applied to any deposit containing magnetic minerals, meaning that if soils and anthropogenic deposits containing magnetic minerals are heated (or reheated) their weak and/or random magnetizations will be replaced by a stronger, more consistent partial or complete TRM record of the most recent field in which they have cooled.

This principle of TRM acquisition means that a substrate that is heated by an active or cooling over-riding lava flow will gain a new strong, consistent partial TRM (pTRM) in the direction of the ambient magnetic field carried by grains with blocking temperatures up to the temperature to which it was heated. This can be detected in a laboratory setting by progressive thermal demagnetization of samples of the substrate. In general, at each depth sampled, the temperature to which a strong pTRM in a consistent direction is removed during progressive demagnetization will represent the temperature to which the substrate was heated. A random, weak signal at higher temperatures represents the original magnetization that was not replaced (Figure 1). This allows the resolution of heating up to the Curie temperature of the substrate's magnetic carrier 580 °C for magnetite). All substrates heated above the Curie temperature of their magnetic carrier (regardless of the temperature) will acquire a single, stable TRM, which will be revealed during demagnetization. The age of the reheating event also imposes a lower limit on temperatures that can be resolved by this method, due to possible viscous remanent magnetization (VRM) acquired by subsequent relaxation of grain magnetic moments in the ambient field [Bardot and McClelland 2000]. The maximum unblocking temperature of such a VRM can be estimated using the nomograms of Pullaiah et al. [1975] or an empirical formula given by Bardot and McClelland [2000].

This method of determining substrate heating temperature can be extended by sampling at increasing distance from the point of contact between the substrate and the lava flow. By evaluating the maximum unblocking temperature of the consistent pTRM at different depths [e.g. Tsang et al. 2019], it is possible to derive a depth profile of the maximum temperature reached.

2 Sampling and measurement procedures

2.1 Sites

Paleomagnetic samples were collected from three independent sites resulting from three separate volcanic eruptions. Two sites were located within the Auckland Volcanic Field (Aotearoa New Zealand), a monogenetic volcanic field with activity ranging from ~190 ka to 600 years BP [Hopkins et al. 2020]. The first was a series of consolidated, baked clays from Puketutu eruptive centre previously covered by a 29.8 ka lava flow (36.96965° S, 174.73609° E). The second were baked soils adjacent to and under a ~600-year-old lava flow from Rangitoto volcano (36.79070° S, 174.83171° E). The third site was a man-made scoria berm covered by the June 27th Lava Flow (2014–2015) in 2014 by the eruption of Kīlauea (Hawaii, USA) from the Puʻu ʻŌʻō scoria cone on its flank (19.49514° N, 154.95343° W). All of the sampling sites are in locations where local indigenous cultures have strong attachments to the land; our sampling methods reflect local cultural sensitivities about coring and removing material from lava flows.

2.2 Sampling

The differing conditions of the substrates sampled required a slightly different sampling procedure at each site. For the highly consolidated baked clays at Puketutu, three upward-oriented hand samples were collected in the field, and 2.5 cm diameter cores were drilled in the laboratory to create ~2 cm long specimens, creating sets of 3, 4, and 6 specimens; 13 specimens in total, reaching a maximum depth of 21 cm below the lava contact (Table 1). The baked soil from Rangitoto and the scoria berm from Kīlauea were sampled using standard 2 × 2 × 2 cm plastic paleomagnetic sampling cubes. The Kīlauea samples were taken at 5 cm intervals from the lava flow contact to a maximum depth of 25 cm in two locations (9 specimens in total; Figure 1, Table 1). For Rangitoto, three specimens were collected at increasing depth to a maximum depth of 6 cm. Following the procedures of Schnepp et al. [2008] and Lerner et al. [2019], soils were treated within the plastic cubes using Wacker SILRES® BS OH 100 (a non-magnetic silica-based consolidating liquid which penetrates the samples) and thereafter removed from the plastic cubes so they could be thermally demagnetized. Due to deterioration at higher temperatures, some specimens were also reconsolidated with plaster of Paris after the 150 °C heating step to allow the continuation of demagnetization. For all specimens, the distance from the contact with the adjacent flow was noted.

Some complications due to the delicate nature of the samples included difficulty of orienting and maintaining orientation during specimen preparation. While the absolute azimuthal orientation could not always be maintained, vertical orientation was preserved, meaning that absolute inclination values could be obtained. Relative orientation of samples within a site was maintained as well as possible, and each specimen was oriented consistently throughout the demagnetization process enabling the strength and coherence of the magnetization to be monitored. Additionally, deterioration of some specimens at higher temperatures meant a premature end to their demagnetization.

2.3 Demagnetization and measurement

Specimens were subjected to progressive thermal demagnetization using a Magnetic Measurements thermal demagnetizer in steps of 25 to 200 °C, followed by steps of 40 to 320 °C, and steps of 50 °C thereafter until either near-complete demagnetization or the irretrievable deterioration of the specimen. The peak temperature was maintained for 20 minutes at each step—sufficient to ensure a uniform temperature throughout the samples. Remanence measurements were taken between heating steps using an Agico JR-6 Spinner Magnetometer. Bulk magnetic susceptibility measurements were taken of each specimen using a Bartington MS2 susceptibility meter. The temperature dependence of magnetic susceptibility was measured on representative ~5 g samples from each location using a Bartingon MS-2 magnetic susceptibility meter coupled to a MS2WF furnace and MS2W sensor. This enabled measurement of Curie temperatures and/or detection of thermal alteration to the magnetic minerals in a sample. All measurements were done at the Palaeomagnetism Laboratory at Victoria University of Wellington (Aotearoa New Zealand).

3 Results

The bulk magnetic susceptibility of the specimens, listed in Table 1, showed only minor variation for the light creamy-coloured, weakly magnetic Puketutu samples 1 and 2 (12.2–14.5 × 10^{-5} SI) and the much stronger, dark brown Kīlauea samples (158.5–168.9 × 10^{-5} SI). In Puketutu sample 3, the six specimens show a consistent, decreasing susceptibility with increasing distance from the flow contact (37.1–13.4 × 10^{-5} SI from 3–21 cm depth), as do the three moderate-susceptibility, light brown Rangitoto specimens (124.0–74.9 × 10^{-5} SI). Curie temperatures were determined from temperature dependence of magnetic susceptibility plots (Figure 2). Plots showed a marked decrease in susceptibility at the principal Curie temperature: 560–580 °C for Kīlauea samples, 580 °C for Puketutu (with a potential lower Curie temperature at 220 °C), and ~620 °C for Rangitoto. This indicates a likely magnetic carrier of iron-rich titanomagnetite or magnetite (T_C = 580 °C) at Kīlauea and Puketutu with potential additional titanium-rich titanomagnetite ($T_C \approx$ 220 °C) at Puketutu, and a cation-deficient magnetite or maghaemite (T_C = 590–675 °C) at Rangitoto [Dunlop and Özdemir 1997].

Out of 25 collected specimens, demagnetization and measurement was successfully completed for 18; seven Kīlauea specimens disintegrated before sufficient measurements could be made.

Specimens from all three Puketutu samples show similar behavior, with little demagnetization taking place before the 280 °C heating step, above which a single, unidirectional component of magnetization is removed until the completion of demagnetization at 570 °C (Figure 2A–B). The average Natural Remanent Magnetization (NRM) intensity is 55.9 mA/m, with a maximum of 116 mA/m for the uppermost specimen from sample 3 (PUKE3-A). Although the NRM is relatively weak, the Q ratio (NRM / induced magnetization in a field of 50,000 nT, equivalent to Earth's field) averages 8.5, which indicates a strong NRM compatible with a TRM carried by fine, single-domain, grains. The average inclination from ten of the 13 demagnetized specimens is 64.4 ± 8.5°, which is compatible with the inclination of 61.7 ± 2.5° obtained for the Puketutu lava by Shibuya et al. [1992]. Puketutu is thought to have been erupted during the Mono Lake geomagnetic excursion ca. 30 ka. This is the oldest site sampled in this study, and VRM could extend to a laboratory unblocking temperature of ~150 °C [Pullaiah et al. 1975; Bardot and McClelland 2000]. The NRM is however carried mainly by grains with blocking temperatures above 280 °C, and so is interpreted as a TRM acquired due to heat diffusion from the lava flow.

Specimens from the Rangitoto site show steady, unidirectional demagnetization from approximately the 200 °C heating step until the completion of demagnetization between 470 and 570 °C (Figure 2C). The NRM averages ~200 mA/m, and the Q ratio is between 8 and 11, similar to Puketutu and consistent with a TRM carried by single domain grains. For these 600-year-old samples, VRM is unlikely to affect grains which unblock above 120 °C, supporting this interpretation. The average inclination, −59.9 ± 4° from two specimens is close to the value of −58.0 ± 2.0°, obtained from the New Zealand palaeosecular variation record NZPSV1k of Turner et al. [2015].

The Kīlauea specimens were the most friable and difficult to work with. Two specimens, KIL4-15 and KIL5-10 were successfully demagnetized. Both display gradual demagnetization of a single component, starting at approximately the 200 °C heating step and trending, at shallow inclination, towards the origin until the samples disintegrated at 420 and 470 °C (Figure 2D). Also shown, in Figure 2E, are data from the alternating field demagnetization [Tsang et al. 2019] of a specimen from 5 cm below the lava at a third location, KIL3, which showed a stable direction of remanence with similarly shallow inclination, but, at 5.03 A/m, more than ten times stronger than the remanence at locations KIL4 and KIL5. The susceptibility of this sample was also relatively high, and on heating rose further to a marked "Hopkinson peak" before collapsing to the Curie temperature of 580 °C. This behavior indicates a high concentration of fine-grained magnetite which becomes superparamagnetic (still ferrimagnetic, but with unusually high susceptibility due a very short relaxation time) on unblocking at the Hopkinson peak before losing its ferrimagnetism at the Curie temperature. This is similar to the magnetic enhancement often reported in topsoils due to forest fires [e.g. Borgne 1960; Kletetschka and Banerjee 1995; Clement et al. 2010]. A control sample taken at the same locality in Tsang et al. [2019, Figure 5C] from similar material not impacted by the lava flow has a moderate magnetic susceptibility, but its magnetization is about two orders of magnitude weaker and shows no coherent trend during demagnetization. Although the directional data from the Kīlauea samples are scattered, the shallow inclination is compatible with the inclination of 35.9° at the site in 2014 [International Geomagnetic Reference Field*; Alken et al. 2021].

*https://www.ngdc.noaa.gov/IAGA/vmod/igrf.html

Table 1: Paleomagnetic results.

Site	Specimen	Depth (cm)	Mag susc[a] ($\times 10^{-5}$ SI)	Mag susc[b] ($\times 10^{-6}$ m^3 kg^{-1})	NRM (mA/m)	Q ratio	Stable component (°C)	Temp reached (°C)
Puketutu 1	PUKE1-T	3	12.4	0.064	49.5	10.1	400–570	>570
	PUKE1-M	6	13.0	0.068	55.7	10.8	400–570	>570
	PUKE1-B	9.5	14.2	0.074	60.3	10.7	400–570	>570
Puketutu 2	PUKE2-1	3	11.8	0.063	35.1	7.5	400–570	>570
	PUKE2-2	6	14.5	0.075	42.1	7.3	400–570	>570
	PUKE2-3	9	12.2	0.066	27.0	5.6	400–570	>570
	PUKE2-4	15	13.1	0.097	41.5	8.0	400–570	>570
Puketutu 3	PUKE3-A	3	37.1	0.226	116.3	7.9	400–570	>570
	PUKE3-B	6.5	25.5	0.140	68.7	6.8	400–570	>570
	PUKE3-C	10	18.7	0.105	48.3	6.5	400–570	>570
	PUKE3-D	12	16.6	0.089	66.0	10.0	400–570	>570
	PUKE3-E	16	15.3	0.082	61.6	10.1	400–570	>570
	PUKE3-F	21	13.4	0.073	54.3	10.2	400–570	>570
Rangitoto	RANGI-T	1	124.0	0.616	290	9.0	200–570	>570
	RANGI-M	3.5	91.7	0.686	192	8.1	200–570	>570
	RANGI-B	6	74.9		212	10.9	200–470	>470
Kīlauea	KIL4-10	10		1.55				
	KIL4-15	15	158.5		173	4.2	200–420	>420
	KIL5-5	5		2.50				
	KIL5-10	10	168.9		369	8.4	200–470	>470
	KIL5-15	15		3.06				
	KIL5-25	25		1.89				
Kīlauea[c]	MS1	control		4.10	164			
	MS3B	5		16.25	5030			
	MS3C	10			4760			
	MS3D	15			2810			
	MS3F	25		5.60	4210			

[a] volume specific
[b] mass specific
[c] Tsang et al. [2019]
Mag susc = magnetic susceptibility; NRM = natural remanent magnetization; Q ratio = NRM/induced magnetization in a field of 50,000 nT.

4 Discussion

The strong, stable single components of magnetization displayed in all specimens, which are consistent with known field directions at the time of lava emplacement, indicate that all specimens in this study had been heated at least to the maximum temperature reached in demagnetization experiments (in most cases 570 °C; Table 1). This indicates that enough heat was transferred from the adjacent lava flow to exceed this temperature in each substrate to at least the maximum depth sampled (21 cm at site Puketutu 3). This is in line with the heat transfer modelling Tsang et al. [2019] conducted to create continuous temperature profiles in the Kīlauea berms which showed that the maximum temperature at 10 cm below the 40 cm-thick lava flow (duration of activity: approximately 1 week) is expected to reach approximately 700 °C and just over 570 °C at 15 cm below the flow. These results show that weakly magnetic substrates, carrying at most a weak DRM, adjacent to lava flows are capable of acquiring a strong TRM after reheating and this can be used effectively to infer significant heat transfer under the lava. While it is true that a VRM can be mistaken for pTRM in certain situations [Bardot and McClelland 2000], we have demonstrated that this is not the case here. In most of our samples there is minimal remanence in grains with unblocking temperatures below that required to remove a VRM, and the strong stable TRM which we interpret as having been acquired during heating by the overlying lava flow persists to unblocking temperatures of 470–570 °C.

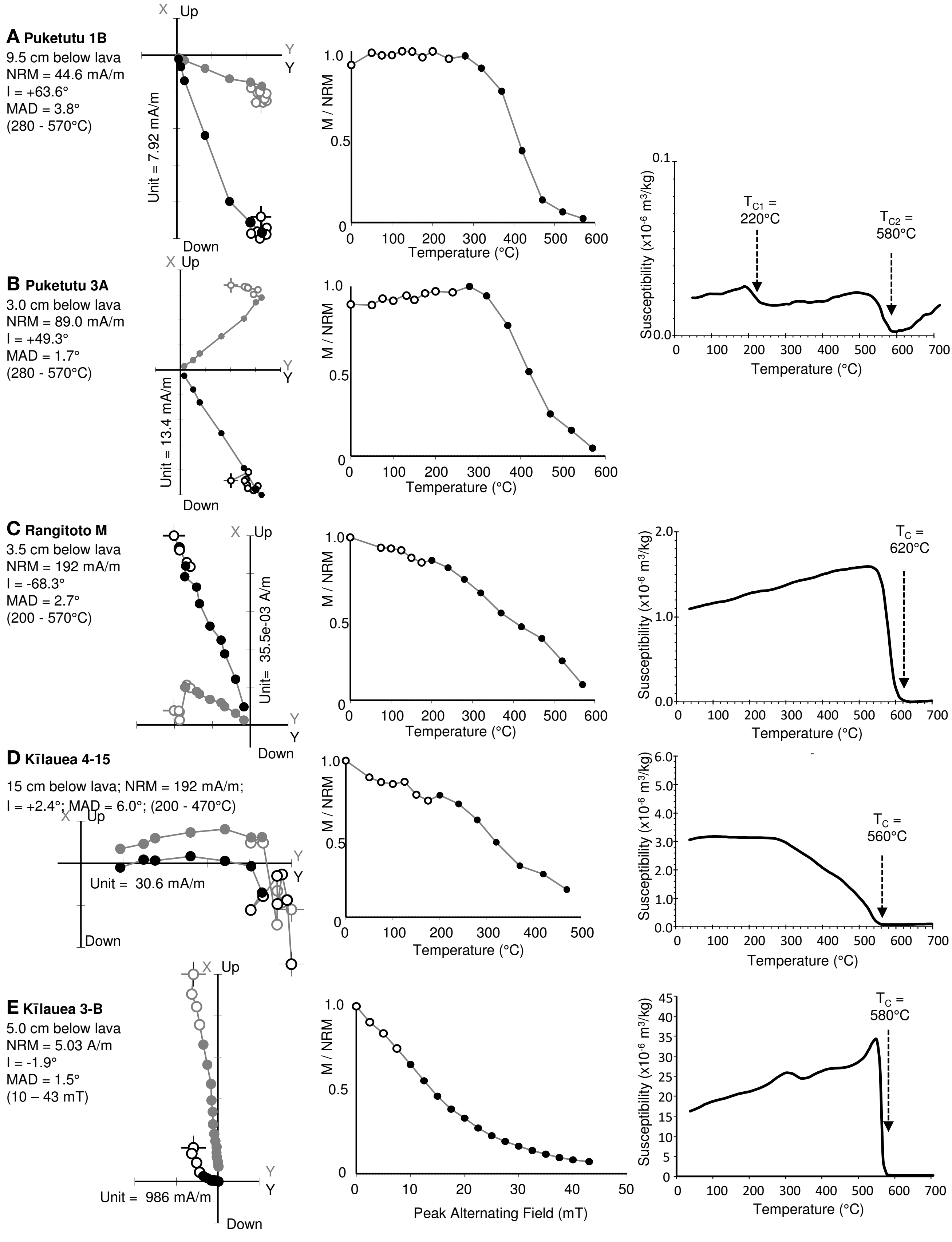

Figure 2: Caption on next page.

Figure 2: (Previous page.) Plots of progressive demagnetization data and temperature dependence of magnetic susceptibility for specimens from Puketutu [A–B], Rangitoto [C] and Kīlauea [D–E]. The left-hand plots are vector component diagrams, with the vertical component shown in black and the horizontal component in grey. Since the specimens are oriented vertically but not azimuthally, X and Y are arbitrary directions in the horizontal plane. The datapoints used in estimation of the Characteristic Remanent Magnetization (ChRM) direction are denoted by solid symbols. The NRM intensity, inclination of ChRM, its maximum angular deviation (MAD) and the range over which estimated are listed. The middle plots show how the intensity of magnetization (normalised by NRM) varies through the demagnetization process. [A]–[D] are thermally demagnetized specimens, described in this paper; [E] is a specimen that has undergone alternating field demagnetization [Tsang et al. 2019]. The right-hand plots show the variation of magnetic susceptibility with temperature on heating from room temperature to 700 °C. Note the different scales. Inferred Curie temperatures are indicated.

The high temperatures reached by the specimens, combined with the deterioration of most of the Kīlauea samples meant that we were unable to resolve more precise temperatures. However, in samples more distant from the flow or under flows of shorter durations and/or lower temperatures, we would expect the method to be able to reveal a profile. Substrates that had not been reheated to the Curie temperatures of their constituent magnetic minerals would be expected to show an underlying weak and/or random component of magnetization at higher unblocking temperatures than the strong, stable component seen at lower temperatures, indicating that the material had not been heated above the maximum unblocking temperature of the stable component. In samples collected at greater depths below the lava flow, it would be expected to see pTRMs reaching a lower maximum unblocking temperature, indicating progressively lower maximum temperatures. Samples taken outside the heating range of the flow would show a weak/random magnetization with no new pTRM [e.g. Tsang et al. 2019]. Altogether, these results demonstrate that substantial heat is being transferred from the lava flow into the ground below despite any insulation afforded by any potentially solidified layer of lava contacting the substrate below. Therefore, when modeling the heat transfer in lava flows such as in Patrick [2004] and Tsang et al. [2020], the ground needs to be included as a heat sink.

Being able to resolve a maximum temperature profile (i.e. set of maximum temperatures at varying depths under the flow) under a lava flow has several implications. First, recent research has demonstrated how computational heat transfer modeling can be used to predict thermal hazard to buried infrastructure [Tsang et al. 2019; 2020]. Measuring maximum temperature profiles under lava flows allows for such models to be validated. Second, if a maximum temperature profile under a lava flow of known thickness and temperature can be extracted from substrates, then computational heat transfer models can be used to calculate how long lava was actively supplied to the lava flow at the sampling site given the soil's physical properties (e.g. heat capacity, density, etc.) are known [see Tsang et al. 2019; 2020, for a full list of modeling parameters that are required for such modeling to be undertaken]. If all of the maximum temperatures are above the Curie temperature, only a minimum duration could be calculated (this can be remedied by sampling to greater depth to create a temperature profile with maximum temperatures below the Curie temperature). Finally, planetary geologists have hypothesized that lava flows could protect subterranean, extra-terrestrial, microbial life from radiation [e.g. Rumpf et al. 2013; Rumpf 2014]. This assumes that such microbial life survived the initial emplacement of the lava flow. Measuring how much heat was transferred into the ground below would allow scientists to determine how deeply a lava flow would have sterilized during emplacement.

For future use and improvement of the method, we make the following recommendations:

- Ideally, future validation of this method would involve sampling to greater depths below the lava flow. This is supported by our results and modelling from Tsang et al. [2019] and other works. For example, collecting specimens at regular intervals to a depth of over 1.5 m below a lava flow of around 50 cm thickness would increase greatly the chance of resolving profiles of maximum temperature and depths of significant heating. The depths affected naturally would be expected to increase with thickness of the lava flow, its temperature and the duration for which it was active.

- Full and accurate orientation of substrate samples in the field would allow a better comparison of the pTRM direction and the direction of the ambient field at the time of the lava flow.

- If possible, samples of the lava flow itself should also be collected.

- When possible, a control sample of the same substrate should be taken at a location distant from the lava flow for comparison.

- As unconsolidated soils can be difficult to sample and consolidate for paleomagnetic studies while maintaining orientation, finding ideal sample material below a lava flow would be beneficial for increasing the chance of maintaining a complete suite of samples to the desired depth below the flow.

- This method could be attempted on substrates contacting intrusive dikes, as this may allow easier sampling at greater distances from the lava. For example, the modified baked contact used by Biasi and Karlstrom [2021] to constrain the active lifetime of dikes is similar to our method and could be extended to assess the heating of adjacent materials. When comparing the heating around dikes to that under lava flows, it is important to note that previous studies have suggested the dominant heat transfer mechanisms in the two contexts may not be the same [Wilson 1962; Baker et al. 2015].

5 Conclusions

In this study we have outlined a method for using progressive thermal demagnetization and paleomagnetic measurements to determine the extent of heating beneath lava flows. Our results from the Auckland Volcanic Field and Kīlauea show heating to temperatures of at least 570 °C at depths of up to 21 cm below the flow contact, indicating significant impacts to anything located within this shallow area beneath the flow. The results in this study show the efficacy of this method, and with our suggested improvements we believe this method can be used and refined in future studies to make precise measurements of temperatures reached as a result of heat transfer from lava flows into adjacent substrates.

Acknowledgements

The authors are grateful to Thomas Berndt and Rosie Cole for constructive reviews that led to improvements in our manuscript. GAL was supported by the Earth Observatory of Singapore via its funding from the National Research Foundation Singapore and the Singapore Ministry of Education under the Research Centres of Excellence initiative. SWRT received financial support from Royal Society Te Apārangi Hutton Fund for this work. We would like to thank Melvin Sugimoto for access to his property and allowing us to sample, the New Zealand Department of Conservation for the sampling permit and helping identify and facilitate conversations with local iwi, and Andres Arcila-Rivera, Dr Gianna Evans, and Prof Shane Cronin for assistance in the laboratory.

Author contributions

GAL wrote the first draft and assisted with fieldwork and paleomagnetic analysis. SWRT conceived of the study, performed fieldwork, prepared the samples, and conducted paleomagnetic measurements and analysis. GMT conducted paleomagnetic measurements and analysis. All authors contributed to and edited the manuscript.

Data availability

Paleomagnetic data files are available via the University of Auckland figshare portal at DOI: 10.17608/k6.auckland.16935013.

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