

Geological Society, London, Special Publications Online First

Evaluating Late Holocene radiocarbon-based chronologies by matching palaeomagnetic secular variations to geomagnetic field models: an example from Lake Kalimpa (Sulawesi, Indonesia)

Torsten Haberzettl, Guillaume St-Onge, Hermann Behling and Wiebke Kirleis

Geological Society, London, Special Publications v.373, first published August 14, 2012; doi 10.1144/SP373.10

Email alerting service

click [here](#) to receive free e-mail alerts when new articles cite this article

Permission request

click [here](#) to seek permission to re-use all or part of this article

Subscribe

click [here](#) to subscribe to Geological Society, London, Special Publications or the Lyell Collection

How to cite

click [here](#) for further information about Online First and how to cite articles

Notes

Evaluating Late Holocene radiocarbon-based chronologies by matching palaeomagnetic secular variations to geomagnetic field models: an example from Lake Kalimpa (Sulawesi, Indonesia)

TORSTEN HABERZETTL^{1*}, GUILLAUME ST-ONGE², HERMANN
BEHLING³ & WIEBKE KIRLEIS⁴

¹*Physical Geography, Institute of Geography, Friedrich-Schiller-University Jena,
Löbdergraben 32, 07743 Jena, Germany*

²*Canada Research Chair in Marine Geology, Institut des sciences de la mer de Rimouski
and GEOTOP Research Center, Université du Québec à Rimouski,
310, allée des Ursulines, Rimouski, Québec, Canada G5L 3A1*

³*Department of Palynology and Climate Dynamics, Albrecht-von-Haller-Institute for Plant
Sciences, University of Göttingen, Untere Karspüle 2, 37073 Göttingen, Germany*

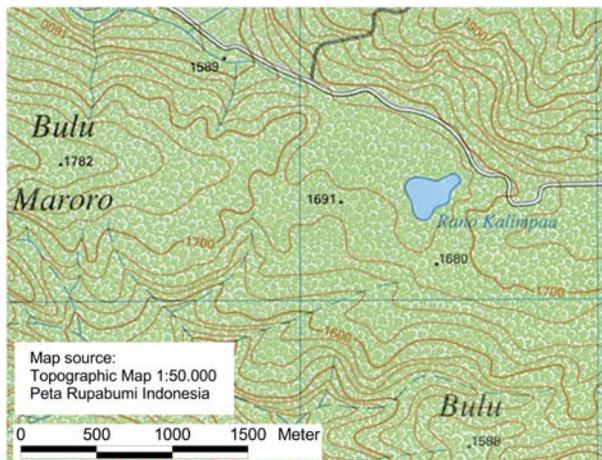
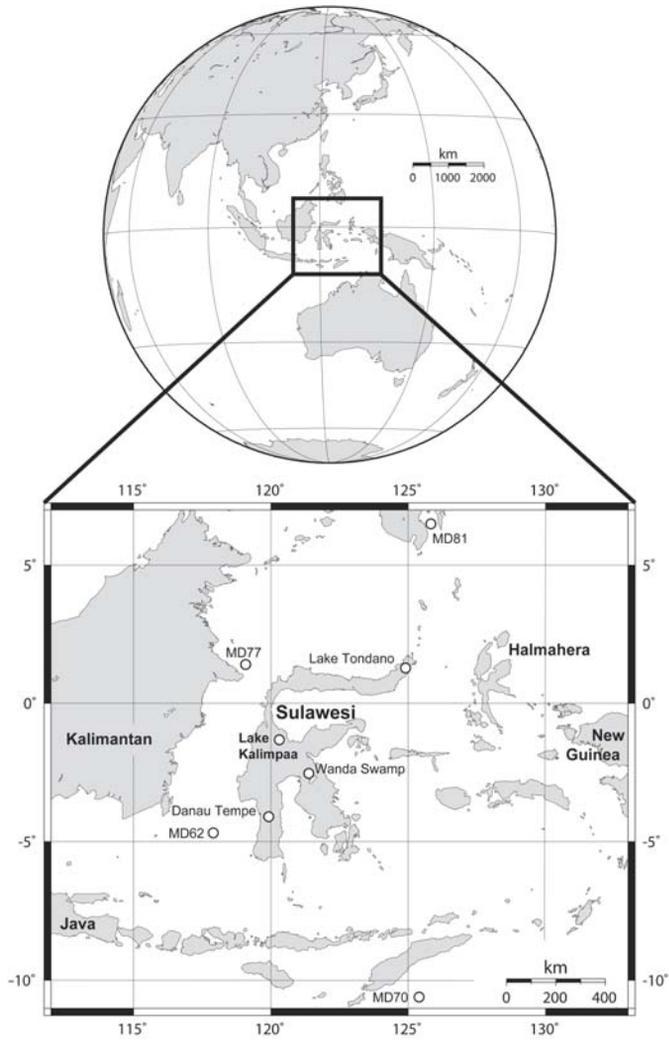
⁴*Graduate School Human Development in Landscapes/Institute for Prehistoric
and Protohistoric Archaeology, Christian-Albrechts-University Kiel,
Johanna-Mestorf-Strasse 2-6, 24118 Kiel, Germany*

*Corresponding author (e-mail: torsten.habertzettl@uni-jena.de)

Abstract: Palaeomagnetic and palaeoenvironmental data from Indonesia and particularly from the Island of Sulawesi are scarce and exact dating has turned out to be a challenge in many archives from this region. Here we outline difficulties in radiocarbon dating of the palaeoenvironmental record from Lake Kalimpa, Sulawesi, Indonesia. These difficulties demand the integration of additional parameters to obtain a reliable chronology for this record. Thus, we compare the palaeomagnetic secular variation data from this record with the CALS3k.4 spherical harmonic geomagnetic model of the 0–3 ka field (Korte & Constable 2011). The resulting age–depth model for the Lake Kalimpa sequence provides a profound basis for further multi-proxy investigations on this record. For the first time, high-resolution palaeomagnetic secular variation data continuously spanning the past 1300 years are presented for this region, which complement existing records with lower temporal resolution or records missing the top-most sections.

The area between mainland Asia and Australia is of great significance for understanding modern climatic processes. Sea surface temperatures in the western Pacific warm pool drive the dynamics of El Niño Southern Oscillation and the Asian Monsoon (Oppo *et al.* 2009; Linsley *et al.* 2010). Influenced by water masses passing from the warm western Pacific to the Indian Ocean, this region acts as a considerable source of latent heat for the globe (Hope 2001). In particular, palaeorecords from the region help to trace the structures behind recurrent environmental changes. However, palaeoenvironmental information from Indonesia, and particularly from the Island of Sulawesi, is scarce. To complement the information derived from marine records and to improve the understanding of SE Asian–Pacific palaeoclimate, its amplitude and the exact timing of palaeoenvironmental variations, further records from terrestrial archives in this region are essential (Dam *et al.* 2001). Palaeoenvironmental studies

have been carried out in Java (Stuijts *et al.* 1988; van der Kaars & Dam 1995; van der Kaars *et al.* 2001; Crausbay *et al.* 2006), Kalimantan (Morley 1981; Anshari *et al.* 2001, 2004; Page *et al.* 2004; Hope *et al.* 2005; Yulianto *et al.* 2005), Halmahera (Suparan *et al.* 2001) and New Guinea (Hope *et al.* 1988; Haberle 1998; Haberle & Ledru 2001; Haberle *et al.* 2001; Hope 2009; Fig. 1). Marine sediment cores are the only sources of palaeoenvironmental information in the intermediate area between the islands (van der Kaars *et al.* 2000; Hope 2001; Spooner *et al.* 2005; Newton *et al.* 2006; Brijker *et al.* 2007; Langton *et al.* 2008). Until now, on the Island of Sulawesi itself, which is the main area of interest for this contribution, palaeoenvironmental knowledge of the past two millennia is extremely limited. Palynological investigations have been carried out on Wanda Swamp (2°33' S, 121°23' E; Hope 2001), Danau (Lake) Tempe (4°5' S, 119°55' E; Gremmen 1990) and



Lake Tondano ($1^{\circ}16'N$, $124^{\circ}54'E$; Dam *et al.* 2001; Fig. 1). However, these studies focus on long-lasting variations like the Pleistocene–Holocene transition and are of low temporal resolution. Recently, a sequence focusing on Late Holocene developments in central Sulawesi was published (Kirleis *et al.* 2011).

As far as palaeomagnetic information is concerned, the lack of spatial coverage is even poorer. A number of deep-sea sediment cores (MD62, MD70, MD77 and MD81) in the vicinity of Indonesia and the Philippine Islands, which form a transect from $6.3^{\circ}N$ to $10.6^{\circ}S$, were recovered (Lund *et al.* 2006; Fig. 1). These are the first high-resolution palaeomagnetic records of Holocene palaeomagnetic secular variation recovered within 17° of the Equator. As the focus of these records has been the entire Holocene, it appears that there is little information about the most recent palaeomagnetic history available in most records; for example, in MD70 (Fig. 1) the last *c.* 2000 years of sediment are missing (Lund *et al.* 2006). The same holds for a marine record recovered further north at ODP Leg 195 Hole 1202B ($24^{\circ}48.24'S$, $122^{\circ}30.00'E$; Richter *et al.* 2006), for four marine cores obtained from the Ontong Java Plateau ($1^{\circ}24.1'N$ – $3^{\circ}36.3'S$, $156^{\circ}59.9'$ – $158^{\circ}41.6'E$; Constable & Tauxe 1987) and for two records from northeastern Australian crater lakes (Constable 1985). Based on the age–depth model of the ODP site, it is possible that the last *c.* 1000 years are missing (Richter *et al.* 2006) and the Ontong Java Plateau study only provides relative palaeointensity data with a resolution of two to three points for the past two millennia (Constable & Tauxe 1987). In the northeastern Australian lakes, the top-most 1000–3000 years are missing completely (Constable 1985). Therefore, comparable archives are only available at a greater distance (e.g. southern Australia).

However, for eastern Asian lake records it was demonstrated that palaeosecular variation dating can be useful for stratigraphic correlation on a regional scale. The method could help to resolve ambiguities in the ages of some high-frequency climate events within different regions and to understand their significance in global change (Yang *et al.* 2009).

In the following, we compile an age control and present the first high-resolution palaeomagnetic data from Lake Kalimpa, located on the Island of Sulawesi (Fig. 1). Radiocarbon dates in former studies on Sulawesi reveal that generating age–depth

models that provide the key to proper palaeoenvironmental reconstruction can be very difficult as they show age reversals, missing surfaces and/or unexpected modern dates (Dam *et al.* 2001; Hope 2001). We will illustrate the difficulties associated with dating at Lake Kalimpa and, in combination with palaeomagnetic data, try to evaluate an age–depth model providing the basis for further multi-proxy investigations. Until now, little attention has been given to the practical use of palaeomagnetic secular variations computed by the CALSxx model series as a dating tool (Barletta *et al.* 2010). Recently, good matches have been shown between the CALS3k.3 model (Donadini *et al.* 2009; Korte *et al.* 2009 – the model preceding the CALS3k.4 model (Korte & Constable 2011) used in this study) and marine sediments from the western (Barletta *et al.* 2010) and eastern (Ledu *et al.* 2010) Canadian Arctic, as well as between the model and lacustrine sediments from Lake Nam Co (Kasper *et al.* 2012), located on the Tibetan Plateau. For the location of lake Kalimpa, some of the above-mentioned archives are contained in the CALS3k.4 model database, as well as higher-resolution records covering the relevant time span from further south (i.e. southern Australia) and further north (e.g. Lake Biwa; Ali *et al.* 1999; Donadini *et al.* 2009; Korte & Constable 2011).

Regional setting

Lake Kalimpa ($1^{\circ}19'34.8''S$, $120^{\circ}18'31.9''E$; Fig. 1), sometimes also referred to as Danau Taming, is located close to the northeastern border of the protected area of the Lore Lindu National Park in Central Sulawesi, Indonesia. The national park has existed since 1993. However, parts of the park have been deforested (Merker 2003). A recreational area was recently constructed in the immediate surroundings of the lake and a small stream was redirected, bringing more water and sediment into the lake.

The lake itself is located at 1660 m asl. The surrounding geology consists of intrusive and metamorphic rocks (Villeneuve *et al.* 2002). Neighbouring crests reach altitudes of >2300 m asl, resulting in distinct topographic differences. The lake covers an area of 6.5 ha and has a maximum depth of 6.6 m. Reeds grow on the shore surrounding the lake. A reed belt is situated in the north and NE that fades to a swamp forest. About 200 m

Fig. 1. Map of the research area showing Sulawesi and adjacent islands as well as locations mentioned in the text. The basic map was created using Online Map Creation. A map of the lake including the immediate surrounding is shown at the bottom. This is based on a Topographic Map, 1:50 000 Peta Rupabumi Indonesia, edited by Badan Koordinasi Survey Dan Pemetaan Nasional (Bakosurtanal) in Cibinong–Bogor, Indonesia.

eastwards from the shoreline the main asphalt road through the National Park passes by (Fig. 1) and divides the lake area from the steeper mountainous area reaching to Mount Rorekatimbu (2300 m asl). Vegetation in the south and west of the lake consists of lower- to mid-mountain rainforest species. Inflow reaches the lake mainly through the swamp forest area in the NE, and an outflow is located to the SW.

Climatic patterns in this area are complex and poorly understood, with considerable variation over short distances (Hope 2001). The general pattern shows constant temperatures throughout the year ranging from 25 °C during the night up to 35 °C during the day. In the mountainous regions where Lake Kalimppaa is located, mean temperatures are around 20 °C. Annual precipitation is in the order of 2000–3000 mm, with less precipitation in the rain shadow of the mountains (Weber 2006).

Materials and methods

In 2006, three sediment cores (KAL1 to 3) were recovered from Lake Kalimppaa. Palaeomagnetic investigations were applied to the irregularly laminated, longest, best-preserved and hence most suitable core, KAL1 (211 cm). KAL2 was investigated by Indonesian counterparts using standard sedimentological analyses. KAL3 is only a short core of 25 cm in length and thus was not considered for further investigations. KAL1 consists of three overlapping sections (KAL1-1 to -3) that were recovered from a water depth of 6.5 m using a Livingstone piston corer. Core sections were recovered in a tube and transported to the laboratory of the Department of Palynology and Climate Dynamics, University of Göttingen, Germany, for further analyses. In the laboratory, cores were stored in darkness at 4 °C before being split, photographed and described lithologically. Sections were correlated using distinct macroscopic marker layers (Gutknecht 2008).

As no macro remains for radiocarbon dating were available, a first set of six bulk sediment samples was submitted to the accelerator mass spectrometry radiocarbon laboratory of the University of Erlangen, Germany (Table 1). Subsequently, three additional bulk sediment samples were sent to the Poznan Radiocarbon Laboratory, Poland (Table 1). Considering inconsistencies, all six samples previously dated in Erlangen were measured a second time (labelled as Erlangen 2 in Table 1). Most radiocarbon ages were calibrated using the Southern Hemisphere calibration curve (shcal04; McCormac *et al.* 2004) of the online CALIB 5.0.2 software (Stuiver & Reimer 1993). Calibrated ages are given as median ages with 2σ errors and are reported as cal BP (Table 1). Ages exceeding this curve were not calibrated and are displayed as BP

(Fig. 2). Modern ages were calibrated using CALIBomb (Reimer *et al.* 2004) and the year of the highest probability was chosen for age–depth modelling (Table 1). As the sediment–water interface was intact, it was used to represent the year of coring, which was 2006. Owing to very low sedimentary calcite contents (Gutknecht 2008), a hard water effect can be excluded for Lake Kalimppaa.

Sections were subsampled with u-channels and subsequently shipped to the Sedimentary Palaeomagnetism Laboratory at the Institut des sciences de la mer de Rimouski of the University of Québec at Rimouski, Canada. u-Channels of sections KAL1-2 and 3 were cut off at a very distinctive correlating marker layer and taped together. Small gaps in KAL1-2 were closed by gently pushing the sediment from the top, avoiding compaction of the sediment itself. This resulted in a reduction of the total length of the record by 3 cm (=208 cm total length). Using the many marker layers, the depths of the radiocarbon ages were adjusted to the new u-channel depth scale.

Palaeomagnetic data were acquired at 1 cm intervals on the u-channels using a 2 G EnterprisesTM 760R cryogenic magnetometer and pulse magnetizer module (for isothermal remanent magnetization, IRM). Owing to the width of the response function of the magnetometer pick-up coils of *c.* 7 cm, some smoothing occurs. As the material in KAL1-2 and -3 seemed to be very different, the last 7 cm of KAL1-2 and the first 7 cm of KAL1-3 were excluded. It was not necessary to exclude the lower part of KAL1-1 or the upper part of KAL1-2 as these sections extended further down and up, respectively, from the main correlating marker layer. Measurements on these overlapping extensions provided identical results, so no data had to be removed.

The natural remanent magnetization (NRM) was measured first using stepwise alternating field (AF) demagnetization at peak fields of 0–75 mT with 5 mT increments. Inclination and declination of the characteristic remanent magnetization (ChRM) were calculated using an Excel spreadsheet developed for that purpose (Mazaud 2005) with AF demagnetization steps from 10 to 50 mT (nine steps). These steps were chosen in order to minimize maximum angular deviation (MAD) values obtained by principal component analysis (Kirschvink 1980) with the same macro. ChRM declinations were corrected for rotation at section breaks, that is, it was assumed that the lowermost data point of the upper section is identical to the uppermost data point of the lower section. Declination data are relative and centred at zero since the coring was not azimuthally oriented. An anhysteretic remanent magnetization (ARM) was then induced at peak AF of 100 mT with a 0.05 mT direct current (DC) biasing field and subsequently demagnetized and measured

Table 1. Accelerator mass spectrometry radiocarbon dates from Lake Kalimpaa. Medians of calibrated ages refer to the 2σ ranges

Sediment depth (cm)		Error	Median calibration age (cal BP)	Error to present (years)	Error to past (years)	Laboratory	Laboratory no.	Dataset	Remark	δ ¹³ C	
	<i>¹⁴C age (BP)</i>										
44	1198	40	1050	85	125	Erlangen	Erl-11299	shcal04.14c		-29.1	
73	1288	32	1160	95	100	Erlangen	Erl-10576	shcal04.14c		-34.0	
94	1963	37	1850	125	95	Erlangen	Erl-11300	shcal04.14c		-30.5	
119	1920	37	1800	90	90	Erlangen	Erl-11301	shcal04.14c		-32.5	
151	1774	39	1630	95	90	Erlangen	Erl-11302	shcal04.14c		-28.6	
204	17893	74				Erlangen	Erl-11303		> shcal04.14c	-25.3	
73	1539	41	1370	70	145	Erlangen 2	Erl-12181	shcal04.14c		-34.8	
94	1649	41	1470	95	120	Erlangen 2	Erl-12182	shcal04.14c		-28.4	
119	1735	43	1590	170	120	Erlangen 2	Erl-12183	shcal04.14c		-31.4	
151	1501	41	1340	50	65	Erlangen 2	Erl-12184	shcal04.14c		- 30.0	
204	13413	91				Erlangen 2	Erl-12185		> shcal04.14c	-26.5	
136	1080	30	940	120	105	Poznan	Poz-24168	shcal04.14c		- 24.0	
203	4300	50	4760	180	195	Poznan	Poz-24169	shcal04.14c	0.4 mg C	-29.5	
	<i>Percentage modern carbon</i>										
	105.75	0.37	- 46								
			-45			Poznan	Poz-24225	SH1.14c	Highest probability printed in bold	- 29.3	
			-43								
			-9								
			-8								
	102.62	0.52	-46			Erlangen 2	Erl-12180	SH1.14c	Highest probability printed in bold	- 30.4	
			-45								
			-9								
			- 8								

Note: Ages labelled 'Erlangen 2' were re-dated and correspond to the same sample as the sample 'Erlangen' at the respective sediment depth. Ages used in the final chronology are printed in bold.

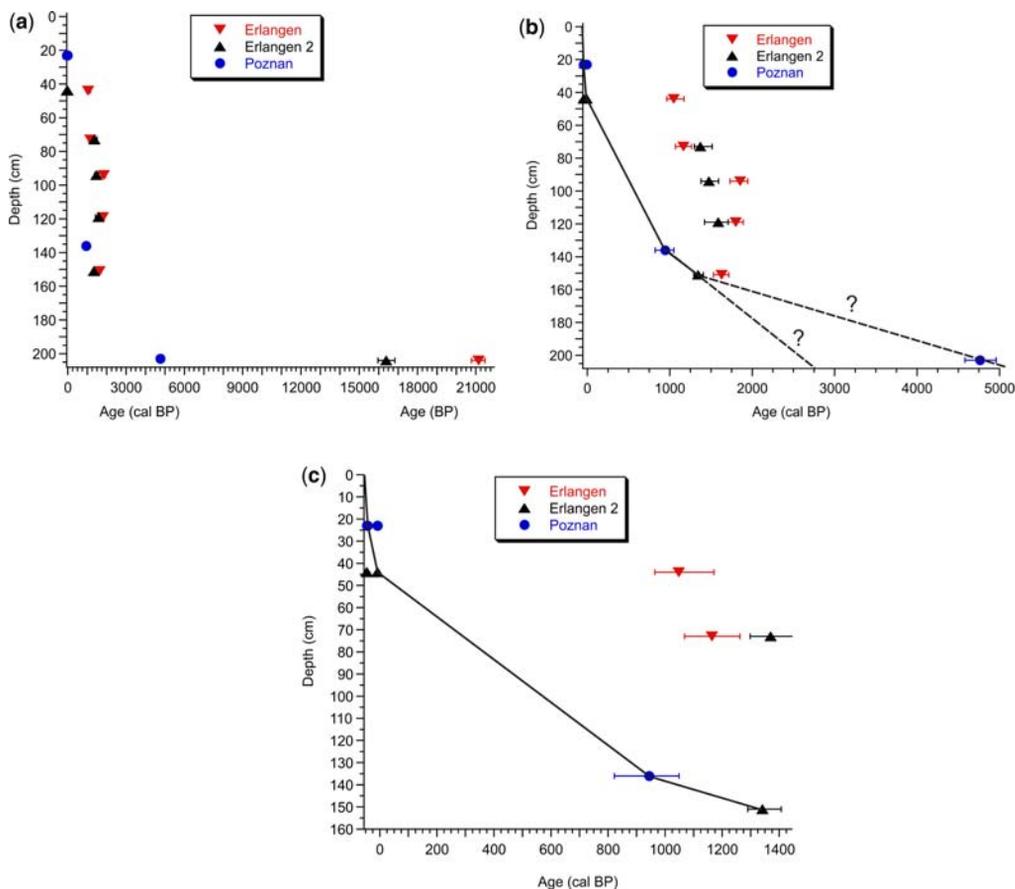


Fig. 2. Age–depth model of the Lake Kalimppaa record. Note different scales. (a) Ages presented as medians of calibrated ages referring to the 2σ ranges (except for two exceeding the Southern Hemisphere calibration curve). The age at 204 cm sediment depth is too old to be calibrated using the Southern Hemisphere calibration curve (McCormac *et al.* 2004). (b) All calibrated ages presented as medians referring to the 2σ ranges. Theoretical age–depth models for the lowermost part of the record are indicated by the dashed lines. (c) Final age–depth model for Lake Kalimppaa cut at 151 cm sediment depth.

from 0 to 60 mT with 5 mT steps as well as at 70 and 80 mT. An isothermal remanent magnetization (IRM) was imparted with a DC field of 0.3 T and subsequently demagnetized and measured using the same steps as with the ARM. Similarly, a second IRM (corresponding to a saturated isothermal remanent magnetization, SIRM) was imparted with a higher DC field of 0.95 T and subsequently demagnetized and measured at 0, 30, 50 and 100 mT.

Hysteresis loops along with remanence curves were measured on small subsamples taken from selected intervals of each u-channel using an alternating gradient force magnetometer (Princeton Measurements Corp., MicroMag model 2900). Magnetization saturation (M_s), coercive force (H_c), saturation remanence (M_{rs}) and coercivity of

remanence (H_{cr}) were extracted from this data to characterize the magnetic mineralogy and magnetic domain state, which can be an indicator of grain size (Day *et al.* 1977).

Results and interpretation

Chronology

Results of the first set of bulk subsamples sent for radiocarbon dating showed inconsistencies, that is, ages were not in stratigraphic order and distinct jumps in sedimentation rate occurred (Fig. 2a, Table 1). Three additional samples dated in a different laboratory revealed even more inconsistencies and would have led to the exclusion of additional

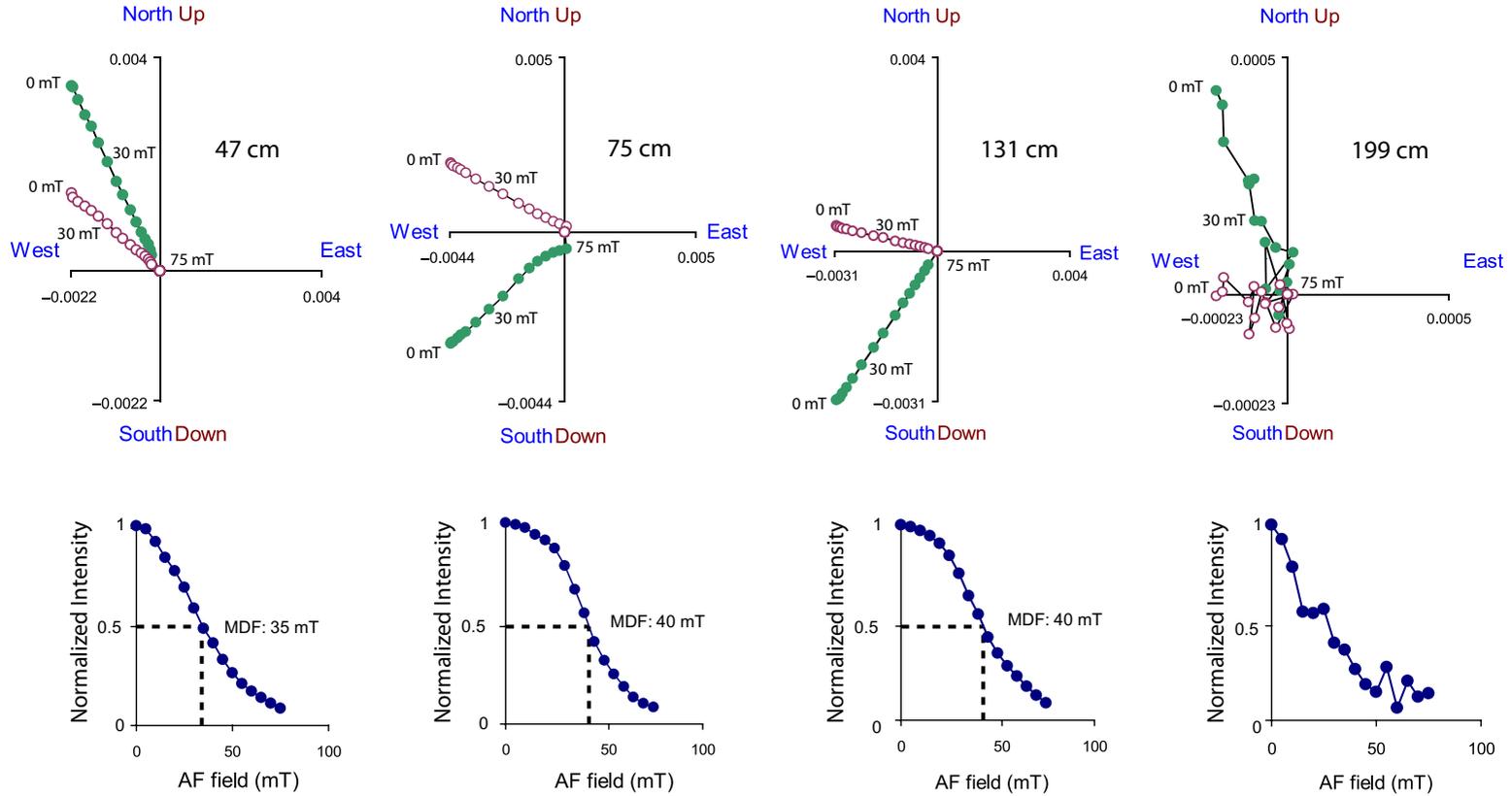


Fig. 3. Typical vector end-point orthogonal projection diagrams for the sediment record of Lake Kalimppaa. Solid dots refer to west–east whereas circles refer to up–down.

ages. For this reason, the first set of subsamples was re-dated and showed different ages from in the first attempt (Fig. 2, Table 1). As a hard-water effect can be excluded at Lake Kalimpaa, this leads to the assumption that there is a different kind of reservoir effect. Most likely, as often happens with bulk sediment samples (Haberzettl *et al.* 2005), not just the autochthonous carbon fraction was dated but also some allochthonous organic matter was

incorporated into the samples. This probably led to the age offsets in either direction between the first and the second dating attempt of the first six samples (Fig. 2, Table 1). This hypothesis is supported by the low $\delta^{13}\text{C}$ values of the dated material ranging from -34.8 to -24.0% , indicating non-algal organic matter contributions (Table 1; Haberzettl *et al.* 2005; Mayr *et al.* 2005). If this is the case, all ages are tentatively too old. In order to

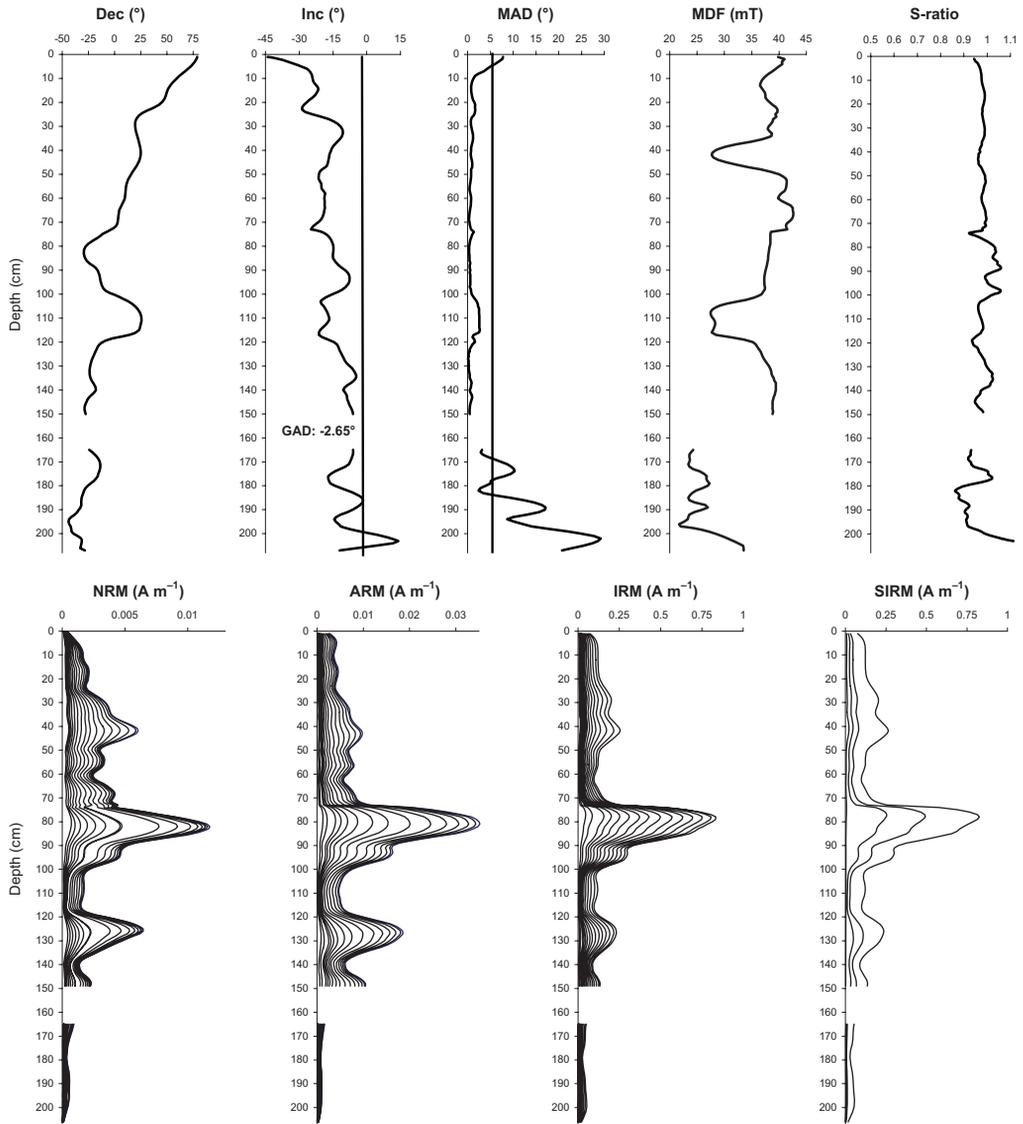


Fig. 4. Declination, inclination, maximum angular deviation, MDF, pseudo S-ratio ($\text{IRM}_{0\text{mT}}/\text{SIRM}_{0\text{mT}}$) as well as downcore variations of NRM, ARM, IRM and SIRM at all demagnetization steps from the Lake Kalimpaa record plotted on a depth scale. Declination and inclination are component directions calculated from the 20–50 mT demagnetization steps.

minimize this error, only the youngest dates were chosen for age–depth modelling and a linear interpolation was applied (Fig. 2). The two/three (one was re-dated) lowermost ages at 203 and 204 cm sediment depth show a clear offset to all ages above. Hence, it was not obvious whether it was suitable to include the youngest of the three in the age model or to do a linear extrapolation using the lowermost more reliable dates above (Fig. 2b). For this reason we decided to cut the record at the lowermost reliable date at 151 cm sediment depth when plotting data on an age scale. Accordingly, the age scale has a basal age of $1340 \pm 65/-50$ cal BP at 151 cm sediment depth (Fig. 2c).

The uppermost 44 cm (-8 cal BP to year of coring, 2006) of the record show an average sedimentation rate of an order of magnitude higher, passing from 0.8 mm a^{-1} to 9.2 mm a^{-1} . This significant increase in the most recent history can probably be explained by human disturbances in the immediate surroundings of the lake (e.g. camp-site or road construction). In order to exclude any impact of this catchment activities, only data before 0 cal BP were used for comparisons later on in this study.

Palaeomagnetic data

A strong and stable characteristic remanent magnetization can be isolated between the AF demagnetization steps of 10 and 50 mT (Fig. 3). Declination data from c. 25–0 cm sediment depth trends from $+79^\circ$ to $+25^\circ$. This seems to be a rather high rate of secular variation for a low-latitude site. We suspect that this is a coring artefact, as is often observed in the uppermost and water saturated part of sediment cores.

Inclination shows an increasing trend with depth (Fig. 4). Values are close to the expected geocentric axial dipole (GAD) (2.65°S for Lake Kalimpaa) showing an average offset of less than c. 12° . Inclination only reaches the expected GAD for the latitude of Lake Kalimpaa in the lowermost part of the record at c. 200 cm, which is in the part of the record that is not plotted on an age scale (Fig. 4).

Maximum angular deviation values are generally lower than 5° in the upper part of the record. MAD values increase to above 10° in the lower part, reaching 30° at the base of the record (Fig. 4). As MAD values can be used to help assess the quality of the directional record, intervals with MAD values above 5 should be considered suspect during times of stable polarity. High MAD values generally reflect a complex magnetization carried by unstable magnetic grains (Stoner & St-Onge 2007). For this reason and because of the uncertainties in the age–depth model in this part of the

record, no palaeomagnetic measurements of section KAL1-3 (165–208 cm sediment depth) were plotted on an age scale.

High MAD values between 208 and 165 cm sediment depth are probably related to the very low magnetic intensity at the base of the record (Fig. 4), resulting in a low signal-noise ratio, and to an increase in magnetic grain size as coarser sediment grains (sand) can be observed macroscopically in this part of the core (Fig. 5). The changes in magnetic grain size are supported by a jump in the median destructive field (MDF) from values oscillating around 40 mT to c. 25 mT (Fig. 4), as well as by samples plotting in the multi-domain range

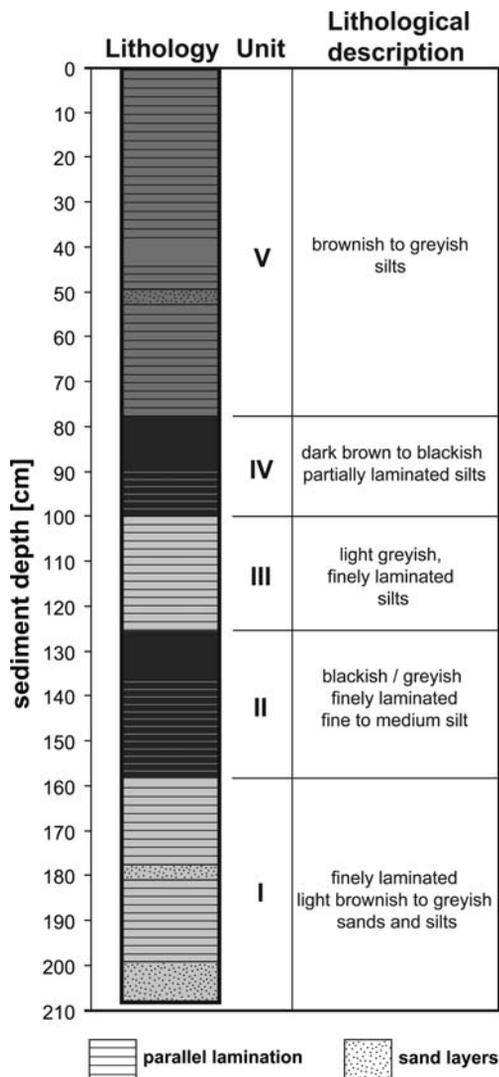


Fig. 5. Lithology of the investigated core.

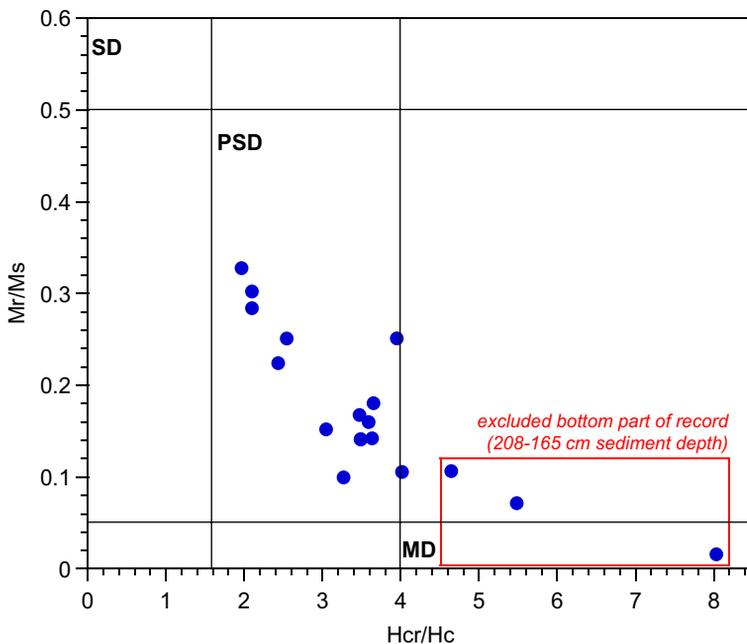


Fig. 6. Day plot using selected samples from the Lake Kalimpaa sediment record.

(Fig. 6). MDF is a grain-size as well as a coercivity-dependent parameter, and is also useful to estimate magnetic mineralogy (Dankers 1981). MDF values of the record indicate low-coercivity minerals in the upper part. This is in agreement with the pseudo *S*-ratio values ($IRM_{0mT}/SIRM_{0mT}$) close to 1, which are also indicative of low coercivity minerals such as magnetite (St-Onge *et al.* 2003). Apart from the excluded basal part of the record with coarser material, changes in magnetic concentration-dependent parameters (NRM, ARM, IRM) are within an order of magnitude (Fig. 4). Finally, most of the studied samples fall in the pseudo-single domain region for magnetite on a Day plot (Day *et al.* 1977). The only exception occurs at the excluded bottom of the record (208–165 cm sediment depth), where samples are in the multi-domain area (Fig. 6) and where MAD values are the highest.

These observations are consistent with a set of criteria (Tauxe 1993; Stoner & St-Onge 2007) proposed to be fulfilled for relative palaeointensity (RPI) determinations. Estimation of RPI of the geomagnetic field in sedimentary sequences is obtained by dividing the measured NRM by an appropriate normalizer in order to compensate for the variable concentration of ferrimagnetic minerals (Tauxe 1993). To construct our RPI proxy, we normalized the NRM_{30mT} by the ARM_{30mT} . No significant correlation between the RPI proxy and its normalizer

was observed ($R^2 = 0.046$), suggesting that ARM is suited for palaeointensity estimations. Additionally, no significant correlation was found between the RPI proxy and magnetic grain size proxies (e.g. ARM/IRM : $R^2 = 0.202$).

No obvious similarities are observed in the details between our RPI reconstruction and the CALS3k.4 (Korte & Constable 2011) spherical harmonic model output for the coring site. However, both graphs show the same trend and slope over the last 1000 cal BP. However, more detailed rock-magnetic work is needed to fully document potential changes in the magnetic carrier and its influence on the RPI estimation.

Discussion

Analogous conservative age–depth modelling approaches were used in other studies before, showing reasonable results when comparing proxy data with nearby other archives (Haberzettl *et al.* 2005; Mayr *et al.* 2005; Kasper *et al.* 2012). Although not to the same extent, similar age reversals observed in Lake Kalimpaa were also found in Wanda Swamp, and were attributed to the mixing of adjacent older sediments (Hope 2001). In Lake Tondano, a modern date was also found at 100–90 cm sediment depth (Dam *et al.* 2001), illustrating that dating lake records from Sulawesi have been similarly

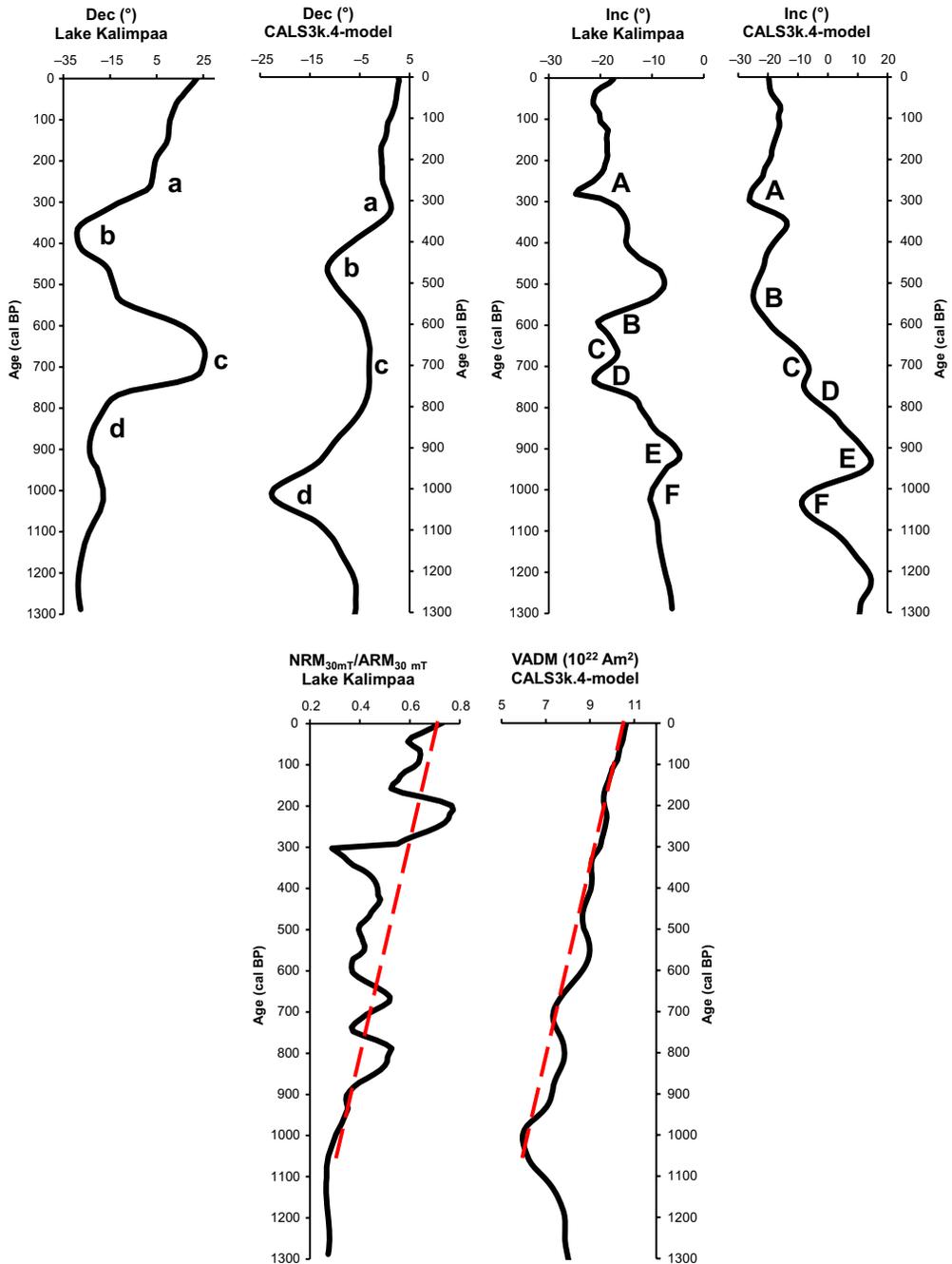


Fig. 7. Comparison of declination, inclination and palaeointensity from the Lake Kalimppaa record with the CALS3k.4 model (Korte & Constable 2011) output for the coordinates of Lake Kalimppaa.

complicated to those at Lake Kalimppaa. However, the authors of the latter do not attribute the young age to an increased sedimentation rate but to an

admixture of recent soil organic matter. At Lake Kalimppaa this seems to be rather unlikely as two ages 21 cm apart show such young (modern) ages

(Fig. 2, Table 1). Hence, we have to assume that both ages are correct and attribute this to human influence in the catchment area.

Although it was challenging to construct an initial age model, there are many similarities in inclination and declination, as well as a similar trend in palaeointensity between the Lake Kalimppaa record and the CALS3k.4 model output (Korte & Constable 2011; Fig. 7). Comparison of the inclination from Lake Kalimppaa to the SE Australia inclination master curve (KBG) consisting of data from three Australian maars, that is, lakes Keilambete, Bullenmerri and Gnotuk in SW Victoria (Barton & Polach 1980; Barton & McElhinny 1981), also reveals similar trends (Fig. 8). This might be attributed to the fact that, after statistical treatment (Donadini *et al.* 2009), parts of the underlying three records are contained in the database of the CALS3k.4 model (Korte & Constable 2011). Correlating the remanence record of the SE Australia master curve is best done using inclination, which displays characteristic swings. The declination record is less suitable because it seems devoid of clear correlatable features between the Australian maars (Anker *et al.* 2001). However, chronologies of Lake Kalimppaa and the KGB are expected to differ distinctively. Comparisons of the KBG record with other data for SE Australia covering the past 2500 years (Barton & Barbetti 1982) suggested that KBG ages might be older by about 350 calendar years owing to a reservoir effect (Barton & Barbetti 1982; Anker *et al.* 2001). Because of these uncertainties, we consider the KBG record to support our measurements but do not use it to date the Kalimppaa record. Furthermore, the resolution of the KBG record is one order of magnitude lower than the Kalimppaa record (13 v. 150 data points, i.e. centennial v. decadal resolution). Despite this different resolution, the SE Australia records deviates from the GAD as in the Lake Kalimppaa record (Anker *et al.* 2001).

When developing the CALS3k.3 model (Korte *et al.* 2009), several inconsistencies either within records or when compared with other nearby records had already been observed for many records (Donadini *et al.* 2009). The authors tried to overcome these problems using a statistical rejection of outliers. This led to a rejection of 34% of the data (Donadini *et al.* 2009) and a resolution of c. 100 years (Korte & Constable 2003).

The similarities of the Lake Kalimppaa full vector palaeomagnetic data to the model (Fig. 7) indicate that the age model is a good first-order approximation. Differences lie within the error in the chronology determined by age-modelling artefacts owing to linear interpolation and the error in the radiocarbon dating method itself, which according to the accepted ages in this study ranges between 50 and

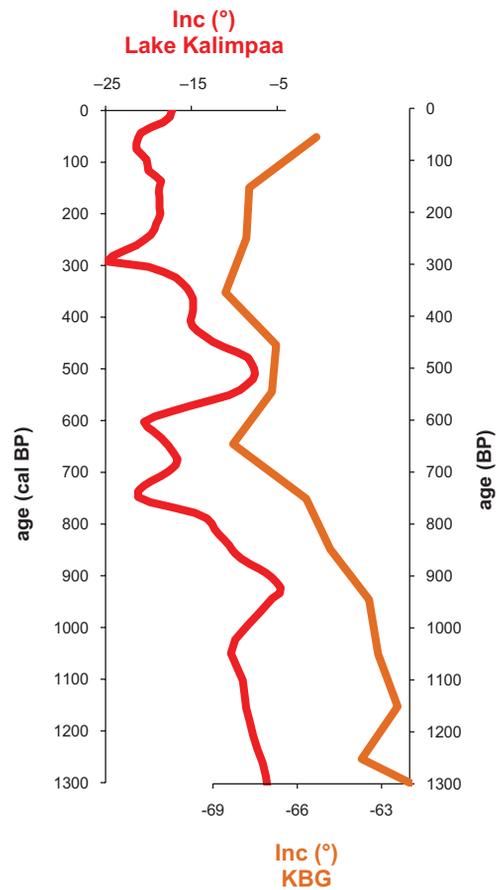


Fig. 8. Comparison of inclination from Lake Kalimppaa with inclination from the SE Australia inclination master curve (KBG; Barton & Polach 1980; Barton & McElhinny 1981) digitized from Anker *et al.* (2001). Note that Lake Kalimppaa data is given in cal BP whereas the KBG data is plotted on a BP age scale. Because of age and reservoir-effect uncertainties (Barton & Barbetti 1982; Anker *et al.* 2001), we consider the KBG record to support our measurements but do not use it to date the Kalimppaa record.

120 years (Table 1, Fig. 7). With the established age model, it is now possible for upcoming studies to set multi-proxy analyses in a time frame. This provides a reliable chronology for this record as further radiocarbon dates would not improve the chronology since they might also be influenced by remobilization of old organic matter. This is very important as the time span covered by the Lake Kalimppaa record is missing in the surrounding archives (Hope 2001).

As far as the palaeomagnetic data are concerned, this paper is the first high-resolution study in this area. Sedimentation rates are up to three times

higher than in the available sediment records from the marine domain surrounding Sulawesi. These marine records normally cover the entire Holocene but often yield only a little information in the top-most part (Lund *et al.* 2006). Our data thus complement the published marine dataset.

The value of the Lake Kalimpa record is increased further as it has good coverage of the past 400 years. There are few archives available for modelling palaeosecular variations after the year 1600, which can be attributed to frequent loss or disturbance of material near the sediment–water interface during coring (Donadini *et al.* 2009). Owing to the high sedimentation rate at the top of the Lake Kalimpa record, even the top-most part (which might be influenced by coring artefacts) can be removed without great loss of information.

Conclusions

Although the radiocarbon-derived age–depth model of Lake Kalimpa is conservative, a comparison of the full vector palaeomagnetic data with the CALS3k.4 geomagnetic spherical harmonic model confirms this approach. This leads to the conclusion that the presented age model is well suited for further multi-proxy palaeoenvironmental investigations, which are necessary as many archives from Indonesia miss the top-most part of the records. Finally, the palaeomagnetic data from this paper constitute the first continuous high-resolution terrestrial record from Indonesia, yielding a detailed full-vector palaeomagnetic record from 1300 cal BP up to the present.

We would like to acknowledge the helping hands of C. Brunshöen and J. Labrie during u-channel sub-sampling and laboratory work as well as comments from Monika Korte on an earlier version of this manuscript. M. Markussen is thanked for background information about the surrounding of Lake Kalimpa, and M. Wüdsch for assistance with graphs. T. Habertzettl was supported by a post-doctoral fellowship scholarship provided by Le Fonds québécois de la recherche sur la nature et les technologies (FQRNT). Guillaume St-Onge was supported by a Natural Sciences and Engineering Research Council of Canada discovery grant and Canadian Foundation for Innovation grants for the acquisition and operation of the cryogenic magnetometer. Sediment coring/research was carried out as part of subproject C7 of the Collaborative Research Centre SFB 552 ‘Stability in Rainforest Margins’, at the University of Göttingen, and was funded by the DFG, Germany. We gratefully acknowledge logistic support from STORMA’s Indonesian partner universities in Bogor and Palu, Institut Pertanian Bogor and Universitas Tadulako, the Ministry of Education in Jakarta, the Indonesian Institute of Sciences, and the authorities of the Lore Lindu National Park. Finally, we would like to thank Mr Iksam, State Museum Central Sulawesi, Palu, Indonesia, for his support with sediment coring.

References

- ALI, M., ODA, H., HAYASHIDA, A., TAKEMURA, K. & TORII, M. 1999. Holocene palaeomagnetic secular variation at Lake Biwa, central Japan. *Geophysical Journal International*, **136**, 218–228.
- ANKER, S. A., COLHOUN, E. A., BARTON, C. E., PETERSON, M. & BARBETTI, M. 2001. Holocene vegetation and paleoclimatic and paleomagnetic history from lake Johnston, Tasmania. *Quaternary Research*, **56**, 264–274.
- ANSHARI, G., PETER KERSHAW, A. & VAN DER KAARS, S. 2001. A Late Pleistocene and Holocene pollen and charcoal record from peat swamp forest, Lake Sentarum Wildlife Reserve, West Kalimantan, Indonesia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **171**, 213–228.
- ANSHARI, G., KERSHAW, A. P., VAN DER KAARS, S. & JACOBSEN, G. 2004. Environmental change and peatland forest dynamics in the Lake Sentarum area, West Kalimantan, Indonesia. *Journal of Quaternary Science*, **19**, 637–655.
- BARLETTA, F., ST-ONGE, G., CHANNELL, J. E. T. & ROCHON, A. 2010. Dating of Holocene western Canadian Arctic sediments by matching paleomagnetic secular variation to a geomagnetic field model. *Quaternary Science Reviews*, **29**, 2315–2324.
- BARTON, C. E. & BARBETTI, M. 1982. Geomagnetic secular variation from recent lake sediments, ancient fireplaces and historical measurements in southeastern Australia. *Earth and Planetary Science Letters*, **59**, 375–387.
- BARTON, C. E. & McELHINNY, M. W. 1981. A 10 000 yr geomagnetic secular variation record from three Australian maars. *Geophysical Journal International*, **67**, 465–485.
- BARTON, C. E. & POLACH, H. A. 1980. ¹⁴C ages and magnetic stratigraphy in 3 Australian maars. *Radiocarbon*, **22**, 728–739.
- BRUIKER, J. M., JUNG, S. J. A., GANSEN, G. M., BICKERT, T. & KROON, D. 2007. ENSO related decadal scale climate variability from the Indo-Pacific Warm Pool. *Earth and Planetary Science Letters*, **253**, 67–82.
- CONSTABLE, C. G. 1985. Eastern Australian geomagnetic field intensity over the past 14000 yr. *Geophysical Journal of the Royal Astronomical Society*, **81**, 121–130.
- CONSTABLE, C. G. & TAUXE, L. 1987. Palaeointensity in the pelagic realm: marine sediment data compared with archaeomagnetic and lake sediment records. *Geophysical Journal of the Royal Astronomical Society*, **90**, 43–59.
- CRAUSBAY, S., RUSSELL, J. & SCHNURRENBERGER, D. 2006. A ca. 800-year lithologic record of drought from sub-annually laminated lake sediment, East Java. *Journal of Paleolimnology*, **35**, 641–659.
- DAM, R. A. C., FLUIN, J., SUPARAN, P. & VAN DER KAARS, S. 2001. Palaeoenvironmental developments in the Lake Tondano area (N. Sulawesi, Indonesia) since 33 000 yr B.P. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **171**, 147–183.
- DANKERS, P. 1981. Relationship between median destructive field and remanent coercive forces for dispersed natural magnetite, titanomagnetite and hematite. *Geophysical Journal of the Royal Astronomical Society*, **64**, 447–461.

- DAY, R., FULLER, M. & SCHMIDT, V. A. 1977. Hysteresis properties of titanomagnetites: grain-size and compositional dependence. *Physics of The Earth and Planetary Interiors*, **13**, 260–267.
- DONADINI, F., KORTE, M. & CONSTABLE, C. G. 2009. Geomagnetic field for 0–3 ka: 1. New data sets for global modeling. *Geochemistry, Geophysics and Geosystems*, **10**, Q06007, <http://dx.doi.org/10.1029/2008GC002295>.
- GREMMEN, W. H. E. 1990. Palynological investigations in the Danau Tempe depression, southwest Sulawesi (Celebes) Indonesia. *Modern Quaternary Research in Southeast Asia*, **11**, 123–134.
- GUTKNECHT, B. 2008. *Organische Geochemie (CNS-Analytik) an einem Sedimentkern des Kalimpaa Sees (Indonesien)*. BSc thesis, University of Göttingen.
- HABERLE, S. G. 1998. Late Quaternary vegetation change in the Tari Basin, Papua New Guinea. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **137**, 1–24.
- HABERLE, S. G. & LEDRU, M. P. 2001. Correlations among charcoal records of fires from the past 16 000 years in Indonesia, Papua New Guinea, and Central and South America. *Quaternary Research*, **55**, 97–104.
- HABERLE, S. G., HOPE, G. S. & VAN DER KAARS, S. 2001. Biomass burning in Indonesia and Papua New Guinea: natural and human induced fire events in the fossil record. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **171**, 259–268.
- HABERZETTL, T., FEY, M. *ET AL.* 2005. Climatically induced lake level changes during the last two millennia as reflected in sediments of Laguna Potrok Aike, southern Patagonia (Santa Cruz, Argentina). *Journal of Paleolimnology*, **33**, 283–302.
- HOPE, G. 2001. Environmental change in the Late Pleistocene and later Holocene at Wanda site, Soroako, South Sulawesi, Indonesia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **171**, 129–145.
- HOPE, G. 2009. Environmental change and fire in the Owen Stanley Ranges, Papua New Guinea. *Quaternary Science Reviews*, **28**, 2261–2276.
- HOPE, G., GILLIESON, D. & HEAD, J. 1988. A comparison of sedimentation and environmental change in New Guinea Shallow Lakes. *Journal of Biogeography*, **15**, 603–618.
- HOPE, G., CHOKKALINGAM, U. & ANWAR, S. 2005. The stratigraphy and fire history of the Kutai Peatlands, Kalimantan, Indonesia. *Quaternary Research*, **64**, 407–417.
- KASPER, T., HABERZETTL, T. *ET AL.* 2012. Indian Ocean Summer Monsoon (IOSM)-dynamics within the past 4 ka in the sediments of Lake Nam Co, central Tibetan Plateau. *Quaternary Science Reviews*, **39**, 73–85.
- KIRLEIS, W., PILLAR, V. & BEHLING, H. 2011. Human–environment interactions in mountain rainforests: archaeobotanical evidence from central Sulawesi, Indonesia. *Vegetation History and Archaeobotany*, **20**, 165–179, <http://dx.doi.org/10.1007/s00334-010-0272-0>.
- KIRSCHVINK, J. L. 1980. The least-squares line and plane and the analysis of palaeomagnetic data. *Geophysical Journal of the Royal Astronomical Society*, **62**, 699–718.
- KORTE, M. & CONSTABLE, C. 2003. Continuous global geomagnetic field models for the past 3000 years. *Physics of the Earth and Planetary Interiors*, **140**, 73–89.
- KORTE, M. & CONSTABLE, C. 2011. Improving geomagnetic field reconstructions for 0–3 ka. *Physics of the Earth and Planetary Interiors*, **188**, 247–259.
- KORTE, M., DONADINI, F. & CONSTABLE, C. G. 2009. Geomagnetic field for 0–3 ka: 2. A new series of time-varying global models. *Geochemistry, Geophysics and Geosystems*, **10**.
- LANGTON, S. J., LINSLEY, B. K. *ET AL.* 2008. 3500 yr record of centennial-scale climate variability from the Western Pacific Warm Pool. *Geology*, **36**, 795–798.
- LEDU, D., ROCHON, A., DE VERNAL, A. & ST-ONGE, G. 2010. Holocene paleoceanography of the northwest passage, Canadian Arctic Archipelago. *Quaternary Science Reviews*, **29**, 3468–3488.
- LINSLEY, B. K., ROSENTHAL, Y. & OPPO, D. W. 2010. Holocene evolution of the Indonesian throughflow and the western Pacific warm pool. *Nature Geoscience*, **3**, 578–583.
- LUND, S. P., STOTT, L., SCHWARTZ, M., THUNELL, R. & CHEN, A. 2006. Holocene paleomagnetic secular variation records from the western Equatorial Pacific Ocean. *Earth and Planetary Science Letters*, **246**, 381–392.
- MAYR, C., FEY, M. *ET AL.* 2005. Palaeoenvironmental changes in southern Patagonia during the last millennium recorded in lake sediments from Laguna Azul (Argentina). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **228**, 203–227.
- MAZAUD, A. 2005. User-friendly software for vector analysis of the magnetization of long sediment cores. *Geochemistry, Geophysics and Geosystems*, **6**, Q12006, <http://dx.doi.org/10.1029/2005GC001036>.
- MCCORMAC, F., HOGG, A., BLACKWELL, P., BUCK, C., HIGHAM, T. & REIMER, P. 2004. SHCal104 Southern Hemisphere calibration 0–11.0 cal kyr BP. *Radiocarbon*, **46**, 1087–1092.
- MERKER, S. 2003. *Vom Aussterben bedroht oder anpassungsfähig? – Der Koboldmaki Tarsius diana in den Regenwäldern Sulawesi*. PhD thesis, University of Göttingen.
- MORLEY, R. J. 1981. Development and vegetation dynamics of a lowland Ombrogenous peat swamp in Kalimantan Tengah, Indonesia. *Journal of Biogeography*, **8**, 383–404.
- NEWTON, A., THUNELL, R. & STOTT, L. 2006. Climate and hydrographic variability in the Indo-Pacific Warm Pool during the last millennium. *Geophysics Research Letters*, **33**, L19710.
- OPPO, D. W., ROSENTHAL, Y. & LINSLEY, B. K. 2009. 2000-Year-long temperature and hydrology reconstructions from the Indo-Pacific warm pool. *Nature*, **460**, 1113–1116.
- PAGE, S. E., WÜST, R. A. J., WEISS, D., RIELEY, J. O., SHOTYK, W. & LIMIN, S. H. 2004. A record of Late Pleistocene and Holocene carbon accumulation and climate change from an equatorial peat bog (Kalimantan, Indonesia): implications for past, present and future carbon dynamics. *Journal of Quaternary Science*, **19**, 625–635.
- REIMER, P. J., BROWN, T. A. & REIMER, R. W. 2004. Discussion: reporting and calibration of post-bomb ¹⁴C data. *Radiocarbon*, **46**, 1299–1304.

- RICHTER, C., VENUTI, A., VEROSUB, K. L. & WEI, K. Y. 2006. Variations of the geomagnetic field during the Holocene: Relative paleointensity and inclination record from the West Pacific (ODP Hole 1202B). *Physics of the Earth and Planetary Interiors*, **156**, 179–193.
- SPOONER, M. I., BARROWS, T. T., DE DECKKER, P. & PATERNE, M. 2005. Palaeoceanography of the Banda Sea, and Late Pleistocene initiation of the Northwest Monsoon. *Global and Planetary Change*, **49**, 28–46.
- STONER, J. S. & ST-ONGE, G. 2007. Magnetic stratigraphy in paleoceanography: reversals, excursions, paleointensity, and secular variation. In: *Developments in Marine Geology*. Elsevier, Amsterdam, **1**, 99–138.
- ST-ONGE, G., STONER, J. S. & HILLAIRE-MARCEL, C. 2003. Holocene paleomagnetic records from the St. Lawrence Estuary, eastern Canada: centennial- to millennial-scale geomagnetic modulation of cosmogenic isotopes. *Earth and Planetary Science Letters*, **209**, 113–130.
- STUIJTS, I., NEWSOME, J. C. & FLENLEY, J. R. 1988. Evidence for late quaternary vegetational change in the Sumatran and Javan highlands. *Review of Palaeobotany and Palynology*, **55**, 207–216.
- STUIVER, M. & REIMER, P. 1993. Extended ^{14}C database and revised CALIB radiocarbon calibration program. *Radiocarbon*, **35**, 215–230.
- SUPARAN, P., DAM, R. A. C., VAN DER KAARS, S. & WONG, T. E. 2001. Late Quaternary tropical lowland environments on Halmahera, Indonesia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **171**, 229–258.
- TAUXE, L. 1993. Sedimentary records of relative paleointensity of the geomagnetic field: theory and practice. *Reviews in Geophysics*, **31**, 319–354.
- VAN DER KAARS, W. A. & DAM, M. A. C. 1995. A 135 000-year record of vegetational and climatic change from the Bandung area, West-Java, Indonesia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **117**, 55–72.
- VAN DER KAARS, S., WANG, X., KERSHAW, P., GUICHARD, F. & ARIFIN SETIABUDI, D. 2000. A Late Quaternary palaeoecological record from the Banda Sea, Indonesia: patterns of vegetation, climate and biomass burning in Indonesia and northern Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **155**, 135–153.
- VAN DER KAARS, S., PENNY, D., TIBBY, J., FLUIN, J., DAM, R. A. C. & SUPARAN, P. 2001. Late Quaternary palaeoecology, palynology and palaeolimnology of a tropical lowland swamp: Rawa Danau, West-Java, Indonesia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **171**, 185–212.
- VILLENEUVE, M., GUNAWAN, W., CORNEE, J. J. & VIDAL, O. 2002. Geology of the central Sulawesi belt (eastern Indonesia): constraints for geodynamic models. *International Journal of Earth Sciences*, **91**, 524–537.
- WEBER, R. 2006. Kulturlandschaftswandel in Zentralsulawesi Historisch-geographische Analyse einer indonesischen Bergregenwaldregion. *Pazifik Forum Band*, **12**, 42–49.
- YANG, X., HELLER, F., YANG, J. & SU, Z. 2009. Paleosecular variations since ~9000 yr BP as recorded by sediments from maar lake Shuangchiling, Hainan, South China. *Earth and Planetary Science Letters*, **288**, 1–9.
- YULIANTO, E., RAHARDJO, A. T., NOERADI, D., SIREGAR, D. A. & HIRAKAWA, K. 2005. A Holocene pollen record of vegetation and coastal environmental changes in the coastal swamp forest at Batulicin, South Kalimantan, Indonesia. *Journal of Asian Earth Sciences*, **25**, 1–8.