The eastern Australian magnetic inclination record: dating the recent past and re-assessing the historical geomagnetic archive

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Abstract

A new compilation of historical observations and archaeomagnetic measurements of magnetic inclination for the last 1000 years from eastern Australia (the *eastern Australian Inclination Record* [*eAIR2012*]) has revealed the existence of a well-defined inclination anomaly in the region. Evidence of this magnetic feature has been preserved in sedimentary records from across eastern Australia, though this has not previously been recognised. Analyses of additional sedimentary sequences have confirmed the incidence and timing of this feature, revealing its presence between the 13th and 18th centuries AD. The inclination of the field during this episode appears to have been steeper than at any time since the start of the Holocene. Lake sediment evidence suggests that the anomaly is a composite feature, displaying a distinct peak at cal AD 1270–1386 (±2 *s* uncertainty), reappearing after cal AD 1431–1651 (±2 *s* uncertainty) and disappearing before AD 1822±46 (±2 *s* uncertainty). The disappearance of the anomaly is tightly bracketed in the historical record between AD 1770 and 1777. The rapid shift in inclination during the 18th century AD offers considerable potential as a means of dating a critical period of Australian environmental history, an episode that currently lies beyond the reach of established dating methods. This information also provides a valuable constraint on models of regional geomagnetic field change over centennial and millennial timescales.

Our examination of the historical record has revealed that the inclination measurements made by the 18th century French explorer La Pérouse are consistently erroneous. Since La Pérouse's data make up 13% of the total body of pre-19th century inclination records, the inclusion of these measurements in global compendia of magnetic observations may seriously skew attempts to model the geomagnetic field. We advocate that La Pérouse's inclination measurements should therefore be employed only with considerable caution.

Keywords

Australia, La Pérouse, recent past, Holocene, dating, magnetic inclination, geomagnetic field, palaeomagnetic secular variation, lake sediment magnetisation

Introduction and aims

The capacity to date deposits laid down over the last few centuries is of especial importance in those locations where documentary records of environmental events are absent and where environmental historians must rely on indirect means of reconstructing chronologies. Such is the case in Australia, where written records of all but the most prosaic information are rare until the middle years of the 19th century and almost non-existent before official colonisation in AD 1788. Unfortunately, with the exception of $^{230}Th/^{234}U$ methods, whose use is restricted to rather specific depositional environments, there is no established geochronometric tool capable of dating more than a fraction of this most recent part of the geological timescale at a resolution adequate to tackle the environmental issues of this period (Gale, 2009).

An alternative approach to dating the recent past, and one that has not so far been widely exploited, involves matching the palaeomagnetic secular variation signatures of recent sedimentary sequences with historically documented geomagnetic field fluctuations (Mackereth, 1971: 337; Turner and Thompson, 1981: 708). Because of the presence of non-dipolar components in the Earth's magnetic field, patterns of secular variation vary from place to place over the Earth's surface. If palaeosecular changes are to be generally used as a dating tool, therefore, detailed regional records of palaeomagnetism are required. The aim of the work reported here is thus to establish a well-dated and continuous record of palaeosecular change that may be used in the palaeomagnetic dating of last millennial stratigraphic sequences in Australia. This episode is of particular importance because it encompasses the period preceding and immediately succeeding the point of European contact, when the continent experienced one of the greatest environmental impacts of all time. In addressing this issue, we have focussed on the pattern of inclination, as palaeomagnetic records from Australian lakes suggest that inclination variations are of higher amplitude and frequency, and display clearer turning points, than variations in declination (Barton and McElhinny, 1981: 479). They are thus better suited for the identification of dated magnetostratigraphic features.

The few depositional records of secular magnetic change from the Australian continent (Barbetti, 1977, 1983; Barton and Polach, 1980; Barton and McElhinny, 1981; Barton and Barbetti, 1982; Barton, 1983; Constable and McElhinny, 1985; Scherrer *et al.*, 1998; Anker *et al.*, 2001; Fischer, 2001; Dorrington, 2008) provide little or no directly-dated information on shifts in magnetic inclination over the last millennium. We have therefore turned to historical and archaeomagnetic data to compile a high-resolution, region-wide record of recent magnetic change.

Methods

We exploited geomagnetic data from two sources. For the period AD 1770 to 2009, we compiled historical observations of magnetic inclination (n = 368). The data from the 18th and 19th centuries were largely assembled from the observations of mariners, whilst the data from the beginning of the 20th century onwards were derived mainly from historical observatory records and from measurements made at other terrestrial locations. The sites selected for inclusion lie between 142° and 160° E and between 33° and 45° S. Earlier compendia of magnetic measurements (Hansteen, 1819; Jonkers *et al.*, 2003) provided the starting point for our compilation. However, after checking their data against the primary records, we chose to use the original sources. By doing this we eliminated errors that have been propagated through previous compilations. We also added numerous historical observations to those listed by previous researchers. Our compilation therefore augments and improves those of earlier workers.

To extend the data set further back in time, we assembled all available records of the magnetic inclination of baked sediments dating from the last millennium in the region. These were obtained from archaeomagnetic measurements of sediments associated with burnt tree-stumps and Aboriginal ovens and fireplaces in southeast Australia (n = 12) (Barbetti, 1977, 1983; Barton and Barbetti, 1982). The archaeomagnetic record has been entirely recalculated using every measurement and date in the published data set, along with data from two sites for which only plotted information is available. All these features have been dated by ^{14}C methods (Barbetti and Polach, 1973; Barbetti, 1983).

A review of the data set showed considerable scatter, particularly in the records from the 1840s and the 1870s. Inspection revealed that the bulk of the observations made in these periods had been undertaken at sea. These recordings are likely to have been compromised by the often-unstable nature of the measurement platform, by the coupling of the oscillations induced in the dip needle by the vessel's motion and those induced by the magnetic field itself, by the unavoidable presence of ferrous materials onboard ship and by the difficulties in fixing the ship's position. In order to improve the quality of the record, all onboard measurements were therefore excluded from the data set. This had no significant effect on the overall pattern of changes in magnetic inclination, but dramatically reduced the scatter of values.

An inclination record of –60°50′05″ made by James Clark Ross (1847: 47) in the period 21 July–28 July 1841 at Garden Island in Sydney differs significantly from seven other observations made during the same period and at the same site during the course of this expedition (Table 1). Given the existence of a considerable number of concordant observations from this site at this time and the unlikelihood of Ross's highly anomalous observation representing the product of short-term fluctuations of the magnetic field, we have removed his record from our data set.

Table 1 Measurements of magnetic inclination made at Garden Island, Sydney in the period 14 July–5 August 1841 by James Clark Ross's Antarctic expedition in the vessels HMS *Erebus* and HMS *Terror*.

Date	Inclination	Source and vessel
14 July–3 August 1841	–62°47′	Sabine (1844: 152) HMS *Erebus*
15 July 1841	–62°52′	Sabine (1844: 196–197, 1868: 399) HMS *Erebus*
15 July–4 August 1841	–62°48′	Sabine (1844: 153) HMS *Erebus*
19 July 1841	–62°59′	Sabine (1844: 170) HMS *Terror*
19 July 1841	–62°57′	Sabine (1844: 204–205, 1868: 399) HMS *Terror*
20 July 1841	–62°49′06″	Sabine (1844: 100, 104) HMS *Erebus* and HMS *Terror*
21 July–28 July 1841	–60°50′05″	Ross (1847: 47) HMS *Erebus* and HMS *Terror*
30 July–5 August 1841	–62°52′	Sabine (1844: 170) HMS *Terror*

The problem with La Pérouse

The earliest observation of magnetic inclination in Australia was made on 1 May 1770 by James Cook, who recorded a dip of –67°01′ at Botany Bay, 16 km south of Sydney (Green and Cook, 1771: 420). Cook's measurement was replicated on 22 January 1788 by the French explorer, Jean-François Galaup de La Pérouse, who reported an inclination of –56°32′00″ less than 250 km offshore of Botany Bay along the same line of latitude (Milet-Mureau, 1797a: 350–351).

The difference of more than 10° between La Pérouse's observation and that of Cook may be the result of operator error. It is also possible that the records reflect a rapid shift in field direction. On the other hand, this is not the only instance of disagreement between the inclination measurements of La Pérouse and those of other explorers from this period. We may consider, for example, the series of observations made in the Sandwich Islands (Hawaiian Islands) by Cook, La Pérouse and George Vancouver between AD 1778 and 1793 (Table 2). Given the close proximity of the measurement sites and the relatively short time span over which recordings were made, these readings might have been anticipated to have been quite similar. Yet, as was the case at Botany Bay, La Pérouse's measurements are much shallower than those of the other observers. Furthermore, the readings of 20°, 28° and 34°, made by La Pérouse over a period of only four days, display a large and worrying variability.

The two inclinometers employed by La Pérouse had been supplied to the expedition by Joseph Banks, the President of the Royal Society. These were the instruments that had been used on Cook's last voyage and were accepted by La Pérouse with, as he put it, feelings of religious respect (Milet-Mureau, 1797b: 247, 1797c: 8). Just over a month after leaving France, La Pérouse took the opportunity of a stop in Tenerife to test the inclinometers:

... nous trouvâmes très-peu d'accord dans les résultats, et nous ne les rapportons que pour prouver combien cette espèce d'instrument est encore éloignée du point de perfection nécessaire pour mériter la confiance des observateurs. [... we discovered very little consistency in the results, and we shall report them only to show how little this instrument has reached the level of perfection necessary to gain the confidence of observers.] (Milet-Mureau, 1797c: 17–18).

Table 2 Measurements of magnetic inclination made in the Sandwich Islands (Hawaiian Islands) between AD 1778 and 1793. The latitudes and longitudes of the measurement sites are those given in the original records. Longitude is expressed with reference to the Greenwich Meridian.

Date	Location	Latitude	Longitude	Inclination	Expedition leader and vessel	Source
15 January 1778	off Kauai	19°00′ N	159°20′ W	39°49′	Cook: HMS *Discovery*	Cooke *et al.* (1782: 304)
18 January 1778	off Kauai	21°17′30″ N	159°12′ W	42°01′07″	Cook: HMS *Resolution*	Cooke *et al.* (1782: 220)
18 January 1778	off Kauai	21°46′ N	159°30′ W	42°36′30″	Cook: HMS *Discovery*	Cooke *et al.* (1782: 304)
28 January 1778	off Kauai	21°21′ N	160°00′ W	42°10′54″	Cook: HMS *Resolution*	Cooke *et al.* (1782: 220)
31 January 1778	off Niihau	21°47′ N	160°05′ W	42°04′30″	Cook: HMS *Discovery*	Cooke *et al.* (1782: 304)
31 January 1778	off Niihau	21°47′ N	160°05′ W	41°54′	Cook: HMS *Discovery*	Cooke *et al.* (1782: 304)
12 January 1779	off Hawaii	18°35′45″ N	155°45′ W	38°30′00″	Cook: HMS *Resolution*	Cooke *et al.* (1782: 221)
25 January 1779	Kealakekua Bay, Hawaii	19°28′ N	156°30′ W	40°22′30″	Cook: HMS *Resolution*	Cooke *et al.* (1782: 221)
25 January 1779	Kealakekua Bay, Hawaii	19°28′ N	156°30′ W	40°41′15″	Cook: HMS *Resolution*	Cooke *et al.* (1782: 221)
3 February 1779	Kealakekua Bay, Hawaii	19°29′ N[1]	155°56′ W[1]	41°50′00″	Cook: HMS *Resolution*	Cooke *et al.* (1782: 221)
3 February 1779	Kealakekua Bay, Hawaii	19°29′ N[1]	155°56′ W[1]	40°30′45″	Cook: HMS *Resolution*	Cooke *et al.* (1782: 221)
6 March 1779	Kauai	21°56′45″ N	159°44′ W	43°11′15″	Cook: HMS *Resolution*	Cooke *et al.* (1782: 222)
29 May 1786	between the islands of Maui and Kahoolawe	20°34′30″ N	156°04′46″ W	28°00′00″	La Pérouse: *La Boussole*	Milet-Mureau (1797a: 288–289)
31 May 1786	off the west coast of Molokai	21°14′36″ N	157°20′46″ W	20°00′00″	La Pérouse: *La Boussole*	Milet-Mureau (1797a: 290–291)
1 June 1786	north of Oahu	22°52′50″ N	158°00′46″ W	34°00′00″	La Pérouse: *La Boussole*	Milet-Mureau (1797a: 290–291)
22 February–9 March 1793	Kealakekua Bay, Hawaii	19°28′12″ N	156°02′06″ W	41°24′	Vancouver: HMS *Discovery*	Vancouver (1798: 169–171)

[1]Latitude and longitude taken from the location of HMS *Resolution* (Beaglehole, 1967: Fig. 14).

La Pérouse suggested that the iron content of the soils on the island (Tenerife is largely composed of basaltic lavas) had contributed to the ‘énormes différences’ between the inclination readings (Milat-Mureau, 1797c: 18), although this seems an unlikely explanation assuming that measurements were made using both instruments at the same sites. In any case, differences of up to 30° between the instruments persisted. Evidence of this comes from a comparison of the measurements of inclination made on the two vessels that constituted La Pérouse's squadron, *La Boussole* and *L'Astrolabe*. It seems reasonable to assume that each craft carried one of the inclinometers loaned to the expedition by Joseph Banks. This being the case, Figure 1 shows the records of inclination for all those days on which measurements were made on both vessels. Although we do not know whether the readings were made concurrently nor do we know how far apart the vessels were on each day, we should anticipate similar results from the two instruments on each occasion. Instead, the data reveal a series of systematic discrepancies between the two sets of measurements. Between September 1785 and January 1786, the measurements made on *L'Astrolabe* were of the order of 10° shallower than those made on *La Boussole*, whilst from April to May 1786, the difference increased to around 25–30°. The final replicate measurement, taken on 25 October 1786, shows *L'Astrolabe*'s reading to be 7° steeper than that of *La Boussole*. This discrepancy did not exist when the same instruments were used during Cook's last voyage (see, for example, the consistent readings from the *Resolution* and the *Discovery* shown in Tables 2 and 3). It is unclear which of the two instruments was giving the incorrect readings (or whether both sets of readings were in error). Nor is it possible to determine whether the step change in the discrepancies in early AD 1786 represents operator error or damage to one of the instruments. However, the fact that the anomalously shallow readings at Botany Bay and Maui were both made with the inclinometer from *La Boussole* (Milet-Mureau, 1797a: 350–351) and that this instrument appears to have consistently yielded steeper measurements than its twin on *L'Astrolabe* might suggest that the readings made using both instruments were in error.

Given the general unreliability of his inclination measurements, we have removed the record of magnetic inclination made in eastern Australia by La Pérouse from our data set. Further support for this step comes from the four inclination readings made by Cook in Tasmania in January 1777 (Cooke *et al.*, 1782: 219, 304) and the six measurements of inclination made in Tasmania in 1792–1793 by Rossel (1808a: 76–77, 247–248, 1808b: 320, 322, 479–480) (Table 3). These observations closely bracket the date of La Pérouse's measurement. After reduction to the latitude of

Sydney (Aitken and Weaver, 1965), it is clear that the Tasmanian readings differ markedly from that of La Pérouse (Table 3). Although this difference may be the result of rapid, short-term variations in field direction, when coupled with the other evidence assembled here, it adds weight to the argument concerning the untrustworthiness of La Pérouse’s measurements.

Table 3 Measurements of magnetic inclination made in southeast Australia between AD 1777 and 1793. The latitudes and longitudes of the measurement sites are those given in the original records. Longitude is expressed with reference to the Greenwich Meridian. The inclination values have been reduced to the latitude of Botany Bay, Sydney, New South Wales (34°00′10″ S) on the assumption of an axial dipole field (Aitken and Weaver, 1965).

Date	Location	Latitude	Longitude	Inclination	Inclination reduced to the latitude of Botany Bay, Sydney	Expedition leader and vessel	Source
22 January 1777	offshore of southeast Tasmania	43°41′ S	147°20′ E	–71°00′00″	–62°05′	Cook: HMS *Discovery*	Cooke *et al.* (1782: 304)
27 January 1777	Adventure Bay, Tasmania	43°21′ S	147°33′ E	–70°55′20″	–62°17′	Cook: HMS *Discovery*	Cooke *et al.* (1782: 304)
28 January 1777	Adventure Bay, Tasmania	43°22′20″ S	147°28′ E	–70°15′37″	–61°36′	Cook: HMS *Resolution*	Cooke *et al.* (1782: 219)
29 January 1777	Adventure Bay, Tasmania	43°21′ S	147°33′ E	–71°00′40″	–62°22′	Cook: HMS *Discovery*	Cooke *et al.* (1782: 304)
22 January 1788	offshore of Sydney, New South Wales	34°08′33″ S	153°45′29″ E	–56°32′00″	–56°23′	La Pérouse: *La Boussole*	Milet-Mureau (1797a: 350–351)
23 April–28 May 1792	Pigsties Bay (Port du Nord), Tasmania	43°32′17″ S	146°56′47″ E	–70°50′	–62°02′	d’Entrecasteaux: *La Recherche* and *L’Espérance*	Rossel (1808a: 76–77)
11 May 1792	Pigsties Bay (Port du Nord), Tasmania	43°32′17″ S	146°56′47″ E	–70°50′	–62°02′	d’Entrecasteaux: *La Recherche* and *L’Espérance*	Rossel (1808a: 248, 1808b: 320, 322)
21 January–13 February 1793	Rocky Bay (Port du Sud), Tasmania	43°34′30″ S	146°57′08″ E	–71°01′	–62°12′	d’Entrecasteaux: *L’Espérance*	Rossel (1808a: 247–248)
21 January–13 February 1793	Rocky Bay (Port du Sud), Tasmania	43°34′30″ S	146°57′08″ E	–72°20′	–63°31′	d’Entrecasteaux: *La Recherche*	Rossel (1808a: 247–248)
7 February 1793	Rocky Bay (Port du Sud), Tasmania	43°34′30″ S	146°57′08″ E	–72°22′	–63°33′	d’Entrecasteaux: *La Recherche* and *L’Espérance*	Rossel (1808a, 248, 1808b, 479–480)
7 February 1793	Rocky Bay (Port du Sud), Tasmania	43°34′30″ S	146°57′08″ E	–70°48′	–61°59′	d’Entrecasteaux: *La Recherche* and *L’Espérance*	Rossel (1808a: 248, 1808b: 480)

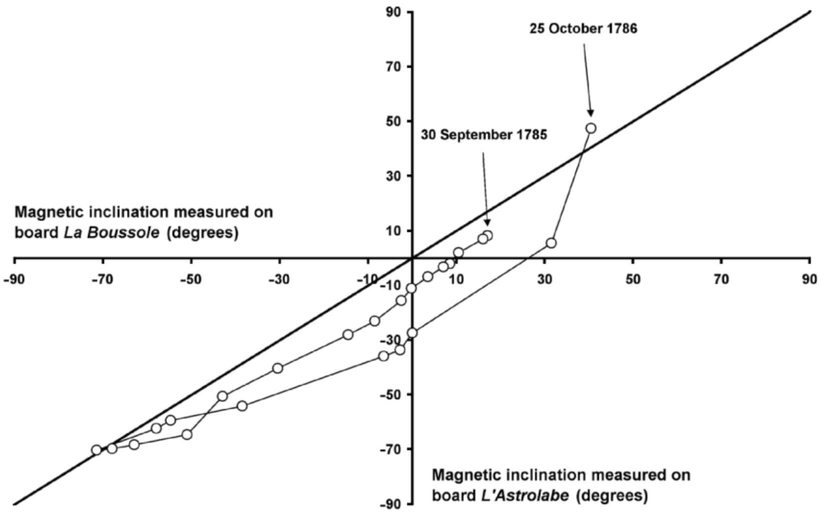

Figure 1 A comparison of the measurements of the inclination of the Earth's magnetic field made onboard *L'Astrolabe* with those made onboard *La Boussole* during La Pérouse's voyage. The records are in chronological order from 30 September 1785 to 25 October 1786 and represent all those days on which inclination was measured on both vessels. Source of data: Milet-Mureau (1797a).

We should point out that discrepancies between the records of La Pérouse and those of other late 18th century observers were noted 200 years ago by the Norwegian astronomer and physicist, Christopher Hansteen (1819, Appendix: 148). However, Hansteen's observation, tucked away as an end note to an appendix, appears to have been overlooked for almost two centuries. Moreover, Hansteen offered no explanation for the difference, which he regarded as an 'insoluble riddle' [unauflöſsliches Räthsel]. This oversight may have had significant implications, for La Pérouse's data, which make up 13% of the total body of pre-19th century inclination records (Jonkers *et al.*, 2003), have repeatedly been employed in efforts to model historical field variations.

The final data set, including the archaeomagnetic records, is given in Table 4. This compilation, excluding all measurements made whilst at sea and excluding the anomalous observations of La Pérouse and Ross, is plotted in Figure 2. This constitutes the *eastern Australian Inclination Record* (*eAIR2012*).

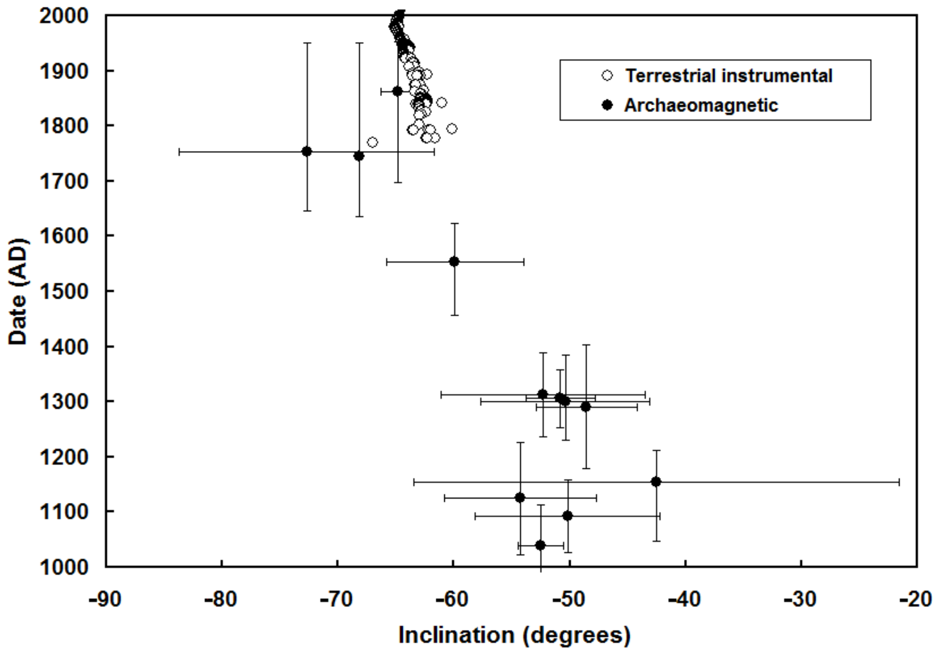

Figure 2 The *eastern Australian Inclination Record* (*eAIR2012*). This is based on terrestrial observations of magnetic inclination made since AD 1770 and archaeomagnetic measurements of sites dating from the last millennium. The inclination values have been reduced to the latitude of Botany Bay, Sydney, New South Wales (34°00′10″ S) on the assumption of an axial dipole field (Aitken and Weaver, 1965). Botany Bay lies 16 km south of the city of Sydney and is the site of the first instrumental measurement of magnetic inclination in Australia. The entire data set, including information on data sources and uncertainties, is given in Table 4.

Table 4 Records of magnetic inclination in eastern Australia between *c.* AD 1000 and AD 2009. These are derived from historical observations of inclination made since AD 1770 and from the archaeomagnetic measurements of Barbetti (1977, 1983) and Barton and Barbetti (1982). The archaeomagnetic record has been entirely recalculated using every measurement and date in the published data set, along with data from two sites for which only plotted information is available. The inclination values have been reduced to the latitude of Botany Bay, Sydney, New South Wales (34°00′10″ S) on the assumption of an axial dipole field (Aitken and Weaver, 1965). Botany Bay lies 16 km south of the city of Sydney and is the site of the first instrumental measurement of magnetic inclination in Australia. The inclination records are expressed with an uncertainty of ±1 *s* based on repeated archaeomagnetic measurements and, where available, on repeated instrumental measurements of inclination. The absence of a record of uncertainty should not be taken to imply that the observation was error free, but that only a single value was reported. Radiocarbon ages are calibrated to calendar years using the CALIB 6.0 Radiocarbon Calibration Program of M. Stuiver, P.J. Reimer and R. Reimer, employing the SHCal04 data set of McCormac *et al.* (2004). Following the recommendations of Telford *et al.* (2004), the central estimates of the ^{14}C dates represent the medians of each calibrated range. Dates are expressed with an uncertainty of ±1 *s*. The ranges of the ^{14}C dates are determined from the complete 1 *s* range of the calibrated values. The absence of a record of uncertainty means that the timing of the observation is known to the day or better.

Mean date (AD)[1]	Date standard deviation (a)	Radiocarbon age (BP ±1 s)	Inclination reduced to the latitude of Botany Bay (°)	Inclination circular standard deviation (°)	Terrestrial (T), marine (M) or archaeo-magnetic (A) data	Source of data
2009.50	0.29		–64.56		T	British Geological Survey
2008.50	0.29		–64.58		T	British Geological Survey
2007.50	0.29		–64.59		T	British Geological Survey
2006.50	0.29		–64.61		T	British Geological Survey
2005.50	0.29		–64.63		T	British Geological Survey
2004.50	0.29		–64.65		T	British Geological Survey
2003.50	0.29		–64.67		T	British Geological Survey
2002.50	0.29		–64.67		T	British Geological Survey
2001.50	0.29		–64.69		T	British Geological Survey
2000.50	0.29		–64.71		T	British Geological Survey

1999.50	0.29	–64.73	T	British Geological Survey
1998.50	0.29	–64.75	T	British Geological Survey
1997.50	0.29	–64.77	T	British Geological Survey
1996.50	0.29	–64.79	T	British Geological Survey
1995.50	0.29	–64.82	T	British Geological Survey
1994.50	0.29	–64.85	T	British Geological Survey
1993.50	0.29	–64.86	T	British Geological Survey
1992.50	0.29	–64.88	T	British Geological Survey
1991.50	0.29	–64.90	T	British Geological Survey
1990.50	0.29	–64.89	T	British Geological Survey
1989.50	0.29	–64.90	T	British Geological Survey
1988.50	0.29	–64.88	T	British Geological Survey
1987.50	0.29	–64.87	T	British Geological Survey
1986.50	0.29	–64.87	T	British Geological Survey
1985.50	0.29	–64.86	T	British Geological Survey
1984.50	0.29	–64.86	T	British Geological Survey
1983.50	0.29	–64.85	T	British Geological Survey
1982.50	0.29	–64.85	T	British Geological Survey
1981.50	0.29	–64.82	T	British Geological Survey
1980.50	0.29	–64.78	T	British Geological Survey
1979.50	0.29	–64.76	T	British Geological Survey
1979.20		–65.11	T	British Geological Survey
1978.50	0.29	–65.08	T	British Geological Survey
1977.50	0.29	–65.04	T	British Geological Survey
1976.50	0.29	–65.01	T	British Geological Survey
1975.50	0.29	–64.99	T	British Geological Survey
1974.50	0.29	–64.96	T	British Geological Survey
1973.50	0.29	–64.93	T	British Geological Survey
1972.50	0.29	–64.90	T	British Geological Survey
1971.50	0.29	–64.87	T	British Geological Survey
1970.50	0.29	–64.85	T	British Geological Survey
1969.50	0.29	–64.83	T	British Geological Survey
1968.50	0.29	–64.80	T	British Geological Survey
1967.50	0.29	–64.78	T	British Geological Survey
1966.50	0.29	–64.74	T	British Geological Survey
1965.50	0.29	–64.72	T	British Geological Survey
1964.50	0.29	–64.70	T	British Geological Survey
1963.50	0.29	–64.68	T	British Geological Survey
1962.50	0.29	–64.66	T	British Geological Survey
1961.50	0.29	–64.64	T	British Geological Survey
1960.50	0.29	–64.62	T	British Geological Survey
1959.50	0.29	–64.60	T	British Geological Survey
1958.50	0.29	–64.59	T	British Geological Survey
1957.50		–64.28	T	British Geological Survey
1957.50	0.29	–64.57	T	British Geological Survey
1956.50	0.29	–64.56	T	British Geological Survey
1955.50	0.29	–64.54	T	British Geological Survey
1954.50	0.29	–64.53	T	British Geological Survey
1953.50	0.29	–64.52	T	British Geological Survey
1952.50	0.29	–64.51	T	British Geological Survey
1951.50	0.29	–64.49	T	British Geological Survey
1950.50	0.29	–64.46	T	British Geological Survey
1949.50	0.29	–64.43	T	British Geological Survey
1948.50	0.29	–64.42	T	British Geological Survey
1947.50	0.29	–64.40	T	British Geological Survey
1947.02		–64.04	T	British Geological Survey
1947.02		–64.03	T	British Geological Survey
1946.50	0.29	–64.40	T	British Geological Survey
1945.93		–64.01	T	British Geological Survey
1945.91		–63.97	T	British Geological Survey
1945.50	0.29	–64.37	T	British Geological Survey
1944.50	0.29	–64.36	T	British Geological Survey
1944.21		–63.92	T	Wallis and Green (1947: 106)
1944.21		–63.92	T	Wallis and Green (1947: 106)
1944.21		–63.92	T	British Geological Survey

1944.19		–63.98	T	British Geological Survey
1944.19		–63.98	T	Wallis and Green (1947: 107)
1944.18		–63.96	T	British Geological Survey
1944.17		–63.95	T	Wallis and Green (1947: 106)
1944.17		–63.96	T	Wallis and Green (1947: 106)
1943.50	0.29	–64.36	T	British Geological Survey
1943.44		–63.95	T	Wallis and Green (1947: 106)
1943.44		–63.96	T	Wallis and Green (1947: 106)
1943.44		–63.96	T	British Geological Survey
1943.44		–63.84	T	Wallis and Green (1947: 105)
1943.44		–63.87	T	Wallis and Green (1947: 105)
1943.43		–63.92	T	Wallis and Green (1947: 105)
1943.39		–63.91	T	British Geological Survey
1943.39		–63.91	T	Wallis and Green (1947: 105)
1943.35		–63.74	T	British Geological Survey
1943.30		–63.90	T	British Geological Survey
1943.30		–64.31	T	Wallis and Green (1947: 105)
1943.26		–64.03	T	British Geological Survey
1943.25		–64.02	T	Wallis and Green (1947: 106)
1943.07		–63.95	T	Wallis and Green (1947: 106)
1943.07		–63.95	T	British Geological Survey
1942.50	0.29	–64.36	T	British Geological Survey
1942.07		–63.93	T	Wallis and Green (1947: 106)
1942.07		–63.94	T	British Geological Survey
1941.50		–63.93	T	British Geological Survey
1941.50	0.29	–64.38	T	British Geological Survey
1941.50		–63.93	T	Wallis and Green (1947: 106)
1940.50	0.29	–64.34	T	British Geological Survey
1940.26		–64.08	T	British Geological Survey
1940.25		–64.07	T	Wallis and Green (1947: 106)
1940.01		–63.97	T	Wallis and Green (1947: 106)
1940.01		–63.97	T	Wallis and Green (1947: 106)
1940.01		–63.97	T	British Geological Survey
1939.50	0.29	–64.34	T	British Geological Survey
1939.33		–63.95	T	British Geological Survey
1939.33		–63.95	T	Wallis and Green (1947: 106)
1938.50	0.29	–64.35	T	British Geological Survey
1938.05		–64.00	T	Wallis and Green (1947: 106)
1938.05		–63.98	T	Wallis and Green (1947: 106)
1938.05		–64.01	T	Wallis and Green (1947: 106)
1938.05		–63.97	T	Wallis and Green (1947: 106)
1938.05		–63.98	T	Wallis and Green (1947: 106)
1938.05		–63.96	T	Wallis and Green (1947: 106)
1938.05		–63.99	T	British Geological Survey
1937.66		–63.93	T	British Geological Survey
1937.65		–63.92	T	Wallis and Green (1947: 106)
1937.65		–63.92	T	Wallis and Green (1947: 106)
1937.50	0.29	–64.33	T	British Geological Survey
1937.17		–63.96	T	British Geological Survey
1937.17		–63.98	T	British Geological Survey
1937.17		–63.96	T	Wallis and Green (1947: 105)
1937.17		–63.96	T	Wallis and Green (1947: 105)
1937.17		–63.98	T	Wallis and Green (1947: 106)
1937.17		–63.97	T	Wallis and Green (1947: 106)
1936.50	0.29	–64.32	T	British Geological Survey
1936.34		–63.87	T	Wallis and Green (1947: 105)
1936.34		–63.87	T	Wallis and Green (1947: 105)
1936.34		–63.87	T	British Geological Survey
1935.50	0.29	–64.32	T	British Geological Survey
1934.50	0.29	–64.33	T	British Geological Survey
1933.50	0.29	–64.34	T	British Geological Survey
1932.50	0.29	–64.36	T	British Geological Survey
1931.50	0.29	–64.36	T	British Geological Survey
1930.50	0.29	–64.37	T	British Geological Survey
1929.50	0.29	–64.35	T	British Geological Survey

1928.50	0.29	–64.33	T	British Geological Survey
1927.50	0.29	–64.31	T	British Geological Survey
1926.50	0.29	–64.29	T	British Geological Survey
1925.50	0.29	–64.25	T	British Geological Survey
1924.50	0.29	–64.22	T	British Geological Survey
1923.50	0.29	–64.19	T	British Geological Survey
1923.48		–63.81	T	British Geological Survey
1922.85		–63.75	T	British Geological Survey
1922.50	0.29	–64.17	T	British Geological Survey
1921.81		–63.66	T	Fisk and Sverdrup (1927: 55)
1916.40		–63.57	T	Bauer *et al.* (1921: 62)
1916.06		–63.55	T	Bauer *et al.* (1921: 62)
1916.06		–63.54	T	Bauer *et al.* (1921: 62)
1916.06		–63.60	T	Bauer *et al.* (1921: 62)
1916.06		–63.57	T	Bauer *et al.* (1921: 62)
1916.05		–63.57	T	Bauer *et al.* (1921: 62)
1916.05		–63.57	T	Bauer *et al.* (1921: 62)
1916.05		–63.56	T	Bauer *et al.* (1921: 62)
1916.05		–63.58	T	Bauer *et al.* (1921: 62)
1916.05		–63.59	T	Bauer *et al.* (1921: 62)
1916.05		–63.56	T	Bauer *et al.* (1921: 62)
1915.03		–63.53	T	Bauer *et al.* (1921: 62)
1913.30		–63.39	T	Bauer and Fleming (1915: 39)
1913.24		–63.43	T	Bauer and Fleming (1915: 40)
1913.17		–63.47	T	Bauer and Fleming (1915: 40)
1913.17		–63.47	T	British Geological Survey
1906.90		–63.35	T	Bauer (1912: 75)
1906.90		–63.82	T	Bauer (1912: 75)
1906.90		–63.85	T	Bauer (1912: 75)
1906.89		–63.85	T	Bauer (1912: 75)
1897.36		–62.94	T	Anon. (1901: 13)
1897.36		–62.97	T	Anon. (1901: 13)
1897.34		–63.02	T	Anon. (1901: 13)
1897.34		–63.01	T	Anon. (1901: 13)
1897.02		–63.05	T	Anon. (1901: 13)
1897.02		–63.01	T	Anon. (1901: 13)
1896.35		–62.98	T	Anon. (1901: 12)
1896.35		–63.02	T	Anon. (1901: 12)
1896.35		–63.01	T	Anon. (1901: 12)
1896.00		–63.56	T	Baracchi (1896: 194)
1896.00		–63.56	T	Baracchi (1896: 194)
1892.10		–62.26	T	British Geological Survey
1891.50	0.29	–63.45	T	Creak (1896: 347)
1891.21		–63.47	T	Creak (1896: 364)
1891.21		–63.49	T	Creak (1896: 364)
1891.21		–63.49	T	Creak (1896: 364)
1891.21		–63.47	T	Creak (1896: 364)
1891.21		–63.49	T	Creak (1896: 364)
1891.21		–63.52	T	Creak (1896: 364)
1891.21		–63.48	T	Creak (1896: 364)
1891.21		–63.52	T	Creak (1896: 364)
1891.16		–62.90	T	Creak (1896: 364)
1891.16		–62.91	T	Creak (1896: 364)
1891.15		–62.90	T	Creak (1896: 364)
1891.15		–62.91	T	Creak (1896: 364)
1891.15		–62.89	T	Creak (1896: 364)
1891.15		–62.89	T	Creak (1896: 364)
1890.87		–63.06	T	Courmes (1892: 328–329)
1890.86		–63.17	T	Courmes (1892: 328–329)
1890.85		–63.17	T	Courmes (1892: 328–329)
1874.47		–61.57	M	Thomson and Murray (1882: 32)
1874.46		–63.22	M	Thomson and Murray (1882: 32)
1874.46		–62.74	M	Thomson and Murray (1882: 32)
1874.45		–64.20	M	Thomson and Murray (1882: 32)
1874.45		–63.84	M	Thomson and Murray (1882: 32)

1874.38			–62.90		T	Thomson and Murray (1882: 32, 48)
1874.30			–62.95		T	Thomson and Murray (1882: 48, 63)
1874.29			–62.86		T	Thomson and Murray (1882: 48, 63)
1874.29			–62.89		T	Thomson and Murray (1882: 48, 63)
1874.26			–64.41		M	Thomson and Murray (1882: 32)
1874.26			–62.86		M	Thomson and Murray (1882: 32)
1874.25			–64.03		M	Thomson and Murray (1882: 32)
1874.25			–64.18		M	Thomson and Murray (1882: 31)
1874.25			–64.13		M	Thomson and Murray (1882: 32)
1874.23			–63.33		T	Thomson and Murray (1882: 31, 48)
1874.22			–63.37		T	Thomson and Murray (1882: 48, 61)
1874.22			–63.30		T	Thomson and Murray (1882: 48, 61)
1874.22			–63.32		T	Thomson and Murray (1882: 48, 61)
1874.21			–64.07		M	Thomson and Murray (1882: 31)
1864.29	0.01		–62.59		T	Neumayer (1869: 199)
1863	+90/–165	106±68	–64.80	1.55	A	Barbetti and Polach (1973), Barbetti (1977)
1861.51	1.49		–63.40		T	Neumayer (1869:199)
1858.93			–62.81		T	von Wüllerstorf-Urbair (1862–1865: 105)
1858.92			–62.84		T	von Wüllerstorf-Urbair (1862–1865: 105)
1852.50	0.29		–62.87		T	Sabine (1877: 497)
1850.50	0.30		–62.35	0.03	T	Sabine (1852: 511–517)
1850.22	0.07		–62.89		T	Dayman (1852)
1849.50	0.30		–62.39	0.04	T	Sabine (1852: 511–517)
1849.20	0.02		–62.88		T	Dayman (1852)
1848.50	0.30		–62.36	0.06	T	Sabine (1850: lxxiii)
1848.29	0.02		–62.87		T	Dayman (1852)
1847.66	0.07		–62.92		T	Dayman (1852)
1847.50	0.30		–62.34	0.09	T	Sabine (1850: lxxiii)
1847.25			–63.82		M	Thomson and Murray (1882: 32)
1846.50	0.30		–62.31	0.05	T	Sabine (1850: lxxiii)
1845.87	0.02		–62.66		T	Jukes (1847: 272)
1845.50	0.30		–62.30	0.06	T	Sabine (1850: lxxiii)
1844.96			–61.88		M	Sabine (1846: 426)
1844.96			–61.25		M	Sabine (1846: 426)
1844.96			–61.78		M	Sabine (1846: 426)
1844.93			–62.43		T	Sabine (1846: 426)
1844.50	0.30		–62.32	0.05	T	Sabine (1850: lxxiii)
1844.12	0.02		–62.89		T	Jukes (1847: 272)
1843.50	0.30		–62.40	0.05	T	Sabine (1850: lxxiii)
1842.87	0.02		–62.76		T	Jukes (1847: 272)
1842.50	0.30		–62.47	0.03	T	Sabine (1850: lxxiii)
1841.60			–62.27		M	Sabine (1844: 153)
1841.60			–61.84		M	Sabine (1844: 170)
1841.60			–62.59		M	Sabine (1844: 196–197, 1868: 399)
1841.60			–62.12		M	Sabine (1844: 204–205, 1868: 399)
1841.60			–62.77		M	Sabine (1844: 127)
1841.60			–62.74		M	Sabine (1844: 141)
1841.60			–62.92		M	Sabine (1844: 153)
1841.60			–62.55		M	Sabine (1844: 170)
1841.60			–63.22		M	Sabine (1844: 196–197, 1868: 399)
1841.60			–62.77		M	Sabine (1844: 204–205, 1868: 399)
1841.60			–62.82		M	Ross (1847: 49)
1841.59			–62.88		M	Sabine (1844: 153)
1841.58	0.01		–63.01		T	Sabine (1844: 170)
1841.56	0.01		–60.98		T	Ross (1847: 47)
1841.56	0.02		–62.94		T	Sabine (1844: 153)
1841.56	0.02		–62.92		T	Sabine (1844: 152)
1841.55			–62.96		T	Sabine (1844: 100, 104)
1841.55			–63.12		T	Sabine (1844: 170)
1841.55			–63.09		T	Sabine (1844: 204–205, 1868: 399)
1841.54			–63.01		T	Sabine (1844: 196–197, 1868: 399)
1841.53			–62.87		M	Sabine (1844: 170)
1841.53			–63.92		M	Sabine (1844: 196–197, 1868: 399)
1841.53			–63.30		M	Sabine (1844: 204–205, 1868: 399)
1841.53			–62.57		M	Sabine (1844: 127)

1841.53		–62.71		M	Sabine (1844: 141)
1841.53		–63.04		M	Sabine (1844: 152)
1841.53		–63.83		M	Sabine (1844: 170)
1841.53		–63.46		M	Sabine (1844: 196–197, 1868: 399)
1841.53		–64.00		M	Sabine (1844: 204–205, 1868: 399)
1841.53		–62.74		M	Sabine (1844: 127)
1841.53		–62.72		M	Sabine (1844: 141)
1841.53		–62.70		M	Sabine (1844: 152)
1841.53		–62.94		M	Sabine (1844: 170)
1841.53		–63.09		M	Sabine (1844: 196–197, 1868: 399)
1841.53		–63.17		M	Sabine (1844: 204–205, 1868: 399)
1841.53		–62.96		M	Sabine (1844: 127)
1841.53		–62.72		M	Sabine (1844: 141)
1841.53		–62.83		M	Sabine (1844: 152)
1841.53		–62.76		M	Sabine (1844: 169)
1841.53		–63.23		M	Sabine (1844: 196–197, 1868: 399)
1841.53		–63.12		M	Sabine (1844: 204–205, 1868: 399)
1841.52		–62.31		M	Sabine (1844: 127)
1841.52		–62.25		M	Sabine (1844: 141)
1841.52		–62.12		M	Sabine (1844: 152)
1841.52		–62.58		M	Sabine (1844: 169)
1841.52		–62.45		M	Sabine (1844: 196–197, 1868: 399)
1841.52		–62.91		M	Sabine (1844: 204–205, 1868: 399)
1841.52		–62.11		M	Sabine (1844: 127)
1841.52		–62.11		M	Sabine (1844: 141)
1841.52		–61.93		M	Sabine (1844: 152)
1841.52		–62.32		M	Sabine (1844: 169)
1841.52		–62.26		M	Sabine (1844: 196–197, 1868: 399)
1841.52		–62.56		M	Sabine (1844: 204–205, 1868: 399)
1841.52		–62.62		M	Sabine (1844: 122, 204–205)
1841.52		–62.07		M	Sabine (1844: 152)
1841.52		–62.91		M	Sabine (1844: 169)
1841.52		–62.39		M	Sabine (1844: 196–197, 1868: 399)
1841.52		–63.03		M	Sabine (1844: 204–205, 1868: 399)
1841.52		–62.25		M	Sabine (1844: 127)
1841.52		–62.35		M	Sabine (1844: 152)
1841.52		–62.24		M	Sabine (1844: 141, 169)
1841.50	0.30	–62.41	0.05	T	Sabine (1850: lxxiii)
1841.49		–62.40		M	Sabine (1844: 151)
1841.38	0.05	–62.42	0.05	T	Sabine (1843: 165)
1841.31	0.01	–62.30		T	Sabine (1844: 151)
1841.30		–62.63		T	Sabine (1844: 169)
1841.26		–62.57		M	Sabine (1843: 192)
1841.26		–63.21		M	Sabine (1843: 207)
1841.26		–63.46		M	Sabine (1843: 192)
1841.26		–63.96		M	Sabine (1843: 207)
1841.26		–63.41		M	Sabine (1843: 226)
1841.06	0.12	–63.53		M	Sabine (1868: 398)
1841.06	0.12	–64.24		M	Sabine (1868: 398)
1841.06	0.12	–63.28		M	Sabine (1868: 398)
1841.06	0.12	–63.48		M	Sabine (1868: 398)
1841.06	0.12	–62.43		M	Sabine (1868: 398)
1840.87	0.02	–62.43		T	Sabine (1843: 159)
1840.87		–62.17		M	Sabine (1843: 217)
1840.87		–61.29		M	Sabine (1843: 194)
1840.87		–61.54		M	Sabine (1843: 194, 1868: 397)
1840.83		–62.50		M	Sabine (1843: 193–194)
1840.75	0.03	–62.46	0.09	T	Sabine (1843: 165)
1840.73	0.01	–62.40		T	Sabine (1843: 193)
1840.62	0.02	–62.40		T	Sabine (1868: 395)
1840.61		–63.66		M	Sabine (1843: 175)
1840.61		–63.93		M	Sabine (1843: 175, 1868: 395)
1840.61		–63.42		M	Sabine (1843: 175, 1868: 395)
1840.21	0.0248	–62.38		T	Ennis (1934: 94)
1840.00		–60.50		M	Ennis (1934: 97)

1839.99			–61.40		M	Ennis (1934: 97)
1839.99			–61.46		M	Ennis (1934: 97)
1839.99			–64.72		M	Ennis (1934: 97)
1839.96	0.0249		–63.23		T	Ennis (1934: 94)
1839.29			–62.95		T	Sabine (1840: 134, 141, 147, 150)
1839.29			–63.02		T	Sabine (1840: 134, 141, 147, 150)
1839.26			–63.03		T	Sabine (1840: 134, 141, 147, 150)
1839.22			–63.02		T	Sabine (1840: 134, 141, 147, 150)
1839.22			–63.02		T	Sabine (1840: 134, 141, 147, 150)
1838.82			–63.03		T	Sabine (1840: 134, 141, 147, 150)
1838.82			–63.02		T	Sabine (1840: 134, 141, 147, 150)
1837.50	0.29		–63.02		T	Sabine (1840: 134, 141, 147, 150)
1837.50	0.29		–62.94		T	Sabine (1877: 497)
1836.04			–62.97		T	Sabine (1839: 500, 526)
1831.50	0.29		–62.99		T	Sabine (1877: 497)
1826.96	0.025		–62.85	0.01	T	Anon. (1834: 6)[2]
1826.87	0.024		–62.78	0.06	T	Anon. (1834: 6)[2]
1824.12	0.05		–62.44		T	Duperrey (1827: 77)
1821.50	0.29		–62.80		T	Sabine (1839: 500, 526)
1819.95	0.02		–62.94		T	Freycinet (1842: 206)
1802.46	0.06		–63.01		T	Flinders (1814a: 226, 237–238, 1814b: 2)
1793.21			–60.16		T	Malaspina (*c.* 1793), Collins (1798: 275), Espinosa y Tello (1809: 119)
1793.10			–63.54		T	Rossel (1808a: 248, 1808b: 479–480)
1793.10			–61.98		T	Rossel (1808a: 248, 1808b: 480)
1793.09	0.02		–62.19		T	Rossel (1808a: 247–248)
1793.09	0.02		–63.51		T	Rossel (1808a: 247–248)
1792.36			–62.04		T	Rossel (1808a: 248, 1808b: 320, 322)
1792.36	0.03		–62.04		T	Rossel (1808a: 76–77)
1788.06			–56.39		M	Milet-Mureau (1797a: 350–351)
1777.08			–62.37		T	Cooke *et al.* (1782: 304)
1777.08			–61.60		T	Cooke *et al.* (1782: 219)
1777.07			–62.28		T	Cooke *et al.* (1782: 304)
1777.06			–62.09		M	Cooke *et al.* (1782: 304)
1770.33			–67.02		T	Green and Cook (1771: 420)
1754	+196/–108	220±60	–72.69	11.01	A	Barbetti and Polach (1973), Barbetti (1977)
1744	+206/–109	240±60	–68.12		A	Barbetti and Polach (1973), Barbetti (1977)
1554	+69/–98	400±70	–59.91	5.91	A	Barbetti and Polach (1973), Barbetti (1977)
1313	+75/–76	740±70	–52.30	8.82	A	Barbetti and Polach (1973), Barbetti (1977)
1306	53		–50.81	3	A	Barbetti (1983)
1300	+85/–69	750±70	–50.37	7.31	A	Barbetti and Polach (1973), Barbetti (1977)
1291	112	760±150	–48.57	4.35	A	Barbetti and Polach (1973), Barbetti (1977)
1154	+57/–107	940±50	–42.54	20.94	A	Barbetti and Polach (1973), Barbetti (1977)
1125	102	950±120	–54.25	6.55	A	Barbetti and Polach (1973), Barbetti (1977)
1093	66	990±70	–50.19	7.97	A	Barbetti and Polach (1973), Barbetti (1977)
1039	75		–52.51	2	A	Barton and Barbetti (1982), Barbetti (1983)

[1]The central estimates of the ^{14}C dates represent the medians of each calibrated range.

[2]Mean of the measurements made using the two reliable dipping needles.

The eastern Australian Inclination Record

Historical observations of the 18th century inclination anomaly

The most striking feature of the *eAIR2012* data set is the inclination anomaly of the 18th century, when inclinations appear to have been steeper than at any time since the start of the Holocene. The evidence for this feature is based on three data points. One of these, Cook's measurement at Botany Bay, is of critical significance since it represents the earliest direct observation of inclination in the entire record. Measurements of inclination during this period were laborious and time-consuming to make (Hutchins, 1776: 179) and the dipping needles employed for this task had a reputation for being difficult to use (Nugent, 1800: 379–381). Given this, how much confidence may we place in Cook's records? Cook and his astronomer, Charles Green, measured magnetic inclination at 13 locations during their voyage. At least six of these locations were at sea and Green and Cook (1771: 419) considered these '... a little dubious on account of the motion of the ship ...'. At least one and perhaps three of the remaining observations were made onboard the ship whilst at anchor. These measurements may have been compromised by the presence of ferrous materials on the vessel. Compounding these problems of data quality is Green's death on the homeward leg of the voyage, which meant that he was unable to supervise the final publication of his data (Green and Cook, 1771: 421). His observations were collated by Cook and by Nevil Maskelyne, the Astronomer Royal, from what appears to have been a confused and incomplete set of records (Cook, 1771).

For those observations made at sea and for the three sets of measurements that may have been made onboard the ship, only a single mean value of inclination survives and we possess no measure of the precision of the observations from which this value was calculated. Of the remaining four locations, three possess a complete record of every measurement made. Importantly, at these locations, all measurements were made onshore and under no pressure of time. The sites in question are King George's Island (Tahiti), Botany Bay and the Endeavour River, close to Cooktown in modern Queensland. The records from these sites are given in Table 5. In each case, the values lie within a narrow range and the precision of the measurements is relatively high. Testing for systematic errors, however, is less straightforward. One approach is to compare Green's observations with similar measurements made shortly afterwards at nearby locations. This involves making assumptions about variations in magnetic inclination over space (since some of the comparative data come from different locations to those studied by Green) and time (since it was at least four years before suitably equipped vessels returned to these waters and additional measurements were made). Perhaps more significantly, the only corroborative records of Green's Botany Bay observations, those of La Pérouse, have been shown to be badly compromised and thus cannot be used to check measurements at this site. The available comparative data for Tahiti and the Endeavour River are shown in Tables 6–7. The measurements (particularly those made most shortly after Cook's voyage) are closely comparable with those of Green. Those terrestrial locations for which full accounts exist thus appear to possess credible and precise records of the dip of the Earth's field at the time of measurement. The measurements made at Botany Bay are likely to be similarly reliable.

Table 5 Those sites at which magnetic inclination was measured by Charles Green during James Cook's 1768–1771 voyage (Green and Cook, 1771) and from which the original field observations survive. The latitudes and longitudes of the measurement sites are those given in the original records. Longitude is expressed with reference to the Greenwich Meridian.

Location	Date	Latitude	Longitude	Inclination	Notes
Fort Venus, King George's Island (Tahiti)	30 May 1769	17°29′15″ S	149°36′38″ W	–29°26′	Needle facing east
				–29°40′	Needle facing west
				–30°10′	Needle facing east
				–31°45′	Needle facing west
				–31°00′	Needle facing east
				–31°00′	Needle facing west
				–30°51′	Needle facing east
				–30°40′	Needle facing west

				–30°18′	Needle facing east
				–30°25′	Needle facing west
				–30°21′	Needle facing east
				–30°40′	Needle facing west
				–31°00′	Needle facing east
				–30°42′	Needle facing west
				–30°45′	Needle facing east
				–31°30′	Needle facing west
				–31°50′	Needle facing east
				–30°16′	Needle facing west
				–30°16′	Needle facing east
				–30°48′	Needle facing west
				–31°45′	Needle facing east
				–30°43′	Mean
Botany Bay, Sydney, New South Wales, Australia	1 May 1770	34°00′ S	208°37′ W	–67°20′	Needle facing east
				–66°40′	Needle facing west
				–66°55′	Needle facing east
				–67°08′	Needle facing west
				–67°01′	Mean

Endeavour River, Cooktown, Queensland, Australia	18 July 1770	15°26′ S	214°48′ W	–36°54′	Needle facing west
				–36°40′	Needle facing east
				–36°06′	Needle facing west
				–35°14′	Needle facing east
				–35°14′	Needle facing west
				–36°00′	Needle facing east
				–36°00′	Needle facing west
				–36°00′	Mean

Sedimentary records of the 18th century inclination anomaly

Evidence of the 18th century inclination anomaly may also be preserved in sedimentary records from across eastern Australia, although this has not previously been recognised. In southwest Victoria, for example, the steepest inclinations of the last 10 000 years occur just below the top of core KF from Lake Keilambete (Barton and McElhinny, 1981), whilst cores K1D and K1F from the same lake show inclinations steepening steadily after the middle of the first millennium AD, reaching a maximum in the last 500 years (Barton and Barbetti, 1982). The composite record from Lakes Keilambete, Bullenmerri and Gnotuk (Anker *et al.*, 2001) displays twin peaks in inclination during the last 800 years. A similar story comes from eastern New South Wales where sediments from Little Llangothlin Lagoon, Lake Couridjah, Blue Hole Swamp and Little Blue Hole Swamp all display peaks in inclination during the last millennium (Dorrington, 2008).

Table 6 Measurements of magnetic inclination made in Tahiti between AD 1769 and 1777. The latitudes and longitudes of the measurement sites are those given in the original records. Longitude is expressed with reference to the Greenwich Meridian.

Date	Location	Latitude	Longitude	Inclination	Source
30 May 1769	Fort Venus, King George's Island (Tahiti)	17°29′15″ S	149°36′38″ W	–30°43′	Green and Cook (1771: 406, 408, 419)
27–31 August 1773	Point Venus, Tahiti	17°29′13.7″ S	149°27′–149°14′52.5″ W	–29°43′07.5″	Wales and Bayly (1777: 53–55)
23 April–10 May 1774	Point Venus, Tahiti	17°29′17″–17°29′35″ S	150°21′45″–148°55′00″ W	–29°58′45″	Wales and Bayly (1777: 88–94)
8 September 1777	Point Venus, Tahiti	17°29′ S	149°50′ W	–29°03′22″	Cooke *et al.* (1782: 219)

The sediments from Lake Eacham in northeast Queensland may also record the 18th century inclination anomaly, exhibiting an inclination peak (of nearly –80°) in the last few centuries, with the overlying measurements recording a rapid shift in inclination towards that of the axial dipole (Constable and McElhinny, 1985). Similarly, the 18th century inclination peak may be recognised in speleothem deposits from Forbes' Second Discovery Cave in northwest Queensland (Fischer, 2001). Although the low chronological resolution and slow sedimentation rate demand caution in interpretation, the actively growing stalagmite exhibits an inclination maximum immediately beneath a ^{230}Th/^{234}U age of 200±200 years (±1 *s* uncertainty). This is the steepest record in a sequence believed to be continuous back to approximately 300 BC.

Table 7 Measurements of magnetic inclination made in northeast Australia and Vanuatu between AD 1777 and 1803. The latitudes and longitudes of the measurement sites are those given in the original records. Longitude is expressed with reference to the Greenwich Meridian. The inclination values have been reduced to the latitude of the Endeavour River, Cooktown, Queensland (15°26′ S) on the assumption of an axial dipole field (Aitken and Weaver, 1965).

Date	**Location**	**Latitude**	**Longitude**	**Inclination**	**Inclination reduced to the latitude of the Endeavour River, Cooktown**	**Source**
18 July 1770	Endeavour River, Cooktown, Queensland	15°26′ S	145°12′ E	–36°00′	–36°00′	Green and Cook (1771: 420)
7–17 August 1774	Port Resolution, Tanna, New Hebrides (Vanuatu)	19°32′25.5″ S	169°48′49.5″ E	–45°02′20″	–38°35′	Wales and Bayly (1777: 98–100)
21–23 August 1802	Entrance Island, Port Bowen, Queensland	22°28′28″ S	150°45′00″ E	–50°20′	–39°38′	Flinders (1814b: 36–39)
5–6 September 1802	Summit of Pier Head, Thirsty Sound, Queensland	22°06′53″ S	150°00′10″ E	–53°20′	–43°08′	Flinders (1814b: 53–57)

5–6 September 1802	Summit of Pier Head, Thirsty Sound, Queensland	22°06′53″ S	150°00′10″ E	–52°19′	–42°07′	Flinders (1814b: 53–57)
5–6 September 1802	Summit of Pier Head, Thirsty Sound, Queensland	22°06′53″ S	150°00′10″ E	–50°35′	–40°23′	Flinders (1814b: 53–57)
5–6 September 1802	Summit of Pier Head, Thirsty Sound, Queensland	22°06′53″ S	150°00′10″ E	–50°28′	–40°16′	Flinders (1814b: 53–57)
5–6 September 1802	Summit of Pier Head, Thirsty Sound, Queensland	22°06′53″ S	150°00′10″ E	–50°50′	–40°38′	Flinders (1814b: 53–57)
17–28 November 1802	Sweers' Island, Gulf of Carpentaria, Queensland	17°08′15″ S	139°44′52″ E	–44°27′	–41°41′	Flinders (1814b: 134–149)
15–16 January 1803	Finch's Island, Groote Eylandt, Gulf of Carpentaria, Northern Territory	14°43′31″ S	136°36′53″ E	–39°22′	–40°32′	Flinders (1814b: 189–192)

4–9 February 1803	Caledon Bay, Gulf of Carpentaria, Northern Territory	12°47′16″ S	136°35′47.5″ E	–36°28′	–40°58′	Flinders (1814b: 205–219)

To the east, the record of magnetic inclination from New Zealand (Robertson, 2007) reveals a progressive steepening of inclination over the last 1000 years that is closely comparable with that shown by the *eAIR2012*. The 18th century inclination anomaly is missing from the New Zealand record, however, suggesting an eastward limit to the extent of this phenomenon.

Testing the eAIR2012 *against independent sedimentary records*

Evidence of the 18th century inclination anomaly may thus be observed at a range of sites throughout eastern Australia. Unfortunately, these records are poorly dated. Significantly too, the existence of the anomaly in the *eAIR2012* is based on only three data points, two of which are associated with significant chronological and directional uncertainties. In addition, the archaeomagnetic measurements that make up the basal part of the *eAIR2012* are too sparse and too uncertain to provide a reliable measure of changes in field direction over the earlier part of the period. In order to assess the reliability of the *eAIR2012*, and particularly the 18th century inclination anomaly, we therefore sought to compare the record with independent histories of magnetic inclination in eastern Australia over the last millennium. To obtain this information we sampled lake sediments from Tocal Homestead Lagoon in the Hunter valley of central eastern New South Wales and Big Jibbon Lagoon to the south of Port Hacking in central eastern New South Wales. Percussion cores of sediments were obtained from each site using 50 mm diameter polyvinyl chloride tubing. Each tube was sealed and transported directly to the laboratory, where repeated downcore measurements of magnetic inclination were made using a *2G Enterprises* long-core cryogenic magnetometer.

Tocal Homestead Lagoon. Tocal Homestead Lagoon is known to possess an undisturbed, well-dated and high-resolution record of sedimentation extending back at least two millennia (Cook, 2006; Gale and Cook, 2006). Two cores (TCA9e and TCA9f) were extracted from site TCA9 in the lake. The inclination patterns of each core were closely comparable (Figure 3). Since core TCA9f possesses a longer and more highly resolved record than TCA9e, this was selected for more detailed analysis. An oriented pilot specimen from the core was chosen and the stability of its remanent magnetisation was examined by progressive stepwise demagnetisation in alternating fields up to a maximum strength of 40 mT. The direction and intensity of magnetisation after each demagnetisation step was measured using a *2G Enterprises* cryogenic magnetometer. The direction of magnetisation did not change significantly with demagnetisation, with no indication of a viscous or weaker secondary chemical remanence (Figure 4). Measurements of natural remanent magnetisation were therefore considered to be indicative of primary magnetisation and thus of the direction of the past field at the site.

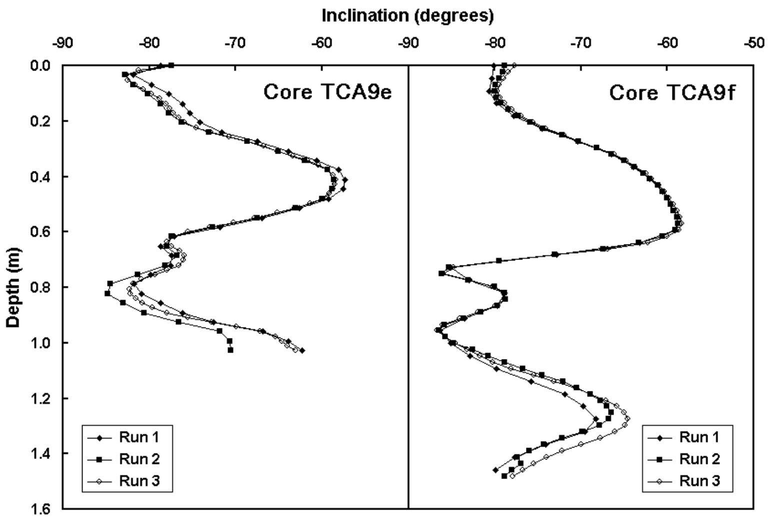

Figure 3 The results of repeat measurements of the downcore variation in the inclination of the natural remanent magnetisation of cores TCA9e and TCA9f from Tocal Homestead Lagoon, central eastern New South Wales, Australia.

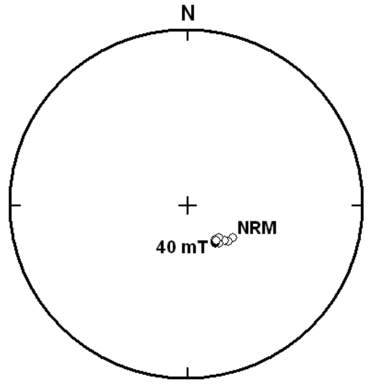

Figure 4 The direction of magnetisation of specimen TCA9f2 from 0.06–0.12 m in core TCA9f from Tocal Homestead Lagoon, central eastern New South Wales, Australia during progressive stepwise demagnetisation in successive peak alternating fields of 2, 4, 6, 8, 10, 12, 16, 20, 30 and 40 mT. The natural remanent magnetisation is labelled NRM. The measurements are plotted on the upper hemisphere of an equal-angle stereographic projection. Note that the measurements of declination were made with respect to an arbitrary datum and should not be taken as representative of actual palaeomagnetic direction.

The increase in inclination in the upper few centimetres of each core is probably an edge effect resulting from the integration of magnetometer sensor readings beyond the top of the core barrel. Below this, there are notable similarities between the inclination records of TCA9e and TCA9f and those of the *eAIR2012*. In both the sediments and the observational records, inclinations become gentler with depth, reaching a minimum of around –60°, although the amplitude of change is greater in the sediment records. Below this point, both sets of inclination records steepen sharply to the steepest values in the sequence. The sediment records indicate that this feature is made up of twin peaks, although the sparsity of data means that these individual components cannot be distinguished in the *eAIR2012* sequence. Beneath this, inclination values in both records become progressively less steep. In the longer of the two sedimentary records, TCA9f, the basal part of the sequence is characterised by a steepening of inclination. This may correspond with the shift that occurs in the *eAIR2012* during the 11th century, though the incomplete nature of the archaeomagnetic data set means that such a correlation can only be speculative at this stage.

In order to constrain the timing of the inclination episode in the sedimentary sequence, samples were taken for accelerator mass spectrometric ^{14}C analysis from the two inclination peaks in the record. The results are shown in Table 8.

Table 8 Accelerator mass spectrometric ^{14}C determinations from core TCA9f, Tocal Homestead Lagoon, central eastern New South Wales, Australia. The ages have been calibrated to calendar years using the CALIB 6.0 Radiocarbon Calibration Program of M. Stuiver, P.J. Reimer and R. Reimer, employing the SHCal04 data set of McCormac *et al.* (2004).

Depth (m)	Laboratory code	Radiocarbon age (BP±1 *s*)	Calibrated date (cal AD±2 *s*)
0.74–0.68	Wk-23995	152±30	1678–1734
			1800–1952
0.97–0.91	Wk-23996	738±30	1270–1320
			1350–1386

The younger of the two dates is statistically indistinguishable from, but is more precise than the date of cal AD 1790±162 (±2 *s* uncertainty) (Table 4) for the inclination peak in the *eAIR2012* record. This suggests that the features in the *eAIR2012* and the lake sediment record are a product of the same change in field direction, strongly supporting the reality of the inclination anomaly. The age of the feature may be constrained by reference to the historical geomagnetic record, which tightly brackets the disappearance of the anomaly between

AD 1770 and 1777 (Figure 2). The timing of the anomaly may thus be refined to between the end of the 17th century and the end of the 18th century.

The older of the two inclination peaks in the Tocal Homestead Lagoon record is associated with a date of cal AD 1270–1386 (±2 *s* uncertainty). There is no evidence of such a feature in the *eAIR2012* archaeomagnetic record. On the other hand, the composite record from Lakes Keilambete, Bullenmerri and Gnotuk in southwest Victoria (Anker *et al.*, 2001) displays twin peaks in inclination during the last 800 years that may be compared with those observed in Tocal Homestead Lagoon. This assessment should be qualified, however, by acknowledging the low resolution of the Victorian record and the evidence that the chronology of the sedimentary sequences may be in error by perhaps 350 years (Barton and Barbetti, 1982; Anker *et al.*, 2001: 269).

Big Jibbon Lagoon. The record of magnetic inclination from core BJL B4.0 from Big Jibbon Lagoon in central eastern New South Wales is shown in Figure 5. The results are equivocal, but they display evidence of similar trends to those observed in Tocal Homestead Lagoon. In particular, the upper part of the sequence exhibits twin peaks in inclination comparable with those seen in the Tocal Homestead Lagoon record. This part of the Big Jibbon Lagoon sequence is not well dated, though the basal date of the ^{210}Pb chronology lies just above the upper inclination peak, confirming that both the inclination peaks pre-date European contact.

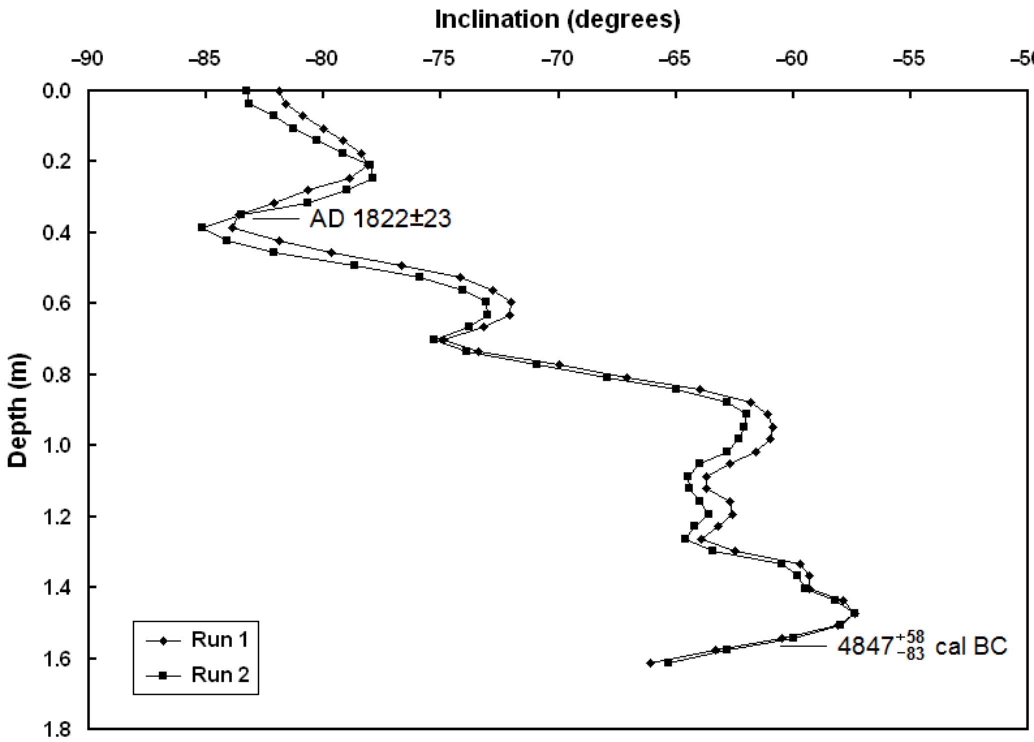

Figure 5 The results of repeat measurements of the downcore variation in the inclination of the natural remanent magnetisation of core BJL B4.0 from Big Jibbon Lagoon, central eastern New South Wales, Australia. The upper date is the basal value of a ^{210}Pb chronological sequence, the lower date is an accelerator mass spectrometric ^{14}C determination (Beta-305851) calibrated to calendar years using the CALIB 6.0 Radiocarbon Calibration Program of M. Stuiver, P.J. Reimer and R. Reimer, employing the SHCal04 data set of McCormac *et al.* (2004). Following the recommendations of Telford *et al.* (2004), the central estimate of the ^{14}C date represents the median of the calibrated range. Dates are expressed with an uncertainty of ±1 *s*.

It is thus possible that the inclination anomaly is more complex than revealed by the *eAIR2012* record and that it may be a composite feature characterised by two inclination peaks, the entire episode having a lifetime of around 500 years.

Discussion

Although the 13th–18th century inclination anomaly has not previously been identified in Australia, it may be associated with a short-lived, large-scale magnetic feature to the north of Australia that is revealed in a series of global geomagnetic field models. These include *gufm1* (Jackson *et al.*, 2000), based largely on historical maritime records, and a sequence of models derived from archaeomagnetic, lava flow and lake sediment records (Constable *et al.*, 2000; Korte and Constable, 2003, 2005). Despite employing rather sparse sets of data from the Australian region, all these models show the presence of a negative inclination anomaly in the region during this period. The *CALS7.2* model (Korte and Constable, 2005), for example, clearly reveals the development of a large-scale negative anomaly to the north of Australia in the decades before AD 1300. This reached its climax in the early 18th century when the feature extended over the northern part of the continent.

The rapid shifts in the inclination of the geomagnetic field during this period provide easily identifiable palaeomagnetic event markers that offer considerable potential for dating materials deposited immediately prior to the European colonisation of the eastern seaboard of the continent. There are few established dating techniques capable of providing a high-resolution chronology of this period. These markers afford a means of improving this situation. In particular, the steep shift and finely resolved chronology that mark the end of the 18th century inclination maximum provide a tool for the identification one of southeast Australia's most intractable chronological datums, the point of European contact.

Conclusions

The *eAIR2012* offers three important insights into recent secular magnetic change. First, it has allowed us to identify a well-defined magnetic inclination anomaly in eastern Australia that may have spanned the period between the 13th and 18th centuries. The dip of the field during this time seems to have been greater than at any stage since the start of the Holocene. The episode appears to have been characterised by two steep inclination peaks. Although the earlier is of equivocal status, it has been identified in the sediments of Tocal Homestead Lagoon, where it has been dated to cal AD 1270–1386 (±2 *s* uncertainty). The later peak is bracketed between cal AD 1431–1651 (±2 *s* uncertainty) and its disappearance between AD 1770 and 1777. Further evidence of these features may be observed in sedimentary sequences throughout eastern Australia. The discovery of these distinct time-markers is of great importance to the dating of recent environmental records in the region. This critical period of environmental history is at present difficult and often impossible to date by established means; the identification of these chronological datums has the potential to improve significantly this situation.

Secondly, the *eAIR2012* provides valuable constraints on attempts to model regional changes in the geomagnetic field over millennial and centennial timescales. In particular, it yields information on the timing and extent of the major inclination anomaly revealed by global magnetic field models across island southeast Asia and Australasia during the last 700 years.

Thirdly, the inclination measurements made by the 18th century French explorer La Pérouse appear to be consistently erroneous. As there are so few geomagnetic data from this period, the inclusion of these measurements in global compendia of magnetic observations may seriously skew attempts to model the geomagnetic field. We advocate that La Pérouse’s data should be employed only with considerable caution.

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