Understanding the life history of nineteenth century Australian bricks using archaeomagnetism and the establishment of the South East Australian Archaeomagnetic Dating Reference Curve (SEAARC)

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Abstract

Archaeomagnetism is a versatile tool for archaeologists and historians. In addition to being a robust dating method when sufficient data and reference curves are available, archaeomagnetic data can provide a wealth of information on artefacts and site histories. Here we present the first archaeomagnetic study on Australian bricks to assess the potential of this technique, and as a first stage in building the South East Australian Archaeomagnetic Reference Curve (SEAARC) for dating sites in the future. In collaboration with consulting archaeologists and Heritage Victoria, two types of nineteenth century bricks were analysed: handmade bricks, which were made and used in southeastern Australia, and refractory bricks, which were manufactured in Scotland and used in an iron foundry in Melbourne. The results provide meaningful insights into the bricks' histories, including their provenance, manufacturing method and use. They also provide independent age estimates, and the capacity to unravel historical events such as fires. Moreover, the first archaeointensity experiments are in agreement with geomagnetic field modelling based on historical mariners' measurements at sea, which is promising for palaeo-geomagnetic field research using Australian bricks.

Introduction

Archaeomagnetism is defined here as the application of magnetic methods of analysis drawn from the fields of palaeomagnetism (i.e. looking at ancient fossil remanence) and rock magnetism (i.e. investigating magnetic properties) to archaeological sites and artefacts (Herries 2009). Archaeomagnetic studies of archaeological artefacts, features and deposits for dating purposes has become a major field of archaeological science and geophysics over the last 50 years (Aitken 1970; Batt 2015; Belshé 1961; Cook and Belshé 1958; Herries et al. 2007; Kovacheva et al. 2014), most notably within a European and North American context (Goguitchaichvili et al. 2012; Herries et al. 2008). Most attempts to recover palaeomagnetic data in Australia have been from archives such as Aboriginal hearths and lake sediments (Barbetti 1977, 1983; Barbetti and McElhinny 1972; 1976; Barton and Barbetti 1982; Barton and McElhinny 1981). The pioneering archaeomagnetic work of Barbetti and others (Downey and Frankel 1992; Lawler et al. 2015) in southeastern Australia has shown that pre-colonial, Aboriginal burnt features can be used to recover archaeomagnetic data—although little follow-up work has been undertaken. This is perhaps in part because the early study by Barbetti and McElhinny (1972), which suggested the occurrence of a geomagnetic excursion at Lake Mungo (Lake Mungo Event), has been disputed (Huxtable and Aitken 1977). However, more recent work on the dating of these deposits (Bowler et al. 2003) suggests that they occurred 30–40 ka, a time period now known to include two globally recognized geomagnetic excursions (Mono Lake at 32 ka and Laschamp at 41 ka; Cassata et al. 2008; Singer 2014). The Lake Mungo record alone contains suitable material spanning the last 42,000 years, or possibly 50,000 years (Bowler et al. 2003), revealing excellent potential for building the oldest archaeomagnetic regional dating reference curve in the world.

More recently, archaeomagnetic methods have been expanded to answer questions about archaeological material and sites unrelated to dating, such as the identification of heat treatment of silcrete and chert to make flaked stone artefacts (Brown et al. 2009; Rowney and White 1997), and for understanding site formation processes (Gose 2000; Herries 2009), occupation intensity (Herries and Fisher 2010), ochre sourcing (Mooney et al. 2003) and climate change (Herries 2006). Archaeomagnetism is thus a very versatile method that should be employed as a standard method for all archaeological projects because it is inexpensive and, in

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most cases, samples are easy to collect (Herries 2009).

Thermo-archaeomagnetic techniques are based on the ability of archaeological materials that were heated in the past to record all or part of the thermal history of an artefact, feature or deposit. Materials of this kind record the direction and intensity of the magnetic field when they were heated and cooled in that ancient field. This information can be used for dating purposes, as the ancient direction and intensity of the Earth's magnetic field varies according to its vector components: declination, inclination and intensity. These components of the field vary over timescales of less than one second to millions of years, and they can include fluctuations such as complete 180° polarity reversals, geomagnetic excursions, jerks and pulsations. For dating to be effective, samples heated to high temperatures above the Curie temperature (T_c) of the magnetic mineral holding the remanence (e.g. T_c ~575 °C for magnetite) are ideal. As a sample is heated past the Curie temperature, any previous net magnetisation exhibited will be disrupted. As the sample begins to cool below the T_c, these minerals will become magnetised proportional to the prevailing field at the time, thus archiving a thermomagnetic remanence (TRM) of the direction and intensity.

With an archaeomagnetic dating reference curve, the direction and intensity of the TRM in the archaeological material being investigated can be compared to known changes in the geomagnetic field to estimate a date with an error range of a few hundred years (McIntosh and Catanzariti 2006). If such a curve does not exist, then the data recovered can still be useful for establishing a relative age for different archaeological material and features by looking at variability in the field direction between different hearths on an open landscape, features in different excavation trenches with unknown stratigraphic correlation, or different bricks in a building to understand reuse history (Herries et al. 2007; Herries and Kovacheva 2007).

If samples are not heated through the Curie point of the relevant mineral in the sample, then a partial thermomagnetic remanence (pTRM) is formed. This does not completely overprint the original remanence in the sample, and thus can be used to understand the different heating events that a sample has experienced. Examples of this include the heating of silcrete to make flaked stone tools, where the original geological remanence is overprinted by a pTRM derived from heating in a campfire (Brown et al. 2009), or the use of a brick in a fireplace within a house, where a pTRM overprints the original TRM formed during brick manufacture. In this case, the thermal use history of the artefact or feature can be reconstructed to understand if more than one heating event has occurred, if there was movement between heating events (i.e. over short distances or between countries) and if material is still in the original location where it was heated. This can inform about site formation processes and deliberate versus accidental heating episodes, which has implications for our understanding of past human behaviour.

The sampling of materials in their original context of heating is also ideal for creating and using an archaeomagnetic dating reference curve. For example, a brick part of a standing fireplace, a kiln, or a furnace in its heating context can provide both field directional (i.e. declination and inclination) and intensity data. In contrast, samples recovered from secondary, non-heating contexts cannot be used to obtain reliable geomagnetic directional data as their original orientation during TRM acquisition is unknown. In this regard, samples from secondary contexts may include bricks derived from a feature or structure that was not heated, or bricks originating from archaeological deposits (e.g. construction or demolition fills). Nevertheless, as this paper demonstrates, archaeomagnetic analysis of bricks from secondary contexts is useful for recovering paleointensity data, and it can also provide meaningful archaeological and historical data.

This paper discusses the results and prospects of an exploratory study into the archaeomagnetic properties of nineteenth century bricks derived from Victorian historical sites. Bricks were selected for study as they frequently occur at historical sites, and, in general, only a few representative samples are retained for analysis and curation during commercial projects. Specifically, the aims are to assess the suitability of historical bricks for use as geomagnetic field recorders in Australia, so that they can be used to create a South East Australian Archaeomagnetic Referenced Curve (SEAARC); and to investigate the potential for extracting archaeological data concerning the manufacture and life history of bricks. This project, which is in its preliminary phase, was born out of collaboration between consulting archaeologists, researchers and Heritage Victoria, and it forms the first archaeomagnetic study applied to the field of historical archaeology in Australia.

Sites and materials

The bricks analysed in this study include imported firebricks from Scotland, and handmade bricks that were made locally (i.e. Victorian) (**Table 1**). All samples were obtained from two nineteenth century archaeological sites in Victoria, although in secondary contexts to any TRM-forming heating events. TRM-forming heating events can include a TRM acquired during initial manufacture (i.e. firing) of the brick (herein after $_{m}$TRM), or a TRM acquired during any heating events post-manufacture (herein after $_{p\text{-}m}$TRM).

'Harp of Erin Hotel, Burrumbeet' (H7623-0324)

'Harp of Erin Hotel' is an informal name given to two nearby, yet separate, sets of nineteenth century structural remains located in Burrumbeet, western Victoria (**Figure 1A-i and -ii**). The two sites, separated by a distance of 100 m, were recorded and excavated by Dr Vincent Clark and Associates P/L in 2011–2012 as part of road duplication works for the Western Highway near Ballarat (Anderson et al. 2013). The two sites, designated the East Site and West Site, were partially exposed and buried at shallow depths in an open paddock. Both sites date to the mid- to late-nineteenth century, with additional evidence for occupation during the early-twentieth century at the East

Sample ID	Brick type	Manufacturer	Location of manufacture	Date of manufacture	Site	Context and date	Reference
FBW1	Refractory	John Grieve Bank Park Firebrick Works	East Lothian, Scotland	1860–1893	FS	Fill deposit, 1842–1864	Douglas et al. 1985; Mallett et al. 2015
FBW2	Refractory	John Grieve Bank Park Firebrick Works	East Lothian, Scotland	1860–1893	FS	Fill deposit, 1842–1864	Douglas et al. 1985; Mallett et al. 2015
FBG	Refractory	Garnkirk Fire Clay Company	Garnkirk, Lanarkshire, Scotland	1837–1901	FS	Fill deposit, 1842–1864	Douglas et al. 1985; Mallett et al. 2015
HB1	Handmade	Unknown	Victoria, Australia	19th century	HE	Archaeological deposit, 19th century	Anderson et al. 2013
HB2	Handmade	Unknown	Victoria, Australia	19th century	HE	Structural feature, 19th century	Anderson et al. 2013

Table 1. Details of brick samples. FS = 556–560 Flinders Street, Melbourne; HE = 'Harp of Erin Hotel', Melbourne

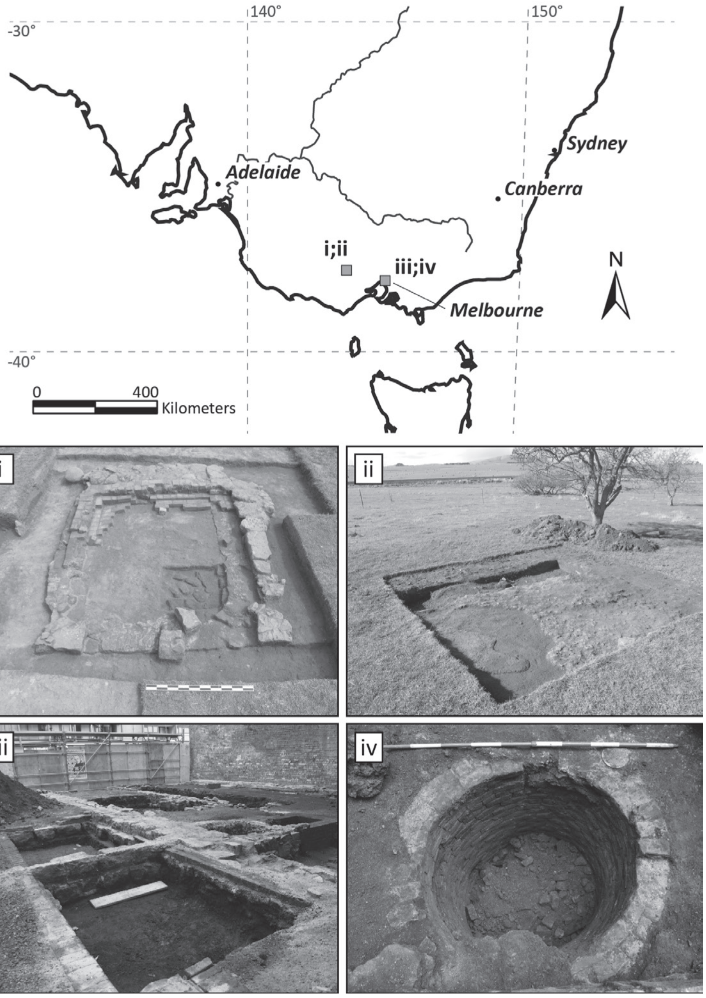

Figure 1. (A) Map of southeastern Australia, site locations and photos showing (i) Harp of Erin: East Site, Feature B; (ii) Harp of Erin: East Site, Trench 7, cobbled surface; (iii) 556–560 Flinders Street general site photo; and (iv) 556–560 Flinders Street, handmade brick well. (B) Photos of representative brick samples, showing (i) Harp of Erin handmade brick (HB1 and HB2); (ii) 556–560 Flinders Street, 'John Grieve Bank Park Firebrick Works' firebrick (FBW1 and FBW2); and (iii) 556–560 Flinders Street, 'Garnkirk Warranted' firebrick (FBG) with iron-slag staining

Site. Both sites can be associated with the expansion of European settlement in western Victoria during the Gold Rush. The coins identified during excavations support this interpretation, with dates ranging from 1818–1857 (Anderson et al. 2013).

The West Site formed part of a single structure, possibly the historically known Harp of Erin Hotel based on the remaining structural features and associated artefact assemblage. It can also be inferred that the building was occupied for a short period of time given evidence for its sudden destruction by fire and subsequent abandonment (Anderson et al. 2013). However, the nature of occupation at the East Site, where the handmade bricks in this study originate, is not so clear. This locality comprised isolated stone and brick features that were associated with a single wooden building, or multiple wooden buildings. While a specific function could not be ascertained, there were indications, particularly from the artefact assemblage, that the site comprised a semi-public space—possibly a shop or store, or perhaps even a toll-gate that was known to be present in the area at the time. Artefact chronologies indicate that the East Site was potentially occupied during two separate phases: the first was during the mid-nineteenth century; and the second was probably during the early-twentieth century. No other obvious connection could be established between the two sites.

The handmade bricks used for the magnetic analysis were derived from the East Site (**Table 1**; **Figure 1B-i**). HB2 was sampled in situ from the wall of Feature B (**Figure 1A-i**), which was identified as a cool storage room on the basis of its size, form and elaborate construction (Anderson et al. 2013). This feature included a double-layered wall of stone, brick and mortar, deep foundations, and a complex floor construction which may have been intended to create a sealed area for the storage of foodstuffs. The various phases of construction at the site and associated artefact assemblages suggest that the structure probably dates to the third quarter of the nineteenth century. In addition, isolated evidence in the form of charcoal patches, burnt glass and ceramic fragments suggests that the building suffered fire damage (Anderson et al. 2013:34). This fire is unlikely to have been as severe as the West Site fire. HB1 was derived from shallow subsurface deposits overlaying a cobbled surface area (Trench 7), and its context is therefore unclear (**Figure 1A-ii**). Nevertheless, an 1857 trade token found amongst the cobbles provides the earlier date for the cobble surface (Anderson et al. 2013:218). This archaeological evidence informs on the period of site occupation, which post-dates the manufacture of the bricks.

All of the bricks recovered from the East and West sites during excavations were handmade (i.e. sandstock) and reddish-yellow in colour (e.g. HB1 and HB2: 5YR 6/6). None of the bricks have frog marks, maker's marks or impressed thumb prints. On the basis of their attributes—including uneven colour, course inclusions and signs of uneven firing—the bricks can be described as "poor" in quality (Anderson et al. 2013; Stuart 2005:84). While the specific location and date of manufacture are unknown, Anderson et al. (2013:101) suggest that the material used to make the bricks was sourced from local clays, thus it is likely that these bricks were made locally. Given the presence of material dating occupation from at least ca 1857, the timing of the first survey of settlement in Burrumbeet (ca 1855; James 2007; Watson 2003) and the presence of a single handmade brick type, it is likely that HB2 and HB1 were fired originally (and thus $_m$TRM formed) during the mid- to late-nineteenth century. Of course, it cannot be ruled out that the bricks were manufactured elsewhere at an earlier date, then transported to and reused at the site, although this is less likely given the prevalence of regional and even mobile brick makers operating in Victoria during the 1850s, and the cost and lack of infrastructure for transporting heavy materials (Stuart 1987:36–37). In light of this uncertainty, HB1 and HB2 and any associated $_m$TRM signals are interpreted conservatively as dating to the nineteenth century for the purposes of the analyses (Table 1).

556–560 Flinders Street, Melbourne (H7822-1847)

556–560 Flinders Street comprises a number of small, inner-city allotments that were occupied by industrial and commercial businesses during the nineteenth century (**Figure 1A-iii** and **-iv**). The ~300 m^2 site was subject to salvage excavations and archaeological monitoring by ArchLink Archaeologists and Heritage Advisors P/L in 2014, as part of redevelopment works on the property (Myers et al. 2015).

From 1842–1864, the site formed part of 'Langlands Iron Foundry', which was Victoria's first iron foundry and engineering firm (Burnell 1934). At its height, the foundry (along with the neighbouring 'Fulton Foundry Company') occupied much of the Melbourne CBD block bound by Flinders Street, Spencer Street, Flinders Lane and King Street. 556–560 Flinders Street encompassed a small area of the former foundry grounds, which was interpreted as yard space given the lack of structural evidence identified on-site (Mallett et al. 2015). Major features of the site during the foundry phase included a handmade brick well (with potentially associated wooden features), and various occupational surfaces including handmade brick paving and compacted pebble flooring. Towards the end of the foundry phase, the site was cleared and backfilled with extensive deposits of iron slag, a foundry waste product. These deposits and underlying occupational surfaces were subsequently cut for the construction of new buildings on the allotments, with the construction of 558/560 Flinders Street (Building 1) and 556 Flinders Street (Building 2) taking place in 1864 and 1876, respectively (Mallett et al. 2015). This construction phase marked the transition between the industrial and commercial use of the site, although Langlands Iron Foundry continued to operate from the wider Flinders Street city block until 1881 (Weickhardt 1983).

Two types of imported firebricks from Scotland were analysed. The first type is stamped 'Garnkirk Warranted' (FBG), and the second is stamped 'John Grieve Bank Park Firebrick Works' (FBW1 and FBW2) (**Table 1**). All firebricks were found in secondary fill deposits sealed within the brick well (**Figure 1A-iv**; **Figure 1B-ii** and **-iii**). Stratigraphic and historical evidence demonstrate that the well was in use during the foundry phase of occupation (1842–1864). It was backfilled some time before the 1864 building works, and capped with iron slag. This slag layer was subsequently cut for the placement of foundations for Building 1, and the well was covered by the footprint of this new structure (Mallett et al. 2015). The sealed and capped nature of the deposit limits the potential for post-depositional artefact mixing.

The firebricks themselves were all manufactured in Scotland during the nineteenth century (**Table 1**), and were later imported to Melbourne for use in the foundry, as inferred from their archaeological context, the presence of iron-slag staining, evidence for iron-slag adherence, and the associated deposits and artefact assemblage (Mallett et al. 2015; Myers et al. 2015). While the specific life histories of the firebricks are unknown, the foundry association of the firebricks—which were specialty bricks imported for use during high-temperature heating processes—are such that FBW1, FBW2 and FBG have the potential to record an original ${}_{m}$TRM component originating from their manufacture in the northern hemisphere; and/or a ${}_{p\text{-}m}$TRM derived from foundry heating processes in the southern hemisphere. This means that any potential southern hemisphere ${}_{p\text{-}m}$TRM component would have formed between 1842–1864, during the foundry occupation at 556–560 Flinders Street. Thus, an original ${}_{m}$TRM signal should have been acquired between the earliest known manufacturing date for the brick (**Table 1**), and the latest capping age of the 556–560 Flinders Street well deposit in 1864.

Archaeomagnetic analysis

Sample preparation

Each brick was drilled with 22 mm diameter cylinder cores at The Australian Archaeomagnetic Laboratory (TAAL), with special care taken to preserve the integrity of the brick stamps which are visible in **Figure1B-ii** and **-iii**. The cores were then cut into ca 25 mm sections, and each ca 10 cc sample was weighed and identified (see sample photo; **Figure 4**). For this study, a total of 29 samples were analysed, including six samples for HB1 (from two perpendicular cores; HB1-A2, -A3, -B1b, -B2a, -B2b, -B3), five samples for HB2 (from one core; HB2-1, -2, -3, -4, -5), seven samples for FBW1 (from two parallel cores; FBW1-A1, -A2, -A3, -A4, -B2, -B3, -B4), five samples for FBW2 (from one core; FBW2-1, -2, -3, -4, -5) and six samples for FBG (from one core; FWG-1, -2, -3, -4, -5, -6). The measurement of a transect of samples across a brick facilitates the replication and identification of eventual gradient in the magnetic mineralogy and/or in the temperature at which the brick was fired.

Magnetic properties

Samples from each type of brick (i.e. handmade and refractory) were submitted to stepwise thermal and alternating field demagnetisations at TAAL to identify the magnetic mineralogy and to recover the archaeomagnetic directional record. Thermal demagnetisation was performed in 29–33 steps up to 700°C, and alternating field demagnetisation in 28 steps up to 70 mT. The Excel Workbook 'Demagnetization Analysis in Excel' (DAIE; Sagnotti 2013) was used for data analysis and visualisation. The magnetic susceptibility was measured prior to demagnetisation and after each thermal demagnetisation step, using a Bartington dual frequency sensor MS2B to monitor magnetic mineralogy change upon heating. Finally, hysteresis loops for the handmade brick HB1 and firebrick FBW1 were analysed using a Princeton Measurements Corporation 'Vibrating Sample Magnetometer' (VSM) at the Environmental Magnetism Laboratory of the Australian National University. This instrument measures the magnetic remanence acquired by a small powdered sample (ca 0.1 g) into laboratory fields building up to 1 T and decreasing to -1 T at room temperature. The shape of the resulting hysteresis loop informs on the coercivity of the magnetic grains assemblage (Tauxe et al. 1996).

Archaeointensity experiment

Archaeointensity experiments are designed to check the ability of a sample to acquire a TRM, and to recover the palaeo-geomagnetic field intensity value. The aim is to replace the natural remanence of the sample progressively with a laboratory-induced TRM, following a stepwise approach. Then, assuming that the acquired remanence is linear with the magnetic field, the slope of the natural remanence to the laboratory-induced remanence is the archaeointensity. The Thellier-Coe palaeointensity method was used for four pilot samples from the handmade brick HB1 and firebrick FBW1, with in-field and zero-field pTRM checks (Coe 1967; Riisager and Riisager 2001; Thellier and Thellier 1959) to detect magnetomineralogical changes and coarser-magnetic-grains biasing effects. The applied field of 40 μT was generated using a power supply EL301R plugged into the Magnetic Measurement MMTD80A thermal demagnetiser furnace. The procedure included 12 heating steps to 100°C, 200°C, 250°C, 300°C, 350°C, 400°C, 440°C, 480°C, 500°C, 520°C, 540°C and 580°C. The program ThellierTool 4.22 was used for archaeointensity data analysis (Leonhardt et al. 2004).

Results

The five bricks analysed have complex magnetic mineralogies with admixture of low- and high-coercivity minerals, as indicated by thermal demagnetisation curves with several slopes (**Figure 2**). While the handmade bricks (HB1 and HB2; **Table 1**) and John Grieve Bank Park refractory bricks (FBW1 and FBW2; **Table 1**) have variable complex magnetic mineralogies within the brick itself, the Garnkirk refractory brick (FBG; **Table 1**) is remarkably uniform. Variable mineralogies are indicated by the hysteresis loop shapes that range from pot-bellied to wasp-waisted (**Figure 3**), reflecting variable sets of magnetic coercivity spectra (Tauxe et al. 1996); and by the thermal demagnetisation slopes and alteration (not shown) during heating at variable temperatures (**Figure 2**) within samples from the same brick.

In general, the samples from inside the bricks have higher initial magnetic susceptibility values (100 to 450x10^{-5} SI) and the magnetic minerals alter during the heating experiment, compared to the samples from the surface of the bricks. In contrast, the samples from the surface of the bricks have lower magnetic susceptibility values (<200x10^{-5} SI) and do not alter upon heating, probably because the outside of the bricks was already exposed to air during heating and weathering over time, whereas the interior of the brick was not. While this is true for the handmade bricks and refractory bricks FBW1 and FBW2, once again the refractory brick FBG is different. In addition to having a remarkably uniform mineralogy, this brick does not alter upon heating and the magnetic susceptibility values are low (ca 25x10^{-5} SI).

Importantly, all of the bricks reveal reproducible archaeomagnetic directional histories, despite their complex mineralogies and different degrees of homogeneity or heterogeneity. This means that all of the magnetic minerals within a given brick consistently recorded the same $_{m}$TRM and $_{p\text{-}m}$TRM. **Figure 4** shows the orthogonal projections for selected samples of each brick, and it illustrates that the two handmade bricks (HB1 and HB2) have two components uniformly throughout the bricks. It also shows that the firebrick FBG has one single directional component uniformly throughout the brick, and that FBW1 and FBW2 display two directional components on one side of the brick only.

Discussion

'Harp of Erin Hotel' handmade bricks: Manufacturing history and fire event

The thermal and alternating field demagnetisation results (**Figure 4**) clearly reveal two directional components of magnetisation in the handmade bricks. This result suggests that the bricks were fired to high temperatures (>700°C), and then moved to another location to cool down around 350–480°C to ambient temperature. This temperature range can be calculated by identifying the point at which the different components in the sample switch from one to another (**Figure 4**). The data suggests that the two bricks were heated to quite different temperatures, with HB1 being moved at a higher temperature of ~480°C, and HB2 being moved at ~350–380°C. This may indicate that the two bricks come from different manufacturing events, or were in different parts of the same kiln or stack, or were moved at different times from the same firing event.

These sequences of events are in agreement with the methods of brick firing used during the nineteenth

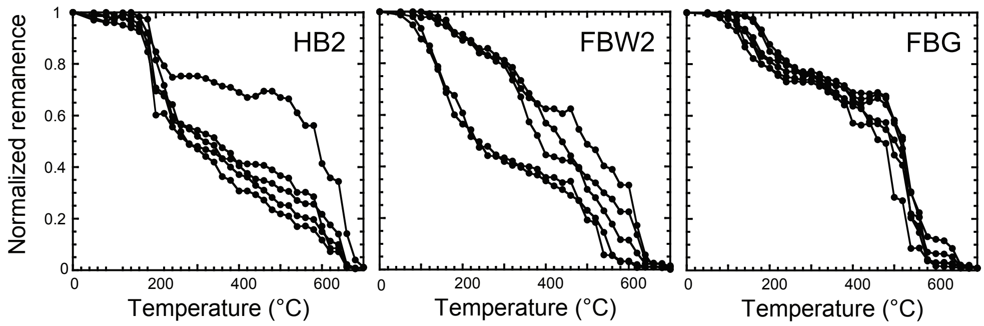

Figure 2. Typical thermal demagnetisation curves for each type of brick (A) handmade—HB; (B) refractory 'John Grieve Bank Park Firebrick Works'—FBW; and (C) refractory 'Garnkirk Warranted'—FBG. The multiple slopes indicate complex magnetic mineralogy. Note that the curve shapes within the same bricks are variable for A and B, and the most uniform for C

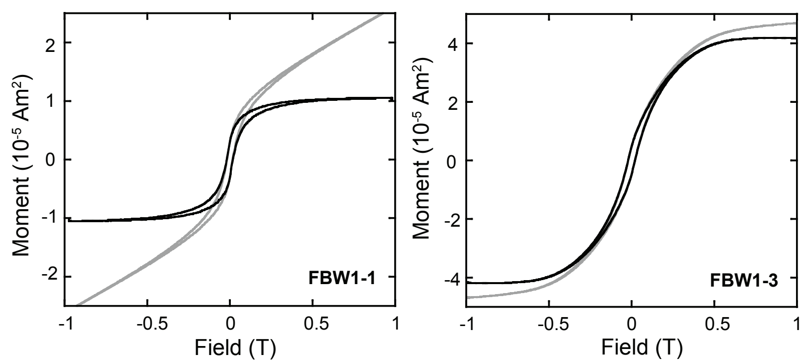

Figure 3. The variable shape of the hysteresis loops reflects the complex magnetic mineralogy of the brick. The shapes vary from (A) wasp-waisted, indicating a mixture of low- and high-coercivity minerals; to (B) pot-bellied, indicating predominantly low-coercivity minerals

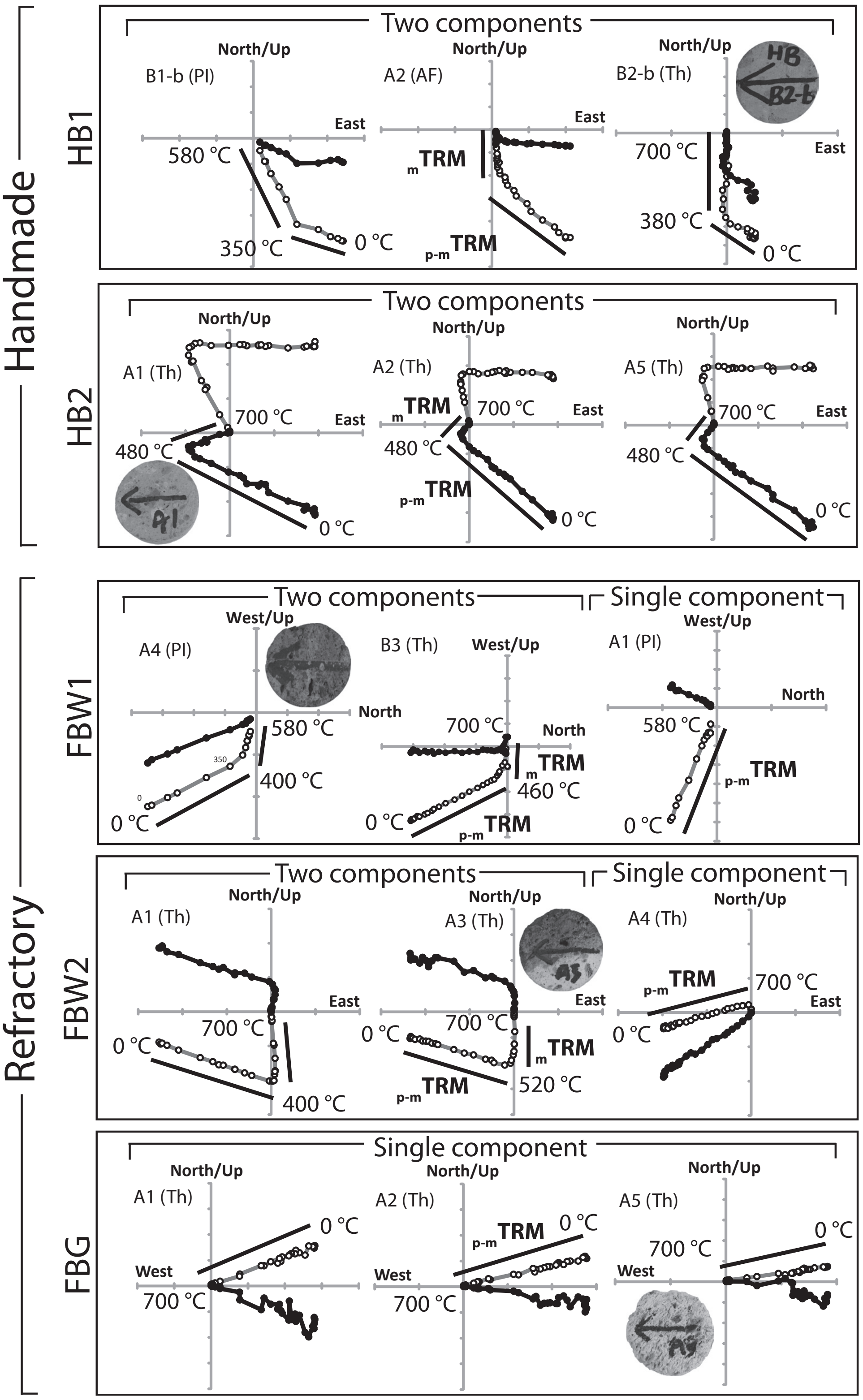

Figure 4. Orthogonal projection (Zijderveld 1967) of selected samples for the two handmade bricks (HB1 and HB2) and the three refractory bricks (FBW1, FBW2 and FBG) discussed in the text. The type of alternating field (AF), thermal (Th) demagnetisation, or archaeointensity experiment (PI) analysis is indicated for each sample. The temperature of transition between two directional components is also indicated, as well as the thermal remanent magnetisation acquired during manufacture ($_m$TRM) and the one acquired during a subsequent heating event ($_{p\text{-}m}$TRM). One sample per brick is shown (the cylinder has a section diameter of 22 mm). Note the change from double component on one side to single component on the other side, and the temperature gradient within the refractory bricks FBW1 and FBW2, indicating that one side of the brick was exposed to higher temperatures

century. The two firing methods used at the time consisted of burning bricks in the open, or firing bricks in the first permanent kilns (Bell 1998). These first kilns were updraught and downdraught designs, depending on where the heat exited the construction, and they needed to be filled with bricks then fired and emptied before the next run began. This means that kilns were not used continuously, and that heating needed to cease so that fired bricks could be removed and others inserted. The Hoffman kilns technology revolutionised brick making in Victoria in the 1870s (Birmingham et al. 1983; Stuart 1987), as these kilns could be used continuously with the heat source being moved around the bricks. The complex and variable magnetic mineralogy within the handmade bricks (**Figure 2**) is consistent with a heterogeneous clay mixture and/or uneven firing temperatures, which further supports the argument for manual manufacture and use of pre-Hoffman brick-firing methods. Overall, the archaeomagnetic data of the handmade bricks is consistent with the firing method used for kilns prior to the 1870s, and it provides independent support for the site chronology.

It is possible that a secondary heating event such as a wildfire or house fire, rather than being moved during cooling, could have imprinted the archaeomagnetic directional record to explain the low temperature component. While the information available for the samples in this study is limited, in the case of a fire event, the low temperature component ($_{p\text{-}m}$TRM) would have overprinted the component acquired during fabrication ($_{m}$TRM) and could have overridden any other $_{p\text{-}m}$TRM acquired before the time of the event. If the low temperature directional components in the handmade bricks were acquired during a fire event, the heat had to be sufficient and maintained long enough to raise the temperature uniformly throughout the bricks up to 350°C and 480°C for HB1 and HB2 bricks, respectively (**Figure 4**). There is some evidence for a fire at the East Site (Anderson et al. 2013), and therefore an unidentified major fire event cannot be eliminated. However, there are no burning stains on the bricks that may indicate such a secondary firing event. Overall, the archaeomagnetic analysis of the handmade bricks reveals excellent potential for identifying their manufacturing history and for documenting historical fire events.

Iron foundry firebricks: Geographic provenance and usage

The two types of imported refractory bricks from Scotland (FBG and FBW1, FBW 2; **Table 1**) reveal different stories. While the brick stamped 'Garnkirk Warranted' (FBG) displays a single directional component, the bricks stamped 'John Grieve Bank Park Firebrick Works' (FBW1, FBW 2) display two components on one side of the brick only (**Figure 4**). If the two types of bricks were part of the same construction, used in a comparable fashion and exposed to similar temperatures, then it is expected that their archaeomagnetic directional record would be the same. The different directional records may be due to different magnetic grains assemblages, such as coarser grains or lower-coercivity minerals that typically reset their magnetic remanence at lower temperature. However, the thermal demagnetisation, isothermal remanent acquisition and hysteresis results indicate that this is not the case. The magnetic properties of the firebricks reveal complex mineralogies, and, when considered together, the total magnetic assemblage for each brick covers a similar range of coercivities and temperatures (**Figure 2; Figure 3**). Therefore, if these firebricks were used in the same way, they would have recorded the same archaeomagentic directional record.

As the firebricks bear stamps from different companies and appear differently to one another (**Figure 1B**; **Figure 4**), they may represent refractory bricks of varying quality and function in the foundry. The archaeomagnetic results suggest that the firebrick FBG was exposed to higher temperatures than the other bricks because it has a single directional component, indicating that the reheating event in Australia completely overprinted any prior manufacturing TRM ($_{m}$TRM) that occurred in Scotland. In addition, the noisy signal of this brick (i.e. the poor alignment of its data points; **Figure 4**) could be the result of strongly magnetic metal having been in close proximity.

This phenomenon is not evident in bricks FBW1 and FBW2. In contrast, these firebricks display two components on one side, suggesting that they were positioned further away from the heat source with only one side heated enough to reset the remanence completely. This is also reflected by a temperature gradient within the brick. The direction change occurs at higher temperatures inside the brick than on the side interpreted as having been further away from the heat source (**Figure 4**). Therefore, the high temperature directional component preserved on one side of the bricks corresponds to a previous firing event that reached a higher temperature, such as the initial fabrication firing in Scotland ($_{m}$TRM).

Interestingly, the preliminary archaeointensity experiments support this possibility with significantly lower paleointensity values associated with the $_{m}$TRM than the $_{p\text{-}m}$TRM. A geomagnetic field intensity value of ca 62 µT was obtained for the low temperature component likely acquired in the Melbourne foundry, and this value is in agreement with the geomagnetic field model 'gufm1' which is derived from compilations in mariners' logbooks (Jackson et al. 2000) (**Figure 5**). Based on this model, the geomagnetic field was approximately one-third higher in Melbourne than in Scotland in 1850, and a lower archaeointensity estimate of 39 µT was obtained for the higher temperature component, which is consistent with acquisition during firebrick manufacture in Scotland. Overall, the archaeomagnetic analysis of refractory bricks provides a wealth of information about their life history, including evidence for their fabrication overseas and subsequent use in the foundry in Melbourne during the nineteenth century.

Conclusion

The archaeomagnetic analysis of a series of nineteenth century Victorian bricks reveals insights into the

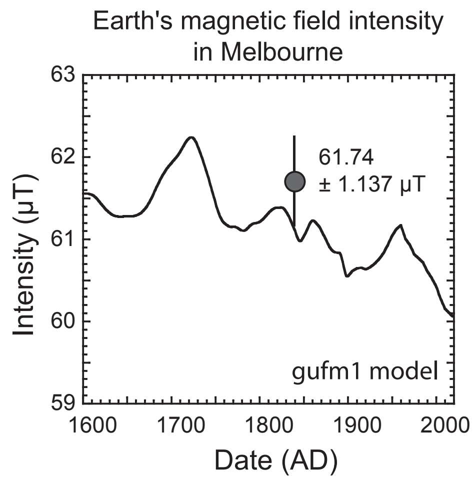

Figure 5. The archaeointensity experiment for the refractory brick 'John Grieve Bank Park Firebrick Works' (sample FBW1-A1) is in agreement with the geomagnetic field model 'gufm1' (Jackson et al. 2000) output for Melbourne

provenance, manufacture and use of these bricks, the dating of the site where they were identified, as well as related historical events such as an unintentional fire. The archaeointensity experiments provide independent support for the Scottish provenance and subsequent use of these bricks in Melbourne. These preliminary results demonstrate excellent potential for pursuing archaeomagnetic investigations of Victorian bricks to generate data for the South East Australian Archaeomagnetic Referenced Curve (SEAARC).

The secondary context of the bricks (i.e. to their heating) highlights the need to undertake in situ sampling of features to extract full-vector field data (i.e. declination, inclination and intensity), so that this information can be related to the known heating context to generate a more diagnostic picture of use history. In historical archaeology, this may include the sampling of well-dated brick or pottery kilns, fireplaces and various other features associated with high-temperature manufacture. However, in commercial archaeology, opportunities for in situ sampling are limited given the time constraints that are commonplace for excavation projects—particularly salvage excavations, where deposits and features can be destroyed for development soon after they are excavated and recorded. Thus, it is hoped that one outcome of this paper is informing a broader audience of consultant archaeologists and heritage practitioners about the application of archaeomagnetism to archaeological sites in Victoria, and about the potential to build future collaborations and plan for on-site sampling when developing timelines for excavation projects. Archaeomagnetism is a powerful, multipurpose tool available to archaeologists and historians in Victoria through The Australian Archaeomagnetism Laboratory at La Trobe University.

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References

Aitken, M.J. 1970 Dating by archaeomagnetic and thermoluminescent methods. *Philosophical Transactions of the Royal Society London. Series A, Mathematical and Physical Sciences* 269(1193):77–88.

Anderson, W., J. Scibilia, K. Oataway, H. Kiddell, and P. Kucera 2013 Harp of Erin Hotel, Burrumbeet, Victorian Heritage Inventory H7623-0324. Unpublished report prepared for John Holland Group and VicRoads.

Barbetti, M. 1977 Measurements of recent geomagnetic secular variation in southeastern Australia and the question of dipole wobble. *Earth and Planetary Science Letters* 36:207–218.

Barbetti, M. 1983 Archaeomagnetic results from Australia. In K.M. Creer, P. Tucholka and C.E. Barton (eds), *Geomagnetism of Baked Clays and Recent Sediments*, pp. 173–175. Amsterdam: Elsevier.

Barbetti, M.F. and M.W. McElhinny 1972 Evidence for a geomagnetic excursion 30 000 yr B.P. *Nature* 239:327–330.

Barbetti, M.F. and M.W. McElhinny 1976 The Lake Mungo geomagnetic excursion. *Philosophical Transactions of the Royal Society London. Series A, Mathematical and Physical Sciences* 281:515–542.

Barton, C.E. and M.W. McElhinny 1981 A 10,000 year geomagnetic secular variation record from three Australian maars. *Geophysical Journal of the Royal Astronomical Society* 67:465–485.

Barton, C.E. and M. Barbetti 1982 Geomagnetic secular variation from recent lake sediments, ancient fireplaces and historical measurements in southeastern Australia. *Earth and Planetary Science Letters* 59:375–387.

Batt, C. 2015 Archaeomagnetic dating. In W.J. Rink and J.W. Thompson (eds), *The Encyclopedia of Scientific Dating Methods*, pp. 73–79. Encyclopedia of Earth Sciences Series. Dordrecht: Springer.

Bell, P. 1998 *Early Bricks and Brickwork in South Australia*. Heritage Conservation Booklet 3.3. Adelaide: Department for Environment, Heritage and Aboriginal Affairs.

Belshé, J.C. 1961 Archaeomagnetism: An indirect study of geomagnetic secular variation. *Vistas in Astronomy* 4(1):127–142.

Birmingham, J., I. Jack and D. Jeans 1983 *Industrial Archaeology in Australia: Rural Industry*. Richmond: Heinemann.

Bowler, J.M., H. Johnston, J.M. Olley, J.R. Prescott, R.G. Roberts, W. Shawcross and N.A. Spooner 2003 New ages for human occupation and climatic change at

Lake Mungo, Australia. *Nature* 421:837–840.

Brown, K.S., C.W. Marean, A.I.R. Herries, Z. Jacobs, C. Tribolo, D. Braun, D.L. Roberts, M.C. Meyer and J. Bernatchez 2009 Fire as an engineering tool of early modern humans. *Science* 325(859):859–862.

Burnell, J.G. 1934 One hundred years of engineering in Victoria: Part II industrial development. *Journal of Institution of Engineers Australia* 6:407–412.

Cassata, W.S., B.S. Singer and J. Cassidy 2008 Laschamp and Mono Lake geomagnetic excursions recorded in New Zealand. *Earth and Planetary Science Letters* 268:76–88.

Coe, R.S. 1967 Palaeointensity of the Earth's magnetic field determined from Tertiary and Quaternary rocks. *Journal of Geophysical Research* 72:3247–3262.

Cook, R.M. and J.C Belshé 1958 Archaeomagnetism: A preliminary report from Britain. *Antiquity* 32:167–178.

Douglas, G.J., J.R. Hume, L. Moir and M.K. Oglethorpe 1985 *A Survey of Scottish Brickmarks*. Glasgow: Scottish Industrial Archaeology Survey, University of Strathclyde.

Downey, B. and D. Frankel 1992 Radiocarbon and thermoluminecence dating of a central Murray mound. *The Artefact* 15:31–35.

Goguitchaichvili, A., D. Loponte, J. Morales and A. Acosta 2012 Archaeointensity of the Earth's magnetic field retrieved from Pampean ceramics (South America). *Archaeometry* 54(2):388–400.

Gose, W.A. 2000 Palaeomagnetic studies of burned rocks. *Journal of Archaeological Science* 27:409–421.

Herries, A.I.R. 2006 Archaeomagnetic evidence for climate change at Sibudu Cave. *Southern African Humanities* 18:131–147.

Herries, A.I.R. 2009 New approaches for integrating palaeomagnetic and mineral magnetic methods to answer archaeological and geological questions on Stone Age sites. In A. Fairbairn, S. O'Conner and B. Marwick (eds), *New Directions in Archaeological Science*, pp. 235–253. Terra Australis 28. Canberra: The Australian National University Press.

Herries, A.I.R. and M. Kovacheva 2007 Using archaeomagnetism to answer archaeological questions about burnt structures at the Thracian site of Halka Bunar, Bulgaria. *Archaeologia Bulgarica* 11(2007/3):25–46.

Herries, A.I.R. and E. Fisher 2010 Multi-dimensional modelling of magnetic mineralogy as a proxy for fire use and spatial patterning: Evidence from the Middle Stone Age sea cave site of Pinnacle Point 13B (Western Cape, South Africa). *Journal of Human Evolution* 59:306–320.

Herries, A.I.R., M. Kovacheva, M. Kostadinova and J. Shaw 2007 Archaeo-directional and -intensity data from burnt structures at the Thracian site of Halka Bunar (Bulgaria): The effect of magnetic mineralogy, temperature and atmosphere of heating in antiquity. *Physics of the Earth and Planetary Interiors* 162:199–216.

Herries, A.I.R., M. Kovacheva and M. Kostadinova 2008 Mineral magnetism and archaeomagnetic dating of a mediaeval oven from Zlatna Livada, Bulgaria. *Physics and Chemistry of the Earth, Parts A/B/C* 33:496–510.

Huxtable, J. and M.J. Aitken 1977 Thermoluminescent dating of Lake Mungo geomagnetic polarity excursion. *Nature* 265:40–41.

Jackson, A., A.R.T. Jonkers and M.R. Walker 2000 Four centuries of geomagnetic secular variation from historical records. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 358:957–99.

James, K. 2007 *Muddy Water: A History of Burrumbeet*. Camberwell: Self-published.

Kovacheva, M., M. Kostadinova-Avramova, N. Jordanova, P.H. Lanos and Y. Boyadzhiev 2014 Extended and revised archaeomagnetic database and secular variation curves from Bulgaria for the last eight millennia. *Physics of the Earth and Planetary Interiors* 236:79–94.

Lawler, M., R. Monk, A.I.R. Herries, A. Lisé-Pronovost, R. Ashton, T. Terry and I. Berelov 2015 Investigations of a Holocene floodplain landscape on the Goulburn River at Yea: Preliminary results. In C. Spry, D. Frankel, S. Lawrence, I. Berelov and S. Canning (eds), *Excavations, Surveys and Heritage Management in Victoria* (Volume 4), pp. 15–24. Melbourne: La Trobe University.

Leonhardt, R., C. Heunemann and D. Krasa 2004 Analyzing absolute paleointensity determinations: Acceptance criteria and the software ThellierTool4.0. *Geochemistry, Geophysics, Geosystems* 5(12):1–11.

Mallett, T., S. Myers, S. Mirams, F. Coleman and F. Shanahan 2015 Preliminary results of excavations at Langlands Iron Foundry and Stooke's Shipping Butchers, 556–560 Flinders Street, Melbourne. In C. Spry, D. Frankel, S. Lawrence, I. Berelov and S. Canning (eds), *Excavations, Surveys and Heritage Management in Victoria* (Volume 4), pp. 85–91. Melbourne: La Trobe University.

McIntosh, G. and G. Catanzariti 2006 An introduction to archaeomagnetic dating. *Geochronometria* 25:11–18.

Mooney, S.D., C. Geiss and M.A. Smith 2003 The use of mineral magnetic parameters to characterize archaeological ochres. *Journal of Archaeological Science* 30:511–523.

Myers, S., T. Mallett and S. Mirams 2015 Langlands Iron Foundry and Stookes Shipping Butchers (H7822-1847) 556–560 Flinders Street, Melbourne: Historical Archaeology Excavation Report. Unpublished report prepared for Flinders Lodge P/L.

Riisager, P. and J. Riisager 2001 Detecting multidomain magnetic grains in Thellier palaeointensity experiments. *Physics of the Earth and Planetary Interiors* 125:111–117.

Rowney, M. and J.P White 1997 Detecting heat treatment on silcretes: Some experiments with method. *Journal of Archaeological Science* 24:649–657.

Sagnotti, L. 2013 Demagnetization Analysis in Excel (DAIE). An open source workbook in Excel for viewing and analyzing demagnetization data from paleomagnetic discrete samples and u-channels. *Annals of Geophysics* 56(1):1–9.

Singer, B.S. 2014 A Quaternary geomagnetic instability time scale. *Quaternary Geochronology* 21:29–52.

Stuart, I. 1987 A history of the Victorian brick industry: 1826–1920. *Australian Archaeology* 24:36–40.

Stuart, I. 2005 The analysis of bricks from archaeological sites in Australia. *Australasian Historical Archaeology* 23:79–88.

Tauxe, L., T.A.T. Mullender and T. Pick 1996 Pot-bellies, wasp-waists and superparamagnetism in magnetic hysteresis. *Journal of Geophysical Research* 101:571–583.

Thellier, E. and O. Thellier 1959 Sur L'intensité de champ magnétique terrestre dans le passé historique et géologique. *Annales de Geophysique* 15:285–376.

Watson, A.B. 2003 *Lost and Almost Forgotten Towns of Colonial Victoria: A Comprehensive Analysis of Census Results for Victoria 1841–1901*. Victoria: Angus B. Watson and Andrew MacMillan Art and Design.

Weickhardt, C.G.T. 1983 The first foundry. *Royal Historical Society of Victoria* 54(3):47–49.

Zijderveld, J.D.A. 1967 A.C. demagnetisation methods. In S.D. Runcorn and D.W. Collinson (eds), *Methods in Palaeomagnetism*, pp. 254–286. Amsterdam: Elsevier.