Earth and Planetary Science Letters 416 (2015) 98–108

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Independently dated paleomagnetic secular variation records from the Tibetan Plateau

Torsten Haberzettl[a,*], Karoline Henkel[a], Thomas Kasper[a], Marieke Ahlborn[a], Youliang Su[b], Junbo Wang[c], Erwin Appel[d], Guillaume St-Onge[e], Joseph Stoner[f], Gerhard Daut[a], Liping Zhu[c], Roland Mäusbacher[a]

[a] Physical Geography, Institute of Geography, Friedrich Schiller University Jena, Löbdergraben 32, 07743 Jena, Germany
[b] Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100101, China
[c] Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100029, China
[d] Department of Geosciences, University of Tübingen, Hölderlinstr. 12, 72074 Tübingen, Germany
[e] Institut des sciences de la mer de Rimouski (ISMER), Université du Québec à Rimouski and GEOTOP, 310 allée des Ursulines, Rimouski G5L 3A1, Canada
[f] Paleomagnetic & Environmental Magnetic Research Laboratory, College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, 104 CEOAS Admin Building, Corvallis, OR 97331, USA

A R T I C L E   I N F O

Article history:
Received 22 August 2014
Received in revised form 21 November 2014
Accepted 9 February 2015
Available online xxxx
Editor: P. Shearer

Keywords:
magnetostratigraphy
inclination
Tibet
lacustrine sediments
Tangra Yumco
Taro Co

A B S T R A C T

Magnetostratigraphy has been serving as a valuable tool for dating and confirming chronologies of lacustrine sediments in many parts of the world. Suitable paleomagnetic records on the Tibetan Plateau (TP) and adjacent areas are, however, extremely scarce. Here, we derive paleomagnetic records from independently radiocarbon-dated sediments from two lakes separated by 250 km on the southern central TP, Tangra Yumco and Taro Co. Studied through alternating field demagnetization of u-channel samples, characteristic remanent magnetization (ChRM) directions document similar inclination patterns in multiple sediment cores for the past 4000 years. Comparisons to an existing record from Nam Co, a lake 350 km east of Tangra Yumco, a varve-dated record from the Makran Accretionary Wedge, records from Lakes Issyk-Kul and Baikal, and a stack record from East Asia reveal many similarities in inclination. This regional similarity demonstrates the high potential of inclination to compare records over the Tibetan Plateau and eventually date other Tibetan records stratigraphically. PSV similarities over such a large area (>3000 km) suggest a large-scale core dynamic origin rather than small scale processes like drift of the non-dipole field often associated with PSV records.

1. Introduction

During the past decade an increasing number of paleoenvironmental studies have been conducted on the Tibetan Plateau (TP) (Doberschütz et al., 2014; Hou et al., 2012). This is due to the fact that the TP is a rather pristine, anthropogenically hardly influenced area that offers many promising archives for paleoenvironmental studies. A significant feature on the TP is the existence of more than 1600 lakes covering an area greater than 1 km^2 (Zheng, 1997) containing often undisturbed thick sediment packages suitable for high-resolution investigations. Thus most of the studies use lacustrine sediments for reconstructions.

Radiocarbon dating has been the most commonly applied method to establish chronologies for these records. Unfortunately, dating these sediments is a challenge since most of the lacustrine archives are affected by a reservoir effect (Mischke et al., 2013). This reservoir effect varies from lake to lake and can be as high as >6000 years (Hou et al., 2012). To overcome this issue usually, an age obtained from the sediment–water interface or modern water plant is subtracted from the remaining ages using the assumption of a constant reservoir effect over time (Hou et al., 2012; Kasper et al., 2012; Mischke et al., 2013).

Environmental magnetism has been commonly used around the TP (Herb et al., 2013; Su et al., 2013a, 2013b; Zhu et al., 2003), however, using magnetostratigraphy to evaluate radiocarbon based chronologies has only been employed in a single study from Nam Co (co means lake, Fig. 1) (Kasper et al., 2012).

Here we present a series of new inclination and declination records from two large lakes on the central TP called Tangra Yumco and Taro Co (Fig. 1). These records will be evaluated against each other and compared to the existing study from Nam Co (Kasper et al., 2012), a varve-dated record from the Makran Accretionary

* Corresponding author. Tel.: +49 (0)3641 948815; fax: +49 (0)3641 948812.
E-mail address: torsten.haberzettl@uni-jena.de (T. Haberzettl).

http://dx.doi.org/10.1016/j.epsl.2015.02.007

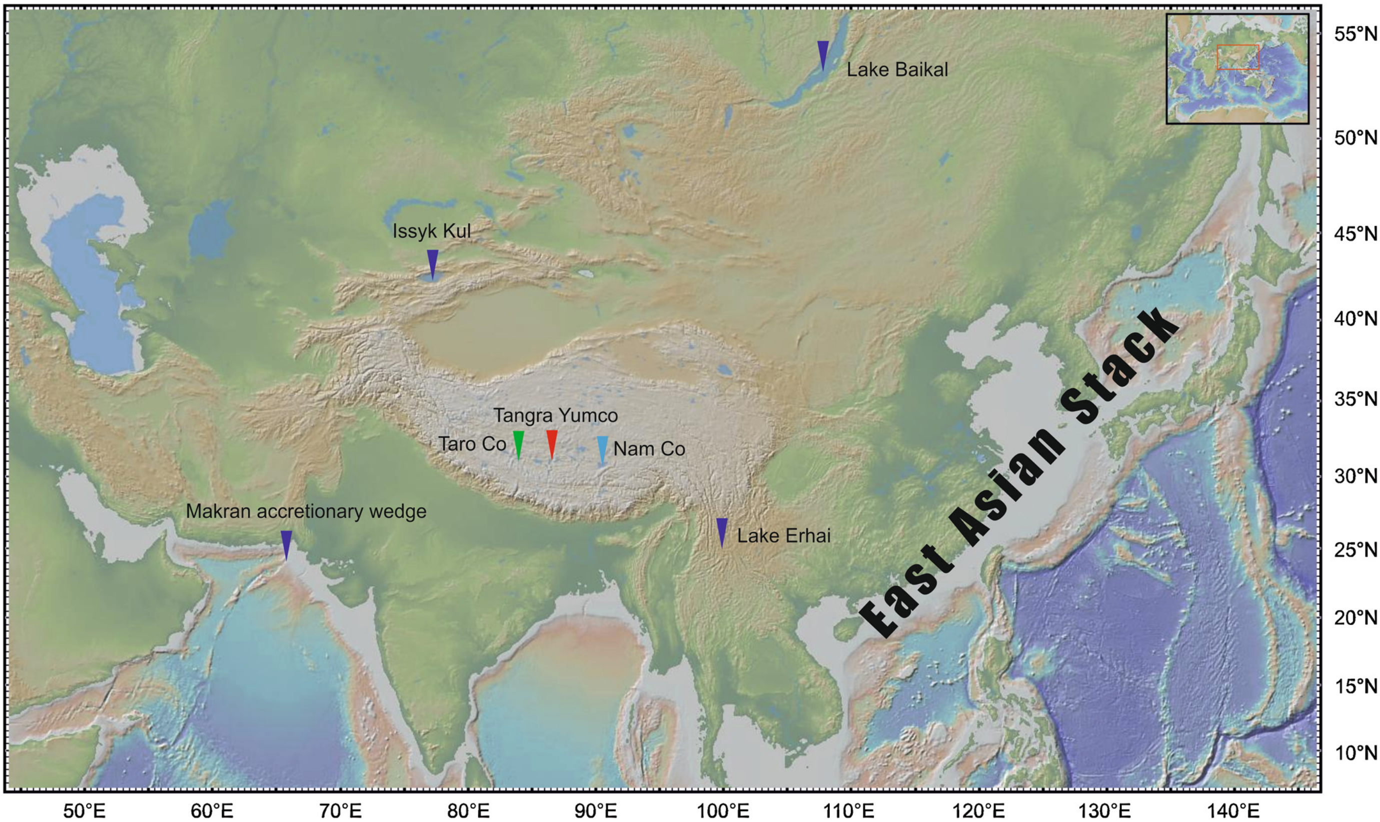

Fig. 1. Map of the research area showing locations mentioned in the text (underlying base map: http://www.geomapapp.org).

Table 1
Characteristics of the investigated u-channels.

Lake	Sediment core	U-channel length [cm] (Record length [cm])	Min. distance to shore [km]	Latitude [°N]	Longitude [°E]	Water depth [m]
Tangra Yumco	TAN 10-1	169	2.9	31.261100	86.667433	186
Tangra Yumco	TAN 10-3	137 (127 after compaction)	4.4	31.249900	86.727150	223
Tangra Yumco	TAN 10-4	162 (128 event corrected)	4.7	31.252650	86.722817	223
Taro Co	TOC 11-3	123	2.8	31.168733	84.201867	68
Taro Co	TOC 11-4	122	2.8	31.168900	84.201933	68

Wedge (Müller, 2004) to the southwest, records from Lakes Issyk-Kul (northwest) (Gómez-Paccard et al., 2012) and Baikal (north) (Peck et al., 1996), the paleomagnetic secular variation (PSV) stack of East Asia (Zheng et al., 2014) to the east as well as predictions from a new global geomagnetic field model, i.e., the pfm9k (Nilsson et al., 2014). The focus of this contribution will be on the past 4000 cal BP since more data for comparison are available for this interval.

2. Site description

Separated by 250 km, Tangra Yumco (31.25° N; 86.72° E) and Taro Co (31.17° N; 84.20° E) are located on the southern central Tibetan Plateau (Fig. 1). Nam Co is located 350 km further east (Fig. 1) forming a transect along the latitude 31° N. Taro Co is a freshwater open lake system, whereas Tangra Yumco is a brackish terminal lake (Dietze et al., 2014). Both lakes are located above 4500 m asl (Taro Co: 4570 m asl; Tangra Yumco: 4550 m asl). With an area of 824 km^2, a catchment of 9893 km^2 (Wang et al., 2010) and water depth of 230 m Tangra Yumco is much larger and deeper than Taro Co which has a size of 474 km^2, a catchment of 7423 km^2 (Dietze et al., 2014) and a maximum water depth of 130 m.

3. Materials and methods

3.1. Core recovery and paleomagnetic measurements

Three sediment cores from Tangra Yumco (TAN) and two sediment cores from Taro Co (TOC) were recovered using a modified ETH-gravity corer (Kelts et al., 1986) (Table 1). Paired cores of TAN10-3 and 4 (first number represents year of coring – followed by core number) and TOC11-3 and 4 are from the same approximate locations with slight differences resulting from drifting during gravity core recovery.

The natural remanent magnetization (NRM) was studied using stepwise (up to 17 steps) alternating field (AF) demagnetization with peak AFs from 0 to 60–100 mT (depending on the sediment core) on u-channels collected from split cores. AFs were incremented at 5 mT steps from 0 to 60 mT, and 10 mT steps from 60 to 100 mT. NRM was acquired continuously at 1 cm intervals using 2G Enterprises DC-4K liquid helium free magnetometers (Model 755-1.65 UC) with a water cooled compressor at the University of Tübingen, Germany and at the University of Québec at Rimouski, Canada. Inclination and declination of the characteristic remanent magnetization (ChRM) and maximum angular deviation (MAD) values were determined using principle compo-

Table 2
Radiocarbon ages from various sediment cores from the Tibetan Plateau.

Sediment core	Sediment depth (cm)/ Event corrected depth (ECD in cm)	Conventional radiocarbon age (BP)	Error	Reservoir corrected radiocarbon age (BP)	Reservoir corrected calibrated median age (cal BP)	Reservoir corrected max age (cal BP)	Reservoir corrected min age (cal BP)	Lab No	Material
TOC11-4	surface	120**	30		−61*	−61*	−61*	322 421	bulk
TOC11-4	25.5	1560	30	1440	1330	1380	1295	322 422	bulk
TOC11-4	47.5	2710	30	2590	2740	2770	2545	322 423	bulk
TOC11-4	76.5	4040	30	3920	4360	4430	4250	322 424	bulk
TOC11-4	98.5	5960	40	5840	6660	6745	6530	322 425	bulk
TOC11-4	121.25	6490	40	6370	7310	7420	7180	322 426	bulk
TAN10-1	surface	2200**	30		−60*	−60*	−60*	291 393	bulk
(*TAN10-1*	*68.5*	5730	*50*	*3530*	*3800*	*3965*	*3650*	*291 394*	*bulk*)****
TAN10-1	91.25	4430	40	2230	2230	2335	2150	291 395	bulk
TAN10-1	108	5240	40	3040	3250	3360	3080	291 396	bulk
(*TAN10-1*	*137*	*7970*	*50*	*5770*	*6570*	*6675*	*6445*	*291 397*	*bulk*)****
(*TAN10-1*	*155.25*	*6140*	*40*	*3940*	*4380*	*4515*	*4250*	*291 398*	*bulk*)****
TAN10-1	168	5880	40	3680	4020	4145	3895	291 399	bulk
TAN10-4	surface	2140**	30		−60*	−60*	−60*	295 002	
(*TAN10-4*	*24* (*ECD: 16*)	*3450*	*40*	*1310*	*1250*	*1300*	*1180*	*295 003*	*bulk*)****
TAN10-4	41 (ECD: 33)	3410	40	1270	1220	1290	1085	295 004	bulk
(*TAN10-4*	*78.5* (*ECD: 70.5*)	*4940*	*30*	*2800*	*2900*	*2975*	*2795*	*382 663*	*bulk*)****
TAN10-4	115.5 (ECD: 100.5)	2480	30	2480	2580	2720	2385	295 005	wood***
TAN10-4	152.25 (ECD: 124.25)	5260	40	3120	3340	3445	3225	295 006	bulk
	modern water plant	2070	40					289 070	modern water plant

* Year of coring.
** Age used for reservoir correction.
*** No reservoir correction.
**** *Not used for chronology*.

nent analyses (Kirschvink, 1980) implemented in an Excel macro (Mazaud, 2005) also allowing to calculate the Median Destructive Field (MDF). Declination data are relative and centered to zero since the azimuth could not be controlled during coring. Owing to the width of the response function of the SQUID sensors some smoothing occurs in the data (Weeks et al., 1993). In order to eliminate edge effects, 6 cm were removed from the top and bottom of each u-channel and the age at the top of plots begins at 0 cal BP (AD 1950).

3.2. Age-depth modeling

Due to a lack of plant macro remains bulk sediments were sampled and sent for radiocarbon dating to Beta Analytic Inc. (USA). Five bulk sediment ages were obtained from gravity core TOC11-4 from Taro Co, six ages from TAN10-1, and four bulk dates and one wood fragment age from TAN10-4 from Tangra Yumco. The sediment–water interface of each core was also radiocarbon-dated to provide information on the recent reservoir effect at each location. Assuming a constant reservoir effect over time except for the age obtained from the terrestrial wood sample, the surface age was subsequently subtracted from the conventional ages of the respective core before calibration (Table 2). To further assess the reliability of these reservoir-effect corrections a modern water plant from Tangra Yumco was also dated. After reservoir correction, calibrated median ages and 2σ errors were calculated with the online version of the software Calib 7.0 (http://calib.qub.ac.uk/calib/) (Stuiver and Reimer, 1993) applying the IntCal13 data set (Reimer et al., 2013). For consistency a linear interpolation between median ages was applied to establish the chronologies of all dated sediment cores. In addition to radiocarbon dating the activity of ^{210}Pb was measured on the upper 7 cm of TOC11-4 with a CRS-model applied (Appleby, 2008; Appleby and Oldfield, 1978). This data was used along with the radiocarbon ages to establish a chronology for this core.

4. Lithology and comparison of paleomagnetic results on a depth scale

Based on sediment color, grain sizes and micro-facies sediment cores from Tangra Yumco can be characterized as horizontally layered with layers of various thicknesses between <1 mm and 5 mm over large parts of the cores. Sediment colors alternate from bright yellowish brown to light brownish gray to blackish (Akita et al., 2015). Detailed lithological and sedimentological descriptions can be found in Akita et al. (2015). Sediment cores from Taro Co are more homogenous, dark gray colored getting light gray at the base and show traces of lamination.

A strong and stable ChRM was isolated between 5 and 90 mT for most sediments (Fig. 2). Little viscous remanent magnetization was observed and, if present at all, was easily removed by 5 mT AF demagnetization in all cores. The existence of magnetic iron sulfites such as greigite is not indicated because no gyroremanent magnetization acquisition is observed at higher AF fields (Fig. 2) although further investigations will be necessary to confirm this assumption. MAD values of the ChRM are entirely below 4° and mostly ranging around 2° in the Tangra Yumco records (TAN, Fig. 3), indicating a well resolved magnetization (Stoner and St-Onge, 2007). Similar behavior was observed for the upper and lower part of TOC11-3 and 4 from Taro Co (Fig. 4). In between (TOC11-3: 24–52 cm; TOC11-4: 23–56 cm sediment depth) where a lower magnetization is observed MAD values are higher, but generally <10°. The MDF is also lower in that part of the cores. However, no obvious lithological change or variations in physical grain sizes are visible. Despite the variations in MAD and MDF, both inclination and declination show patterns comparable to those observed from the other record from Taro Co (Fig. 4) suggesting that a reasonable directional record is preserved in the sediments from this lake. Declination varies in the same range especially in the areas where MAD values are below 5° and magnetization is higher. Inclination resembles the same pattern although TOC11-4 oscillates around the geocentric axial dipole (GAD, Fig. 4) which for

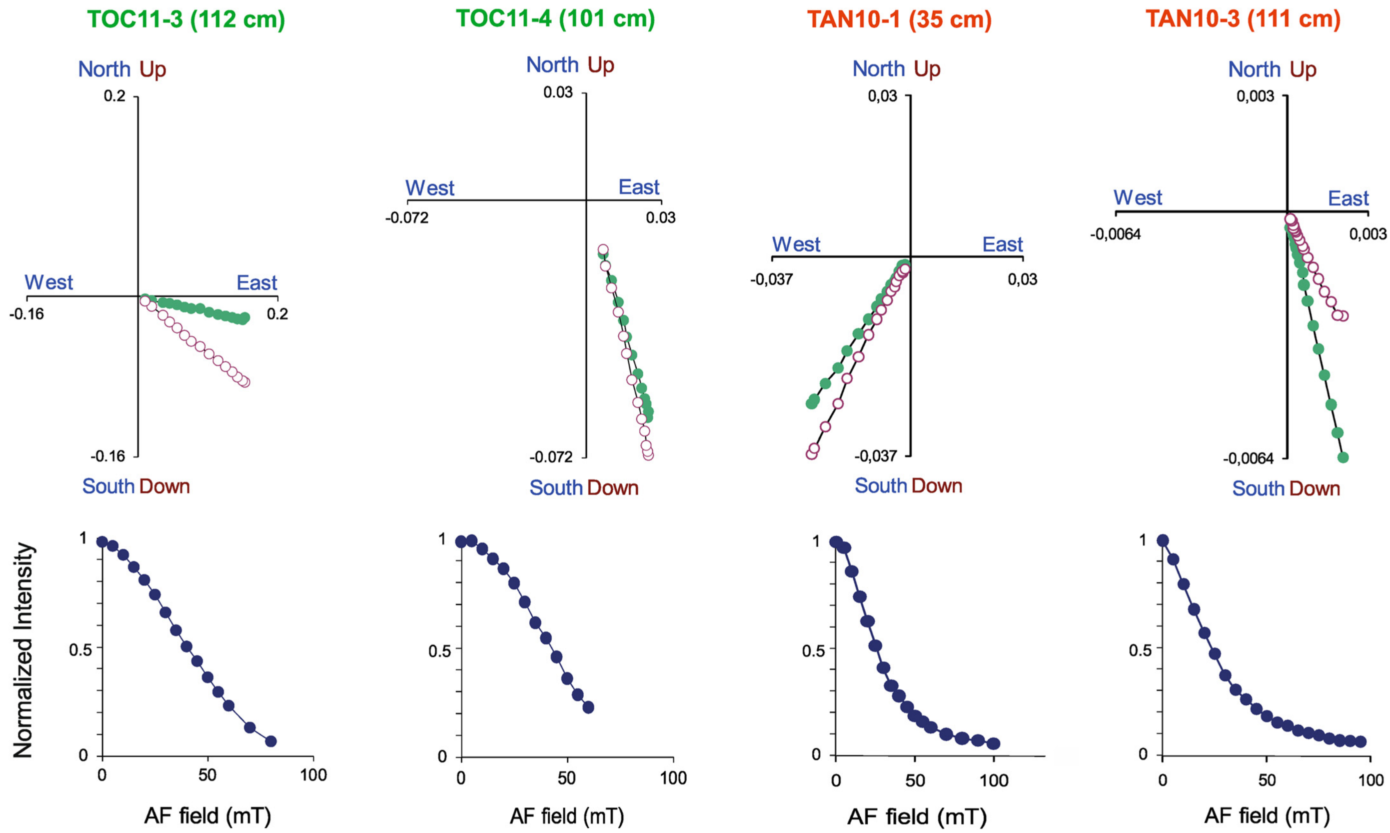

Fig. 2. AF demagnetization behavior for representative samples.

the latitude of both investigated lakes (Tangra Yumco and Taro Co) is at 50.4° whereas TOC11-3 generally has much shallower inclination angles and larger variations (Fig. 4). This might be a coring artifact as it was also observed in other studies before (Hyodo et al., 1999). Since the sealing of the corer did not work properly at the first attempt to recover this gravity core some adjustments had to be made which might have resulted in a not exactly vertical penetration for TOC11-3. In contrast, TOC11-4 was recovered without these adjustments. For this reason TOC11-4 was chosen for dating and further analyses. Nevertheless, since all measured parameters are similar in TOC11-3 and 4, TOC11-3 is still used for an intra-lake comparison.

In all records from Tangra Yumco, the MDF is very stable and ranges between 21 and 28 mT except for the very top of the sediment cores (Fig. 3) consistent with a low coercivity mineral such as magnetite as carrier of the natural remanent magnetization. All records from Tangra Yumco (TAN) plotted on their own depth scale show a similar inclination pattern oscillating around the GAD (Fig. 5). Best matches are found between TAN10-1 and 4. Unfortunately, TAN10-3 was compacted during transport, primarily affecting the upper part of the record and hence this part is condensed.

TAN10-4 contains four turbidites (Akita et al., 2015) which seem to have little effect on either the inclination or the declination records (Fig. 5). Nevertheless, turbidite sections were removed when the data was plotted on an age scale. Besides on TAN10-1, where turbidites are distinctively smaller than in TAN10-4 (Akita et al., 2015) and are hence of minor importance no other investigations to detect turbidites have been performed so far on the other presented sediment cores. The consistent inclinations within the lakes that oscillate around GAD values suggest that the sediments from both lakes are good paleomagnetic recorders.

The compaction of TAN10-3 can clearly be seen in the declination as well. Changes in declination are in the order of 30 to 40° which is typical for paleomagnetic secular variations (Frank, 2007) in the other records but increases to variations >60° in the disturbed parts of TAN10-3 (Fig. 5). In general declination patterns show few similarities. Only in the lower part distinct shifts of approximately 20° can be observed in all records (arrows in Fig. 5).

5. Chronologies

The sediment core from Taro Co (TOC11-4) shows an almost linear age–depth relationship and a small modern reservoir effect of only 120 ± 30 years (Fig. 6). This might be explained by the fact that in contrast to most lakes on the Tibetan Plateau Taro Co is an open lake system. Linear extrapolation of this trend matches the projection determined by ^{210}Pb, consistent with little significant change in reservoir effects at this location. As it is often the case, the sedimentation rates obtained from ^{210}Pb in the soft surface layer are higher than those obtained by radiocarbon in the more dewatered sediments below (Fey et al., 2009; Frank, 2007; Maier et al., 2013; Mayr et al., 2005).

The average sedimentation rate at TOC11-4 of 0.17 mm a^{-1} is very low compared to the two sediment cores from Tangra Yumco. The sedimentation rate of 0.37 mm a^{-1} from TAN10-4 is more than twice as high, even for the turbidite/event corrected record (4.7 km to shoreline, Fig. 6, Table 1). TAN10-1 which is much closer to the shore (3.0 km) shows an even higher sedimentation rate of 0.42 mm a^{-1}.

According to the ages of the sediment water interface both records from Tangra Yumco have a reservoir effect of about 2000 years (TAN10-1: 2200 ± 30 years, TAN10-4: 2140 ± 30 years) consistent with the age of 2070 ± 40 BP for living aquatic vegetation (Table 2). Since some outliers were observed in both records the

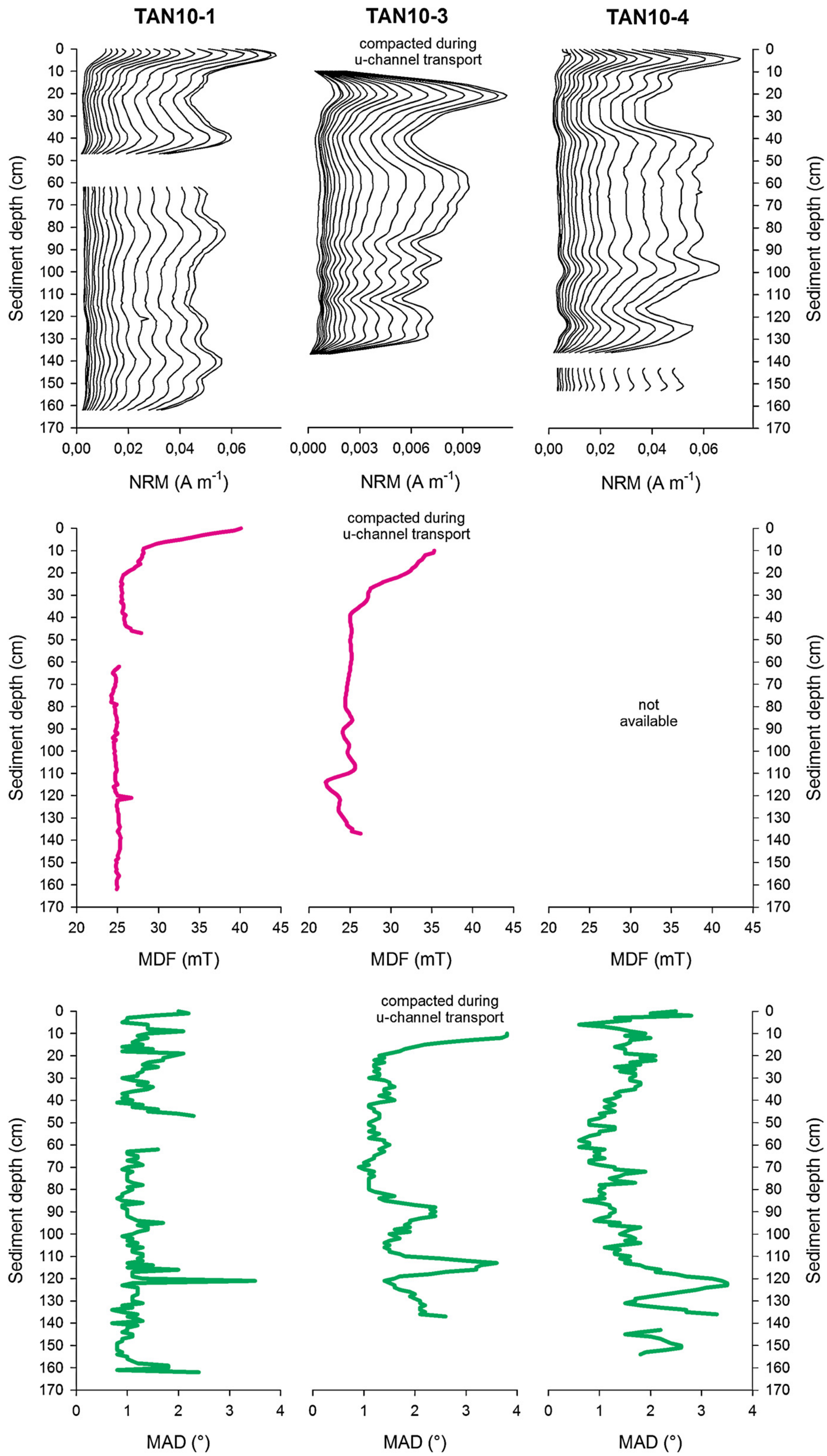

Fig. 3. The natural remanent magnetization (NRM) at all demagnetization steps, median destructive fields (MDF), and maximum angular deviation (MAD) angles from the principal component analysis for all measured sediment cores from Tangra Yumco plotted on a depth scale. Note that NRM at 0 mT was not measured on TAN10-4. Therefore this NRM demagnetization plot only starts at 5 mT and MDF is not available.

median of the youngest ages in stratigraphic order were used to build the chronologies as a natural contamination of the dating samples can occasionally occur by reworking of fine organic particles. Therefore, we excluded all ages which are not in stratigraphic order. In contrast dating results showing too young ages are more difficult to be explained in the case of the investigated lakes. This approach is supported by a wood age of terrestrial origin which should not be affected by a lake water reservoir effect (Fig. 6). The reservoir effect of TAN10-4 was further supported by OSL ages yielding age differences of about 2 ka relative to uncorrected

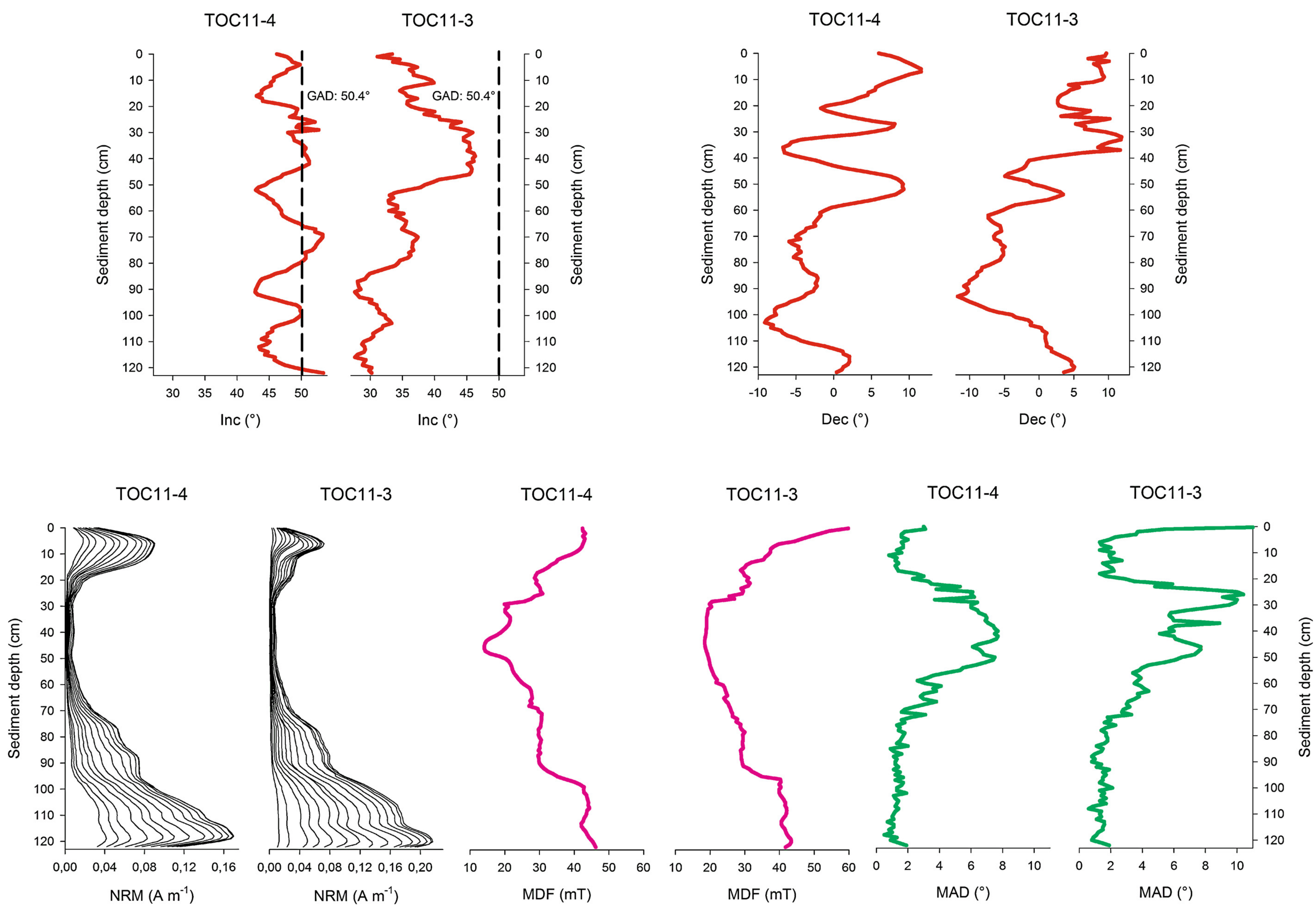

Fig. 4. Inclination, declination, the natural remanent magnetization (NRM) at all demagnetization steps, median destructive fields (MDF), and maximum angular deviation (MAD) angles from the principal component analysis for all measured sediment cores from Taro Co plotted on a depth scale.

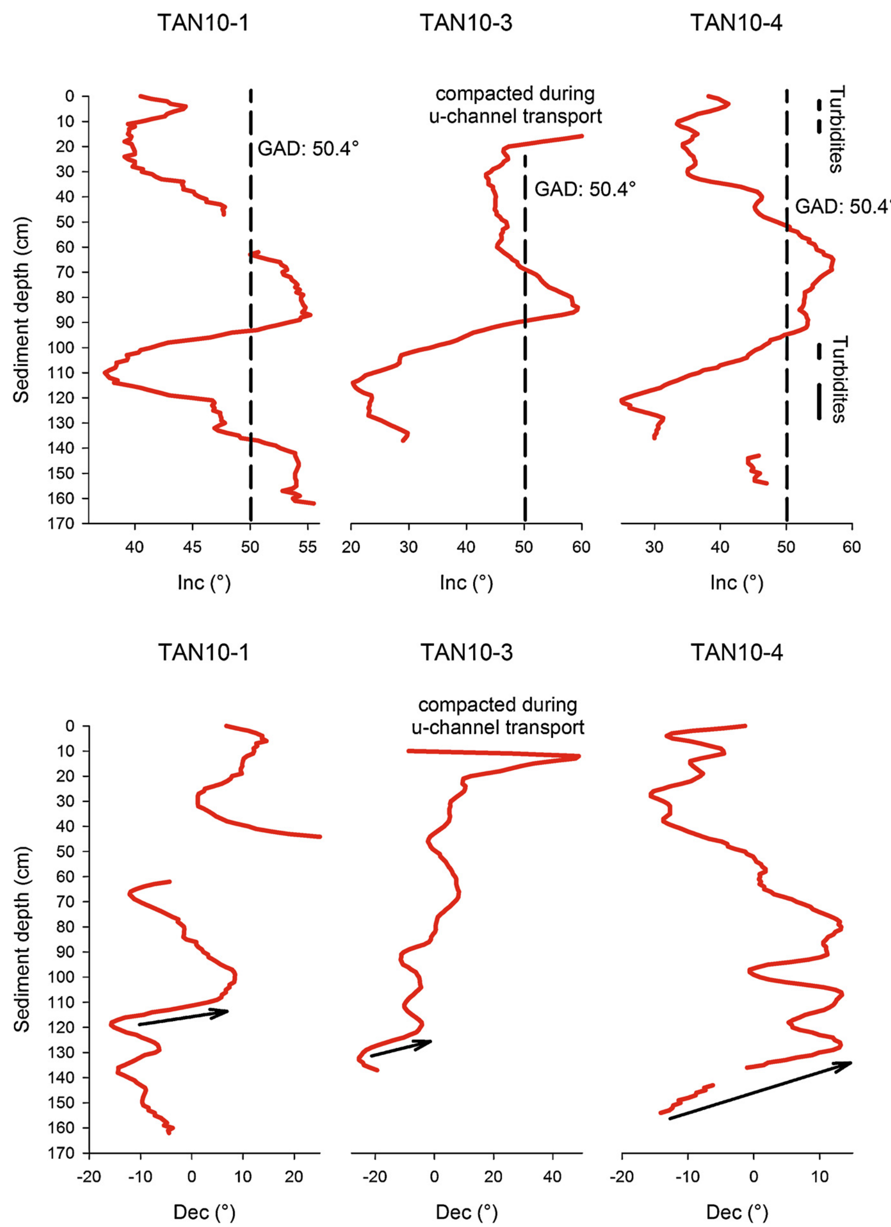

Fig. 5. Inclination and declination derived from principal component analysis for all measured sediment cores from Tangra Yumco plotted on a depth scale. Black arrows indicate one of the few comparable features in the declination record.

radiocarbon ages (Long et al., 2014). For consistency, TAN10-4 is also plotted on its radiocarbon based chronology (Fig. 7).

6. Comparison of Tangra Yumco and Taro Co (TAN and TOC)

Owing to the differences in sedimentation rate more smoothing occurs in the Taro Co record (TOC11-4, Fig. 7) with more details preserved in the sediment records from Tangra Yumco (TAN). As a result the changes in inclination and declination are less pronounced at Taro Co (Fig. 7).

A gradual shallowing from 4000 to 3000 cal BP in inclination is observed in all three records (H-1 to L-1, Fig. 7). After a broad minimum (L-1, Fig. 7) all records show a steepening in inclination at around 2500 cal BP followed by a characteristic feature with three distinct inclination highs (H-2-1 to H-2-3) in TAN10-4. A similar pattern is found in TOC11-4, however with some additional structure (H-2-2, Fig. 7). In TAN10-1 the morphology of the inclination high feature is smoothed out but the characteristic maximum covers the same time interval as the other two records. At around 700 cal BP inclination in all records shallows (L-2, Fig. 7) before a final rise at about 200 cal BP (H3, Fig. 6) which agrees well with the predictions of the gufm1 magnetic field model derived from historical records (Jackson et al., 2000) (Fig. 7).

The overall inclination patterns from the two lakes are similar when plotted on their own individual age–depth models. This supports the accuracy of the chronologies and that the sediments of both lakes are good paleomagnetic secular variation (PSV) recorders. It further indicates that dating uncertainties are in the range of the radiocarbon method and that the performed reservoir correction is reasonable. As observed at the comparison within the records from Tangra Yumco (TAN, Fig. 5) declination is more complex and less similar.

7. Comparison to other studies

Regional support for these observations is limited, as besides Nam Co (Kasper et al., 2012), there are no other Tibetan Plateau records to compare with. Although quite distant, comparisons are

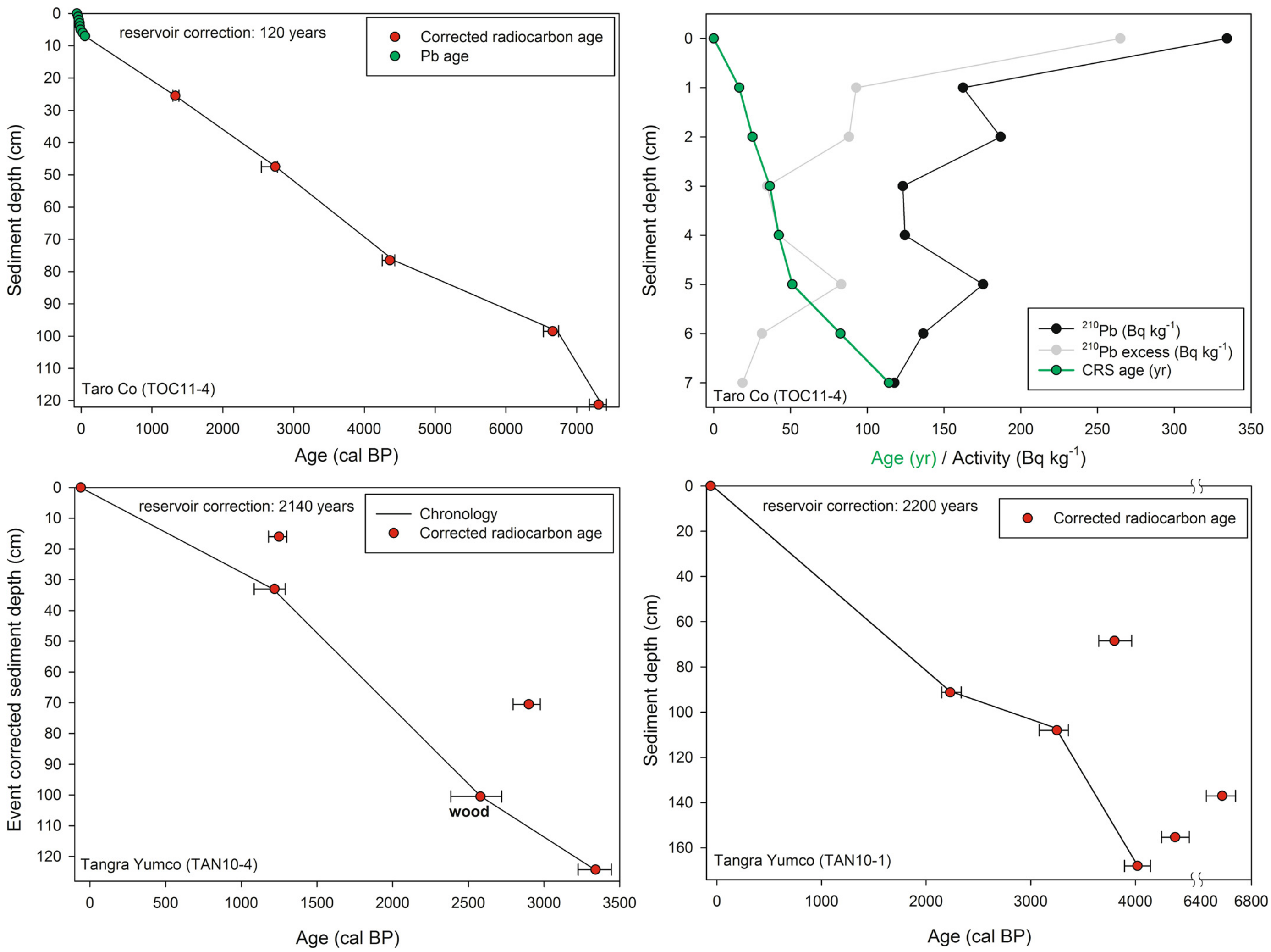

Fig. 6. Mainly radiocarbon based chronologies for TOC11-4 from Taro Co as well as TAN10-1 and TAN10-4 from Tangra Yumco. Note that the upper part of TOC11-4 is ^{210}Pb-dated and that TAN10-4 contains a piece of wood which was not reservoir corrected.

made with a varve dated record from the Makran Accretionary Wedge (Müller, 2004) to the southwest, Lakes Issyk-Kul (northwest) (Gómez-Paccard et al., 2012) and Baikal (north) (Peck et al., 1996), as well as a recently developed PSV stack of East Asia (Zheng et al., 2014) containing a number of recently published, though age adjusted (Zheng et al., 2014) records East of the Tibetan Plateau (Ali et al., 1999; Frank, 2007; Hyodo et al., 1999; Yang et al., 2009, 2012) as well as archeomagnetic data from the GEOMAGIA 50 database (Korhonen et al., 2008). The latter contains a number of recently published, though age adjusted (Zheng et al., 2014) records East of the Tibetan Plateau (Ali et al., 1999; Frank, 2007; Hyodo et al., 1999; Yang et al., 2009, 2012). Moreover, the pfm9k spherical harmonic geomagnetic field model (Nilsson et al., 2014) predictions for Tangra Yumco are considered (Fig. 7). Since the Makran data was measured on discrete samples and has a very high sedimentation rate of 1.16 $mm\,a^{-1}$ (Müller, 2004) it was smoothed by an 11 point running mean to provide similar smoothing to that which occurs due to the response function of the u-channel magnetometers used in this study. This was not applied to the Lake Issyk-Kul and Baikal records as their low sedimentation rates of 0.23 (Gómez-Paccard et al., 2012) and 0.14 $mm\,a^{-1}$ (Peck et al., 1996) already induce significant smoothing. As declination is less robust only inclination is discussed.

The closest comparable record from Nam Co (Fig. 1) shows a similar inclination pattern to those from Tangra Yumco (TAN) and Taro Co (TOC, Fig. 7). Similar mean sedimentation rates of 0.33 to 0.48 $mm\,a^{-1}$ (Kasper et al., 2012) as in the Tangra Yumco cores allow the detection of similar minor variations between Nam Co and TAN10-4 although there might be a slight temporal offset in the featured H-2 maximum (Fig. 7). Unfortunately, the Nam Co record suffers from high MAD values at the beginning of this H-2 inclination maximum (Fig. 7) suggesting that the shallowing at H-2-1 reflects a poorly resolved magnetization. For this reason H-2-1 was subdivided here in a and b (Fig. 7). If the phase containing high MAD values in Nam Co was to be removed, improved similarity would result.

A similar though slightly more detailed three peaked inclination high feature is observed in the PSV stack of East Asia (Zheng et al., 2014) (Fig. 7). Greater variability in this feature may reflect higher resolution records used in the construction of the stack (e.g., 2 $mm\,a^{-1}$ at sediment core MD06-3040 from the East China Sea, Zheng et al., 2014) than in the lakes on the Tibetan Plateau.

Comparisons with predictions from the pfm9k spherical harmonic geomagnetic field model (Nilsson et al., 2014) are quite distinct from the Tibetan Plateau records (Fig. 7). This could be reconciled by significant chronological differences of around 1500 years, or an out of phase geomagnetic pattern where inclination highs predicted by pfm9k during L-1 are associated with inclination lows at the Tibetan Plateau and low values during H-2 (Fig. 7). Similar observations have been made at the Korean penin-

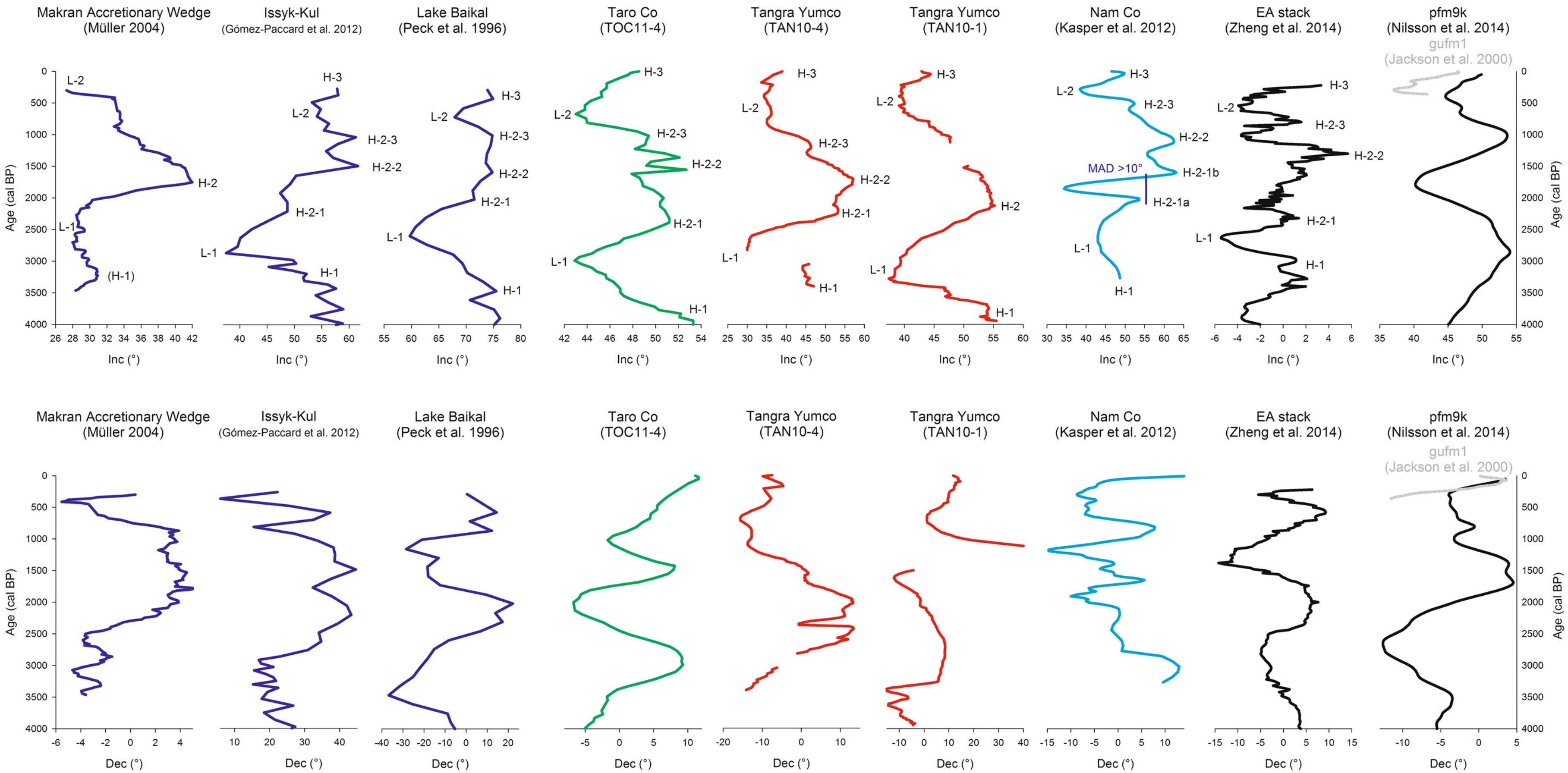

Fig. 7. Comparison of the measured records from Taro Co and Tangra Yumco to records from nearby Nam Co (Fig. 1) (Kasper et al., 2012), varve-dated Makran Accretionary Wedge (Fig. 1) (Müller, 2004), Lake Issyk-Kul (Fig. 1) (Gómez-Paccard et al., 2012), Lake Baikal (Peck et al., 1996), the East Asian PSV stack (Zheng et al., 2014), the pfm9k spherical harmonic geomagnetic field model (Nilsson et al., 2014), and the gufm1 magnetic field model derived from historical records (Jackson et al., 2000).

sula, where inclination differed substantially from the prediction of the CALS3k.3 (Donadini et al., 2009; Korte et al., 2009) or CALS7K.2 (Korte and Constable, 2005; Korte et al., 2005) global field models (Yu et al., 2010) and at Lake Issyk-Kul where the family of spherical harmonic geomagnetic models (Korte and Constable, 2005; Korte et al., 2009) produce 500–1000 year offsets (Gómez-Paccard et al., 2012). On the Tibetan Plateau this difference might reflect the paucity of data since the inherent limitations of such models are the reliability of individual data, age uncertainties, and the regional bias of data availability, rather than the quality of the mathematical model itself (Yu et al., 2010). The paleomagnetic data used to develop the pfm9k models are based on a similar initial data set used to construct the CALS10k.1b model (Korte et al., 2011) in which the closest contained record is from Lake Erhai (Hyodo et al., 1999) which is still 1500 km to the East from the investigated records (Fig. 1). Differences in inclination in the two measured sediment cores from Lake Erhai (Hyodo et al., 1999) and dating uncertainties as illustrated in the development of the East Asia PSV stack (Zheng et al., 2014) may have detrimentally influenced the pfm9k model output. The chronology of Lake Erhai was, therefore, adjusted in the East Asia PSV stack which shows a much better fit to our data. The PSV ages of the stack are constrained by radiocarbon ages with limited errors, and are likely to be more reliable than predictions from spherical harmonic models (Zheng et al., 2014) that have incorporated poorly constrained records.

The smoothed varve-dated record from the Makran Accretionary Wedge (Müller, 2004) 2000 km to the southwest, the records from Lake Issyk-Kul (Gómez-Paccard et al., 2012) 1500 km to the northwest, and Lake Baikal 2800 km to the north resemble inclination of the East Asian PSV stack $>$1500 km to the east. The inclination patterns in these records are also similar to those on the Tibetan Plateau in between (Fig. 7). The spatial similarity of inclination records surrounding the Tibetan Plateau to the east, north, and west, strongly supports the geomagnetic origin of the Tibetan Plateau lake paleomagnetic reconstructions and the independent chronologies that were used to derive them. The implied similarities in inclination variation over such a large spatial scale ($>$3000 km) suggest that it reflects large-scale core dynamics as previously suggest for North America (Lund, 1996) and across the North Atlantic (Stoner et al., 2013) rather than smaller scale processes like drift of the non-dipole field often associated with the PSV record (Merrill et al., 1996).

In general best matches between the East Asian stack and the records investigated in this study can be observed in TAN10-4. Although, all chronologies appear to be rather robust, the dated wood fragment contained in TAN10-4 further supports this chronology.

8. Conclusions

Inclination records in the individual Tibetan Plateau lake records are reproducible, suggesting that paleomagnetic secular variations are recorded and preserved. Inclination appears to be well suited for comparing lacustrine sediment records from the Tibetan Plateau and effective in evaluating their chronologies. Such an approach is likely to be useful for eventually dating other archives stratigraphically. In contrast, declination records have been more problematic, therefore, inhibiting a (detailed) comparison. The chronologies from Tangra Yumco and Taro Co appear to be robust (especially TAN10-4) and well suited for further paleoclimatic reconstructions and comparisons of paleoenvironmental records. Dating uncertainties are in the range of the radiocarbon method and reservoir correction seems to be reasonable. PSV similarities over such a large area indicate that paleomagnetic secular variations derive from large-scale core dynamics, though further work will be needed to refine details and to see how these pattern compare with that of other regions as we improve our understanding of the processes that govern paleo-geomagnetic change.

Acknowledgements

We would like to acknowledge the helping hands of many Canadian, Chinese, and German colleagues in the field, during u-channel sampling, and during measurements. We appreciate discussions on the topic with B. Reilly and L. Ziegler who also provided model output data for comparison. Y. Zheng kindly provided the East Asian PSV stack data. This study greatly benefited from a Young Scientists & Early Career Program scholarship to T. Haberzettl for a visiting research stay at the Paleomagnetic & Environmental Magnetic Research Laboratory at Oregon State University awarded by the steering committee of the priority program (SPP) 1372 of the German Research Foundation (DFG). This work is part of the DFG priority program 1372 "TiP: Tibetan Plateau – Formation – Climate – Ecosystems", grant Nos. MA1308/23-1, MA1308/23-2, and MA1308/23-3. Furthermore we wish to thank the National Natural Science Foundation of China (Grant No. 41271225) for funding. K. Henkel thanks the Max Planck Society and T. Kasper the "Carl Zeiss Stiftung" for their PhD-grants. G. St-Onge was supported by a Natural Sciences and Engineering Research Council of Canada discovery grant no. 312343-2012 and Canada Foundation for Innovation grant no. 10738 for the acquisition and operation of the cryogenic magnetometer. J. Stoner was supported by National Science Foundation awards EAR 0651585 and 1215888.

References

Akita, L.G., Frenzel, P., Haberzettl, T., Kasper, T., Wang, J., Reicherter, K., 2015. Ostracoda (Crustacea) as indicators of subaqueous mass movements: an example from the large brackish lake Tangra Yumco on the southern Tibetan Plateau, China. Palaeogeogr. Palaeoclimatol. Palaeoecol 419, 60–74.

Ali, M., Oda, H., Hayashida, A., Takemura, K., Torii, M., 1999. Holocene palaeomagnetic secular variation at Lake Biwa, central Japan. Geophys. J. Int. 136, 218–228.

Appleby, P.G., 2008. Three decades of dating recent sediments by fallout radionuclides: a review. Holocene 18, 83–93.

Appleby, P.G., Oldfield, F., 1978. The calculation of lead-210 dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. Catena 5, 1–8.

Dietze, E., Maussion, F., Ahlborn, M., Diekmann, B., Hartmann, K., Henkel, K., Kasper, T., Lockot, G., Opitz, S., Haberzettl, T., 2014. Sediment transport processes across the Tibetan Plateau inferred from robust grain-size end members in lake sediments. Clim. Past 10, 91–106.

Doberschütz, S., Frenzel, P., Haberzettl, T., Kasper, T., Wang, J., Zhu, L., Daut, G., Schwalb, A., Mäusbacher, R., 2014. Monsoonal forcing of Holocene paleoenvironmental change on the central Tibetan Plateau inferred using a sediment record from Lake Nam Co (Xizang, China). J. Paleolimnol. 51, 253–266.

Donadini, F., Korte, M., Constable, C.G., 2009. Geomagnetic field for 0–3 ka: 1. New data sets for global modeling. Geochem. Geophys. Geosyst. 10, Q06007.

Fey, M., Korr, C., Maidana, N.I., Carrevedo, M.L., Corbella, H., Dietrich, S., Haberzettl, T., Kuhn, G., Lücke, A., Mayr, C., Ohlendorf, C., Paez, M.M., Quintana, F.A., Schäbitz, F., Zolitschka, B., 2009. Palaeoenvironmental changes during the last 1600 years inferred from the sediment record of a cirque lake in southern Patagonia (Laguna Las Vizcachas, Argentina). Palaeogeogr. Palaeoclimatol. Palaeoecol. 281, 363–375.

Frank, U., 2007. Palaeomagnetic investigations on lake sediments from NE China: a new record of geomagnetic secular variations for the last 37 ka. Geophys. J. Int. 169, 29–40.

Gómez-Paccard, M., Larrasoaña, J.C., Giralt, S., Roberts, A.P., 2012. First paleomagnetic results of mid- to late Holocene sediments from Lake Issyk-Kul (Kyrgyzstan): implications for paleosecular variation in central Asia. Geochem. Geophys. Geosyst. 13, Q03019.

Herb, C., Zhang, W., Koutsodendris, A., Appel, E., Fang, X., Pross, J., 2013. Environmental implications of the magnetic record in Pleistocene lacustrine sediments of the Qaidam Basin, NE Tibetan Plateau. Quat. Int. 313–314, 218–229.

Hou, J., D'Andrea, W.J., Liu, Z., 2012. The influence of ^{14}C reservoir age on interpretation of paleolimnological records from the Tibetan Plateau. Quat. Sci. Rev. 48, 67–79.

Hyodo, M., Yoshihara, A., Kashiwaya, K., Okimura, T., Masuzawa, T., Nomura, R., Tanaka, S., Xing, T.B., Qing, L.S., Jian, L.S., 1999. A Late Holocene geomagnetic secular variation record from Erhai Lake, southwest China. Geophys. J. Int. 136, 784–790.

Jackson, A., Jonkers, A.R.T., Walker, M.R., 2000. Four centuries of geomagnetic secular variation from historical records. Philos. Trans. R. Soc., Math. Phys. Eng. Sci. 358, 957–990.

Kasper, T., Haberzettl, T., Doberschütz, S., Daut, G., Wang, J., Zhu, L., Nowaczyk, N., Mäusbacher, R., 2012. Indian Ocean Summer Monsoon (IOSM)-dynamics within the past 4 ka recorded in the sediments of Lake Nam Co, central Tibetan Plateau (China). Quat. Sci. Rev. 39, 73–85.

Kelts, K., Briegel, U., Ghilardi, K., Hsu, K., 1986. The limnogeology-ETH coring system. Swiss J. Hydrol. 48, 104–115.

Kirschvink, J.L., 1980. The least-squares line and plane and the analysis of palaeomagnetic data. Geophys. J. Int. 62, 699–718.

Korhonen, K., Donadini, F., Riisager, P., Pesonen, L.J., 2008. GEOMAGIA50: an archeointensity database with PHP and MySQL. Geochem. Geophys. Geosyst. 9, Q04029.

Korte, M., Constable, C.G., 2005. Continuous geomagnetic field models for the past 7 millennia: 2. CALS7K. Geochem. Geophys. Geosyst. 6, Q02H16.

Korte, M., Genevey, A., Constable, C.G., Frank, U., Schnepp, E., 2005. Continuous geomagnetic field models for the past 7 millennia: 1. A new global data compilation. Geochem. Geophys. Geosyst. 6, Q02H15.

Korte, M., Donadini, F., Constable, C.G., 2009. Geomagnetic field for 0–3 ka: 2. A new series of time-varying global models. Geochem. Geophys. Geosyst. 10, Q06008.

Korte, M., Constable, C., Donadini, F., Holme, R., 2011. Reconstructing the Holocene geomagnetic field. Earth Planet. Sci. Lett. 312, 497–505.

Long, H., Haberzettl, T., Tsukamoto, S., Shen, J., Kasper, T., Daut, G., Zhu, L., Mäusbacher, R., Frechen, M., 2014. Luminescence dating of lacustrine sediments from Tangra Yumco (southern Tibetan Plateau) using post-IR IRSL (pIRIR) signals from polymineral grains. Boreas 44, 139–152.

Lund, S.P., 1996. A comparison of Holocene paleomagnetic secular variation records from North America. J. Geophys. Res., Solid Earth 101, 8007–8024.

Maier, D.B., Rydberg, J., Bigler, C., Renberg, I., 2013. Compaction of recent varved lake sediments. Gff 135, 231–236.

Mayr, C., Fey, M., Haberzettl, T., Janssen, S., Lücke, A., Maidana, N.I., Ohlendorf, C., Schäbitz, F., Schleser, G.H., Struck, U., Wille, M., Zolitschka, B., 2005. Palaeoenvironmental changes in southern Patagonia during the last millennium recorded in lake sediments from Laguna Azul (Argentina). Palaeogeogr. Palaeoclimatol. Palaeoecol. 228, 203–227.

Mazaud, A., 2005. User-friendly software for vector analysis of the magnetization of long sediment cores. Geochem. Geophys. Geosyst. 6, Q12006.

Merrill, R.T., McElhinny, M.W., MacFadden, P.L., 1996. The Magnetic Field of the Earth Paleomagnetism, the Core, and the Deep Mantle. Int. Geophys. Ser., vol. 63. Academic Press, San Diego.

Mischke, S., Weynell, M., Zhang, C., Wiechert, U., 2013. Spatial variability of ^{14}C reservoir effects in Tibetan Plateau lakes. Quat. Int. 313–314, 147–155.

Müller, M., 2004. Rekonstruktion von Paläosäkularvariationen des Erdmagnetfeldes an holozänen marinen Sedimenten aus der Region des Makran Akkretionskeils. PhD-Thesis. University of Bremen, Bremen, p. 151.

Nilsson, A., Holme, R., Korte, M., Suttie, N., Hill, M., 2014. Reconstructing Holocene geomagnetic field variation: new methods, models and implications. Geophys. J. Int. 198 (1), 229–248.

Peck, J.A., King, J.W., Colman, S.M., Kravchinsky, V.A., 1996. An 84-kyr paleomagnetic record from the sediments of Lake Baikal, Siberia. J. Geophys. Res., Solid Earth 101, 11365–11385.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Staff, R.A., Turney, C.S.M., van der Plicht, J., 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55 (4), 1869–1887.

Stoner, J.S., St-Onge, G., 2007. Chapter Three: Magnetic Stratigraphy in Paleoceanography: Reversals, Excursions, Paleointensity, and Secular Variation, Developments in Marine Geology. Elsevier, pp. 99–138.

Stoner, J.S., Channell, J.E.T., Mazaud, A., Strano, S.E., Xuan, C., 2013. The influence of high-latitude flux lobes on the Holocene paleomagnetic record of IODP Site U1305 and the northern North Atlantic. Geochem. Geophys. Geosyst. 14, 4623–4646.

Stuiver, M., Reimer, P.J., 1993. Extended C-14 data-base and revised calib 3.0 C-14 age calibration program. Radiocarbon 35, 215–230.

Su, Y.L., Gao, X., Liu, Q.S., Hu, P.X., Duan, Z.Q., Jiang, Z.X., Wang, J.B., Zhu, L.P., Doberschütz, S., Mäusbacher, R., Daut, G., Haberzettl, T., 2013a. Mechanism of variations in environmental magnetic proxies of lake sediments from Nam Co, Tibet during the Holocene. Chin. Sci. Bull. 58, 1568–1578.

Su, Y.L., Gao, X., Liu, Q.S., Wang, J.B., Haberzettl, T., Zhu, L.P., Li, J.H., Duan, Z.Q., Tian, L.D., 2013b. Mineral magnetic study of lacustrine sediments from Lake Pumoyum Co, southern Tibet, over the last 19 ka and paleoenvironmental significance. Tectonophysics 588, 209–221.

Wang, J., Peng, P., Ma, Q., Zhu, L., 2010. Modern limnological features of Tangra Yumco and Zhari Namco, Tibetan Plateau. J. Lake Sci. 22, 629–632.

Weeks, R., Laj, C., Endignoux, L., Fuller, M., Roberts, A., Manganne, R., Blanchard, E., Goree, W., 1993. Improvements in long-core measurement techniques: applications in palaeomagnetism and palaeoceanography. Geophys. J. Int. 114, 651–662.

Yang, X., Heller, F., Yang, J., Su, Z., 2009. Paleosecular variations since $\sim$9000 yr BP as recorded by sediments from maar lake Shuangchiling, Hainan, South China. Earth Planet. Sci. Lett. 288, 1–9.

Yang, X., Liu, Q., Duan, Z., Su, Z., Wei, G., Jia, G., Ouyang, T., Su, Y., Xie, L., 2012. A Holocene palaeomagnetic secular variation record from Huguangyan maar Lake, southern China. Geophys. J. Int. 190, 188–200.

Yu, Y., Doh, S.-J., Kim, W., Park, Y.-H., Lee, H.-J., Yim, Y., Cho, S.-G., Oh, Y.-S., Lee, D.-S., Lee, H.-H., Gong, M.-G., Hyun, D.-H., Cho, J.-K., Sin, Y.-S., Do, M.-S., 2010. Archeomagnetic secular variation from Korea: implication for the occurrence of global archeomagnetic jerks. Earth Planet. Sci. Lett. 294, 173–181.

Zheng, M., 1997. An Introduction to Saline Lakes on the Qinghai–Tibet Plateau. Kluwer Academic Publishers, Dordrecht/Boston/London.

Zheng, Y., Zheng, H., Deng, C., Liu, Q., 2014. Holocene paleomagnetic secular variation from East China Sea and a PSV stack of East Asia. Phys. Earth Planet. Inter. 236, 69–78.

Zhu, L., Zhang, P., Xia, W., Li, B., Chen, L., 2003. 1400-year cold/warm fluctuations reflected by environmental magnetism of a lake sediment core from the Chen Co, southern Tibet, China. J. Paleolimnol. 29, 391–401.