Advances in Limnogeology and Paleolimnology

with a special focus on corroborated chronologies using paleomagnetic secular variations

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Thank you so much!
Scientific investigations on lakes started during the 19th century in Europe and the Unites States. Since this time paleolimnological and limnogeological investigations increased distinctly and during the last few years there has been a rapid advance in the understanding of processes operating in lacustrine systems. However, most studies focused on easily accessible locations. Despite major improvements in scientific knowledge of lakes up to now, there still remain gaps especially for the areas investigated in this thesis, i.e., the different rainfall zones of South Africa, the Tibetan Plateau, the steppe parts of Argentinean Patagonia, the eastern Ecuadorian Andes, and the Island of Sulawesi (Indonesia). The papers in this thesis try to close some of these gaps and try to contribute to a better understanding of processes that occurred in the past and their (paleo-)environmental consequences in regions that have rarely been investigated so far. The aim of this thesis is to provide new paleolimnological and limnogeological information and develop process based conceptual models from areas of the world where this kind of information is very scarce to inexistnet. A special emphasis will be on the construction of reliable chronologies using multi-dating approaches. In this context one focus will be on the evaluation of chronologies using paleomagnetic secular variations wherever this was possible depending on sediment properties.

In order to reach this aim the papers forming this thesis are structured as follows:

1. New conceptual approaches
2. Paleoenvironmental reconstructions using simple magnetostratigraphically not confirmed chronologies since no paleomagnetic secular variation data could be obtained from the sediment and other paleolimnological and limnogeological investigations
3. Paleomagnetic investigations and/or magnetostratigraphic evaluations of chronologies
4. Paleoenvironmental information from magnetostratigraphically corroborated chronologies
5. Other dating approaches
Zusammenfassung


1. Neue konzeptionelle Ansätze
2. Paläoumweltrekonstruktionen basierend auf einfachen, nicht magnetostratigraphisch abgesicherten Altersmodellen, da keine Extraktion von paläomagnetischen Säkularvariationen aus diesen Sedimenten möglich war, sowie andere paläolimnologische und limnogeologische Untersuchungen
3. Paläomagnetische Untersuchungen und/oder magnetostratigraphische Evaluierungen von Altersmodellen
4. Paläoumweltrekonstruktionen basierend auf magnetostratigraphisch abgesicherten Altersmodellen
5. Andere Datierungsansätze
The use of lacustrine sediments for paleoenvironmental reconstructions

The currently occurring climate change with its consequences such as rising temperatures or sea level as reported by the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (Masson-Delmotte et al. 2013; Stocker et al. 2013) has major impacts on modern societies and will impose increased stress on many regions of the world (Last 2002; Haberzettl et al. 2014, Appendix 12). Global warming can for example affect human health (Franchini & Mannucci 2015) and climate change is going to alter ecosystems (Scholze et al. 2006; Warszawski et al. 2013) and considerably exacerbate water scarcity in different parts of the world (Schewe et al. 2014). In order to predict future climatic developments, sophisticated models are required which need to be calibrated and evaluated (Bradley & Eddy 1991; Smol 2008). Unfortunately, measured climatic and environmental data for this purpose for western Europe are only available since the late 17th or early 18th century (Jones & Bradley 1995). On a global scale data only go back to the mid-19th century (Stocker et al. 2013). Apart from this, instrumental and observational datasets are very sparse or suffer from an insufficient quality (Smol 2008). Hence, they provide an inadequate perspective on climate variability and the evolution and history of climate (Bradley 1999). In addition to that, the period covered by instrumental data is already intensively influenced by an anthropogenic impact in many regions of the world and many climatic and environmental changes occurred far back in time before observation was possible (Birks & Birks 2006). The only option to overcome this issue of short time series of measured data and anthropogenic impact is the use of natural geoarchives from less anthropogenically influenced areas for paleoenvironmental reconstructions (Bradley & Eddy 1991; Haberzettl 2006; Zolitschka et al. 2006). Paleoclimate reconstructions from such geoarchives can distinctly extend the climatic records further back in time and allow current variations in, for example, sea level or climate (including extreme events like droughts and floods) to be placed in a broader perspective of (paleo-) environmental change (Stocker et al. 2013). Reconstructions may also allow to unravel driving factors and mechanisms for climatic changes. If these causes are understood
it is possible to forecast climatic variations for the future (Bradley & Eddy 1991; Bradley 1999).

Paleoclimate archives also record slowly occurring climate transitions and system feedbacks (Stocker et al. 2013) which due to their long duration are not contained in the short time series derived from instrumental measurements. This allows to assess whether recent changes are unusual or not (Masson-Delmotte et al. 2013). Although in a different context Winston Churchill was right when he said: “The farther backward you can look the farther forward you are likely to see”. This look back in time can be realized by analyses of geoarchives like for example speleothems, glaciers – or lakes.

Today, lakes form only about 1 % of the continental surface of the Earth (Collinson 1978), however, their geological significance is much greater than this percentage suggests (Talbot & Allen 1996). Lakes are remarkable features and their sediments can be used for paleoenvironmental reconstruction in terms of space and time (Meybeck 1995; Verrecchia 2008). This is possible since lacustrine systems mostly continually respond to climatic conditions (Hostetler 1995) which is immediately stored in the sediments. For example climatically induced changes in precipitation and evaporation can induce fluctuations in lake levels (Hostetler 1995; Haberzettl et al. 2005; Haberzettl 2006; Anselmetti et al. 2009; Kasper et al. 2012, Appendix 15; Long et al. 2012, Appendix 22; Kasper et al. 2013, Appendix 16; Ohlendorf et al. 2013, Appendix 26; Doberschütz et al. 2014, Appendix 7; Kasper et al. 2015, Appendix 17) pointing to changes in the hydrological cycle.

Scientific investigations on lakes started during the second half of the 19th century in Switzerland (Last & Ginn 2005) focusing on bathymetry, temperature, modern lake level variations, or turbidity (Forel 1879-1880; Salis 1884; Forel 1887). Pioneering (limno-)geological investigations were also carried out in the European Alps (Forel 1885, 1887) and on Lake Lahontan (Russel 1885) or Pleistocene Lake Bonneville (Gilbert 1890) in the United States. However, for the upcoming almost 100 years only little attention was put on real limnogeological or paleolimnological aspects probably because the water has been a distinct barrier to recover the sediments in a useful way and there was hardly any text dealing solely with paleolimnology (Reeves 1968). Looking at textbooks in the 1980s sedimentological processes in lakes, if mentioned at all, were restricted to only a few pages (Håkanson & Jansson 1983) and
paleoclimatology in general was still in its infancy (Bradley 1999). Therefore, only a few decades ago, the status of lake sediment research was still described as the hole in a donut (Collinson 1978). Since this time limnogeological investigations increased distinctly. During the last few years there has been rapid advance in the understanding of processes operating in lacustrine systems and how these processes influence sedimentological records preserved in these systems (Bradley 1999; Last 2002; Last & Ginn 2005; Cabrera et al. 2009; Birks 2012). Today, paleoclimatology including paleolimnology is a major field in earth sciences (Bradley 1999). Probably no other continental archive has so much to offer for potential significant contributions to geosciences as lacustrine environments (Talbot & Allen 1996; Last 2002; Last & Ginn 2005). Consequently, lacustrine paleoenvironmental reconstructions can be seen as complementary to marine records (Cabrera et al. 2009) since they allow an environmental reconstruction to be performed directly in and from the region of interest. However, most lacustrine studies seem to have focused on easily accessible locations. Despite major improvements in scientific knowledge of lakes up to now there still remain gaps especially for the areas investigated in this thesis, e.g., South Africa (Meadows 2001; Holmgren et al. 2003; Haberzettl et al. 2014, Appendix 12), Patagonia (Argentina) (Anselmetti et al. 2009; Fey et al. 2009, Appendix 8), the Island of Sulawesi (Indonesia) (Kirleis et al. 2011; Wündsch et al. 2014, Appendix 33; Biagioni et al. 2015, Appendix 4), or the only marine archive investigated in this thesis, the epicontinental sea of the Hudson Bay including Hudson Strait (Haberzettl et al. 2010, Appendix 10). This thesis has to be seen in the context and as part of the rapidly progressing fields of limnogeology and paleolimnology. Most papers in this thesis contribute to a better understanding of processes that occurred in the past and their paleoenvironmental consequences in regions that have rarely been investigated so far. In this context, another focus of this thesis will be on the establishment of reliable chronologies by for example testing age-depth models using magnetostratigraphy on geologically seen very young sediments, i.e., <4 ka.
Dating sediments

For all paleoenvironmental studies accurate dating is of crucial importance (Bradley & Eddy 1991). Without an accurate chronology the determination of synchronicities, leads, or lags for certain climatic events or shifts is impossible (Bradley 1999). Dating is also essential if the speed and frequency at which past environmental changes occurred is of interest (Bradley & Eddy 1991; Bradley 1999). On short timescales and for recent sediments chronologies can be established using radioisotopic techniques such as \(^{137}\text{Cs}\) or \(^{210}\text{Pb}\). For longer timescales ages are usually provided by (high-resolution) AMS radiocarbon dating, in an ideal case on determined fragile terrestrial plant material (Birks & Birks 2006) such as leaves which make a reworking of the material unlikely. Unfortunately, such kind of material is rare in many areas of the world as for example the Tibetan Plateau (Kasper et al. 2012, Appendix 15; Doberschütz et al. 2014, Appendix 7; Miehe et al. 2014, Appendix 24; Kasper et al. 2015, Appendix 17) or Patagonia (Fey et al. 2009, Appendix 8; Kastner et al. 2010, Appendix 18). In most cases the only solution in such areas is the application of radiocarbon dating on aquatic plant remains or bulk sediment samples if only radiocarbon dating is available to establish a chronology (Niemann et al. 2009, Appendix 25; Haberzettl et al. 2013, Appendix 11; Reinwarth et al. 2013, Appendix 29). Often such chronologies suffer from a hard water effect which has been overcome by various approaches like for example subtracting the age of the sediment water interface from each individual radiocarbon age (Kasper et al. 2012, Appendix 15). However, even today in some cases imprecise reservoir correction on the Tibetan Plateau leads to troubles in correlating records from different lacustrine archives. If this is the case this inhibits a final conclusion about regional synchronicities of climatic shifts in this area.

Often chronologies based on bulk sediment ages also contain many age reversals due to reworking of fine organic sediment. The only solution in this case is to use the youngest ages in stratigraphic order as maximum ages (Fig. 1). Although this is a very conservative approach, comparisons of climate reconstructions from these archives to reconstructions from nearby archives often reveal remarkable similarities (Wündsch et al. 2014, Appendix 33).
A major step forward in age-depth-modeling is the incorporation of independent time marker layers as for example macro or micro tephras (Lowe 2011) which can either be used to establish or confirm existing chronologies (Haberzettl et al. 2007; Haberzettl et al. 2009, Appendix 9). However, such layers are not globally available. In these cases paleomagnetic data derived from the sediments might help to confirm or establish chronologies as will be illustrated in the following chapter.

**Paleomagnetism and magnetostratigraphy**

Magnetostratigraphy uses magnetic parameters to describe, correlate, and date sediment sequences (Lowrie 2007). Usually this term is associated with recorded polarity reversals of the geomagnetic field on long time scales (Opdyke & Channell 1996). However, in principle, any rock magnetic parameter could be used (Lowrie...
In this thesis the focus will be on magnetic susceptibility and paleomagnetic secular variations which are very important in terms of chronostratigraphy especially when dealing with young, i.e., (Late) Holocene sediments.

**Magnetic susceptibility**

Often the first paleomagnetic measurement is low field magnetic susceptibility which has evolved as a standard technique in core to core correlation on cores from a coherent depositional environment (Thompson 1986; Opdyke & Channell 1996; Ellwood 2007; Maher 2007; Merrill & McFadden 2007; Roberts 2007; Haberzettl *et al.* 2009, Appendix 9; Kastner *et al.* 2010, Appendix 18; Roberts & Turner 2013; Ahlborn *et al.* 2015, Appendix 1; Akita *et al.* 2015, Appendix 2) (Fig. 2). Magnetic susceptibility has the advantage to be measured simple, fast, and easy (Binford *et al.* 1983; Evans & Heller 2003; Ellwood 2007). It measures the magnetizability of a sample which is the

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**Fig. 2:** Core to core correlation using magnetic susceptibility (k) on sediment cores from a coherent depositional environment (Haberzettl *et al.* 2009, Appendix 9).
magnetization of the samples in response to an applied magnetic field. Different mineralogical compositions, concentrations of certain minerals, and their magnetic grain size and morphology affect the magnetic susceptibility signal (Ellwood 2007; Hatfield & Stoner 2013). Therefore magnetic susceptibility can for example help to detect the allochthonous minerogenic input as it has often been the case in various paleolimnological studies (Thompson et al. 1975; Niemann et al. 2009, Appendix 25; Kastner et al. 2010, Appendix 18) (Fig. 3).

If the source of the sediment is very heterogeneous magnetic susceptibility can be used as a provenance indicator (Haberzettl et al. 2010, Appendix 10). For example in Hudson Bay and Strait the final outburst flood of Lake Agassiz-Ojibway deposited a so-called red bed in this area which compared to the surrounding geology yields low magnetic susceptibility due to a dominance of hematite (Haberzettl et al. 2010, Appendix 10). In the same study in combination with total inorganic carbon (TIC) it was possible to further distinguish between Paleozoic limestone sources underlying parts of Hudson Bay and Strait and Precambrian granitoids from the Canadian Shield (Haberzettl et al. 2010, Appendix 10).

A density related settling of comparatively heavy magnetic minerals within a magnetically weak matrix can also create a characteristic magnetic susceptibility signal (Hatfield & Stoner 2013). Magnetic susceptibility spikes can therefore help to identify turbidite layers and to distinguish them from background sedimentation (Hatfield & Stoner 2013; Ahlborn et al. 2015, Appendix 1; Akita et al. 2015, Appendix 2).

Based on comparisons with dust records from Antarctica low field magnetic susceptibility was also suggested as a dust indicator at Laguna Potrok Aike (Argentina).
which is located in the dust source of southern Patagonia (Haberzettl et al. 2009, Appendix 9). Within this archive the difference in magnetic susceptibility between glacial and Holocene times, in concert with the contemporaneous change in grain size as well as the dependency of magnetic susceptibility on grain size (Hatfield & Stoner 2013) indicates a causal relationship between these two parameters (Haberzettl et al. 2009, Appendix 9). This suggests that magnetic susceptibility might be used as chronostratigraphic tool which was similarly assumed for carbonate-free pelagic sediments from the Southern Ocean to constrain chronologies (Pugh et al. 2009; Weber et al. 2012). However, interpreting magnetic susceptibility records is seldom straightforward (Haberzettl et al. 2009, Appendix 9; Lisé-Pronovost et al. 2015, Appendix 21). It is rarely possible to determine the factors driving the magnetic susceptibility signal from the measured susceptibility signal alone. Therefore, a greater suite of magnetic measurements is necessary (Hatfield & Stoner 2013). More detailed magnetic studies on the sediments of Laguna Potrok Aike revealed that magnetic susceptibility reflects the estimated flux of magnetite to the lake and therefore low field magnetic susceptibility can only be interpreted as a dust indicator and for chronostratigraphic purposes at the millennial time scale (Lisé-Pronovost et al. 2015, Appendix 21). In contrast, the median destructive field of isothermal remanent magnetization (MDF$_{IRM}$) was established as a wind intensity indicator at the centennial time scale at Laguna Potrok Aike (Lisé-Pronovost et al. 2015, Appendix 21).

As has been shown in this paragraph magnetic susceptibility has many applications in modern paleolimnology if the process leading to a specific signal is well understood. Therefore, it is essential to interpret the individual magnetic susceptibility record within the context of its location and processes acting in its formation (Hatfield & Stoner 2013). In some cases magnetic susceptibility can even be used for stratigraphic purposes to establish chronologies. However, a much higher potential for stratigraphic purposes is in the application of magnetostratigraphy by using paleomagnetic secular variations (PSV) as described in the following.
Paleomagnetic secular variation (PSV) stratigraphy

As magnetic particles in lakes settle down and get deposited they align themselves with the ambient geomagnetic field (Tauxe 1993; Roberts & Turner 2013) and act like a compass needle (Merrill & McFadden 2007). Subsequently, when further sediment is deposited on top they are mechanically locked-in and therefore preserve the directional record (Fig. 4).

Magnetostratigraphy has long been used as a dating tool and it adds a significant new dimension to paleolimnological studies (Oldfield & Richardson 1990). Up to now the focus has mostly been on the difference between normally and reversed polarity of sedimentary archives the so called Geomagnetic Polarity Time Scale (GPTS). This concept was developed in the early 1960s (Cox et al. 1963; Opdyke & Channell 1996; Laj & Channell 2007; Singer 2007; Stoner & St-Onge 2007) when according to their polarity sediment sequences were divided in polarity chrons (Lowrie 2007). The midpoint of the last magnetic reversal, the Brunhes-Matuyama transition occurred at some time between 786.1 ± 1.5 ka (Sagnotti et al. 2014) and 773.1 ± 0.4 ka (Channell et al. 2010) or 773 ± 1 ka (Singer 2014). However, due to a scarcity of records with long time scales this rather simple method cannot be applied to many lacustrine archives.

On shorter time scales geomagnetic excursions might help. However, Roberts & Turner (2013) argue that excursions are the most abused geomagnetic phenomena and should if at all only be used with extreme caution unless they are accompanied by precise additional chronological constraints since such single events could also be caused by sediment deformation. Geomagnetic excursions occur rather frequently (Laj & Channell 2007) and are described as short episodes when the magnetic field of the

Fig. 4: Settling of magnetic particles and subsequent lock-in (Tauxe 1993, modified).
Earth deviates into an intermediate polarity (Roberts 2008) or simply as a significant departure from the geocentric axial dipole (King & Peck 2001) beyond the normal range of secular variations (Lund et al. 2006; Laj & Channell 2007; Lund 2007). The discovery of 27 well-documented geomagnetic field instabilities manifested in excursions that occurred during the Quaternary with 14 of them occurring during the Brunhes polarity chron (the most recent one we are living in) contributed to the compilation of a geomagnetic instability time scale (GITS) which also delineates the many excursions that took place during periods of stable polarity (Singer 2014). However, this must be viewed as a work in progress that will be subject to refinement in the near future (Singer 2014) as there is no general consensus about the number of excursion found during the Brunhes chron so far (Laj & Channell 2007; Lund 2007). The best known and investigated excursions are the Laschamp Event (40.7 ± 1 ka) (Singer et al. 2009) and the Mono Lake Event (32.4 ± 0.3 ka) (Singer 2007). Both have been demonstrated to occur globally (Lund 2007; Roberts 2008) and either of them (Mazaud et al. 2002) or both (Cassata et al. 2008; Lisé-Pronovost et al. 2013, Appendix 20) were also found on the southern hemisphere. However, ages for these swings differ significantly in many studies (Lisé-Pronovost et al. 2013, Appendix 20). Another geomagnetic excursion, the Hilina Pali excursion is less pronounced and not well established yet (Teanby et al. 2002). Although still much debated it probably occurred between 17 ka (Laj et al. 2002; Singer 2014) and 22 ka cal BP (Peck et al. 1996; Nowaczyk & Knies 2000; Nowaczyk et al. 2003) when distinct inclination lows were found in these studies. It was also found recently in Fram Strait in various archives (Haberzetttl unpublished data) and potentially at Laguna Potrok Aike (Argentina) (Lisé-Pronovost et al. 2013, Appendix 20).

Nevertheless, covering ‘only’ 20 ka is also a challenge for many lacustrine sequences. On shorter time scales smaller geomagnetic directional shifts are called paleomagnetic secular variations (PSVs) (Thompson 1986; Stoner & St-Onge 2007). PSVs which can be used as chronostratigraphic tool especially during the Holocene appear to be better suited for dating purposes than geomagnetic excursion (Roberts & Turner 2013). The first study on PSVs was carried out by Mackereth (1971) on lacustrine sediments from Lake Windermere, UK, where changes in declination were investigated (Creer & Tucholka 1983; Oldfield & Richardson 1990). “This work paved the way for the development of the field of secular variation magnetic
stratigraphy” (Opdyke & Channell 1996) and paleomagnetic “work on lake sediments mushroomed” (Creer & Tucholka 1983). Due to the convenience of not having to open or extrude the cores often only declination was measured these days (Dearing 1986; Oldfield & Richardson 1990; Leemann & Niessen 1994; Opdyke & Channell 1996). Inclination measurements required the cores to be opened and subsampled (Oldfield & Richardson 1990). More recently inclination records turned out to be often more suitable in lacustrine environments, especially in lower latitudes (Creer & Tucholka 1983; Thompson 1986; Oldfield & Richardson 1990; Anker et al. 2001; Haberzettel et al. 2015, Appendix 13). Although the spatial occurrence of lakes suitable for PSV studies is rather erratic most studies establishing PSV records originate from this environment since sedimentation rates in marine archives are often too low for high-resolution records (Opdyke & Channell 1996). However, PSV records from lakes are still patchy with distinct gaps in Tibet (Haberzettel et al. 2015, Appendix 13) and the other regions investigated in this thesis (Korte & Constable 2011; Korte et al. 2011) (Fig. 5).

Fig. 5: Distribution of sediment records contained in the CALS3k.3 global geomagnetic field model (stars) covering the past 3,000 years. Red ellipses indicate new records obtained within this thesis (Korte & Constable 2011, modified).
Due to the absence of measured PSV records magnetostratigraphic comparisons in this thesis were initially drawn with global geomagnetic field models like the CALS3k.x (Korte et al. 2009), the CALS7k.2 (Korte et al. 2005), or the pfm9k (Nilsson et al. 2014) model (Kasper et al. 2012, Appendix 15; Haberzettl et al. 2013, Appendix 11; Ahlborn et al. 2015, Appendix 1). This already helped to improve reservoir effect affected radiocarbon based chronologies distinctively. Unfortunately, such models are limited by the reliability of incorporated data, age uncertainties, and the regional bias of data availability (Yu et al. 2010). This means that due to a lack of data comparisons to such models are sometimes unreliable. This is especially the case for Patagonia (Ohlendorf et al. 2014, Appendix 27) and to a certain extend for Tibet before 2 ka cal BP (Haberzettl et al. 2015, Appendix 13). Hence, after an initial comparison with the models it was always tried to build a data base (≥2 records) with various archives for comparison which was successfully accomplished for Sulawesi (Biagioni et al. 2015, Appendix 3) and Tibet (Haberzettl et al. 2015, Appendix 13) within this thesis.

Finally, it has to be mentioned that each site has to be tested if PSVs can be used as chronostratigraphic tool since not all sediment sequences are suited for paleomagnetic dating (Oldfield & Richardson 1990). Only 20 % of all lake studies generated inclination and declination records are suited for correlation (Opdyke & Channell 1996). In general it is difficult to predict which sites are suited and which are not, though some controlling factors have become apparent (Dearing 1986; Oldfield & Richardson 1990):

a) In coarse grained sediments such as sand the paleomagnetic remanence is not sufficiently well locked to retain a signal from the ambient magnetic field of the Earth at the time of deposition. Therefore, sediments dominated by coarse grains usually do not faithfully record magnetic field information from the time of deposition (Roberts 2007; Roberts & Turner 2013).

b) A high content of diamagnetic components such as carbonates, water, or organic matter and hence a low minerogenic proportion of the sediment often results in a weak unstable natural remanence.

However, once a regional master curve of PSVs is established this can be used as a chronostratigraphic tool (Lund et al. 2006) to date surrounding paleoenvironmental records (Oldfield & Richardson 1990) with a precision of decadal to millennial-scale resolution during the Holocene (Roberts & Turner 2013). Due to non-dipolar
components of the magnetic field of the earth this PSV stratigraphy is limited to the continental scale (Roberts & Turner 2013), i.e., a certain area around the type site typically ranging between 1,000 - 2,000 km (Thompson 1986; Oldfield & Richardson 1990; Lund et al. 2006) and 3,000 - 5,000 km (King & Peck 2001; Lund 2007). Around the Tibetan Plateau PSV similarities over an area of >3,000 km have been observed in this thesis (Haberzettl et al. 2015, Appendix 13).

Multi-dating-approach

The most powerful tool to obtain accurate chronologies from lacustrine archives is a multi-dating-approach (King & Peck 2001). This could consist of radiocarbon dating on various materials (e.g., organic bulk, inorganic bulk, terrestrial organic matter, etc.) (Haberzettl et al. 2005), component specific radiocarbon dating (e.g., lignin phenols) (Hou et al. 2010), optical dating (Long et al. 2015, Appendix 23), $^{230}$Th/$^{234}$U-dating (Wagner 1998), tephrochronology (Haberzettl et al. 2007; Haberzettl et al. 2009, Appendix 9), radioisotopes ($^{137}$Cs/$^{210}$Pb) in the most recent part (Kasper et al. 2012, Appendix 15; Haberzettl et al. 2015, Appendix 13), etc. Subsequently, chronologies should be evaluated using magnetostratigraphy (Kasper et al. 2012, Appendix 15; Haberzettl et al. 2015, Appendix 13). Such approaches need to bring together various expertise and disciplines. However, such an approach often suffers from insufficient time and/or manpower to carry out all these investigations. In some cases also the material turns out to be unsuitable for one or the other method. Within this thesis such an approach was aimed for Lake Tangra Yumco on the Tibetan Plateau. Here radiocarbon dating of lignin phenols and $^{230}$Th/$^{234}$U-dating turned out not to be feasible. Therefore, the focus was put on radiocarbon dating of a piece of wood and reservoir corrected bulk ages (Haberzettl et al. 2015, Appendix 13) (Fig. 1). The chronology was tested with optical dating revealing ages in the range of the reservoir corrected ages (Long et al. 2015, Appendix 23) and magnetostratigraphy (Haberzettl et al. 2015, Appendix 13) confirming this approach.
Conclusions and Outlook

The analysis of lacustrine sediments to extract paleoenvironmental information is a very promising field of research. Their study needs a multidisciplinary approach which involves different proxies, proxy calibration- and monitoring studies, allowing paleoenvironments and paleoclimate, as well as recent climate change, to be investigated with increasing accuracy (Verrecchia 2008). However, it is still a long way to go to fully understand lacustrine systems and their paleoclimatic significance. Any new piece of information will take us closer to the ultimate goal of understanding lacustrine environments through space and time (Cabrera et al. 2009).

Future work beyond this thesis will contribute to a better understanding of system processes, system interactions, and system feedbacks. For this purpose parallel investigations on different but neighboring systems should be carried out. For example a small lake with a limited catchment located close to a larger system could be investigated. Both systems continuously record environmental changes. While the larger system records processes occurring over a large area in the small system large-scale changes might be overprinted by local information. Comparing the two systems (including catchment and monitoring results) and their respective records will provide a deeper insight in processes acting on diverse spatio-temporal scales. First steps concerning this approach are on the way in southern central Tibet where processes affecting the large system of Lake Tangra Yumco (Akita et al. 2015, Appendix 2) and two smaller systems (Miehe et al. 2014, Appendix 24; Ahlborn et al. 2015, Appendix 1) located in the catchment area of this lake have been investigated. Future detailed comparisons will allow for a differentiation of processes acting on different spatial and temporal scales and hence contribute to a better understanding of the individual system.

Most other studies presented in this thesis are also planned to continue in future. Further manuscripts about Tibet, South Africa, and Hudson Bay are in preparation. Additionally, processing of already measured paleomagnetic data from Eilandvlei (South Africa), Xuru and Peiku Co (Tibet), Fram Strait, Maxwell Bay (Antarctica), and some sites in Patagonia (Argentina) is in progress.
In terms of limnogeological investigations future work will focus on the extension of the existing paleoenvironmental database which was gathered within the RAiN (Regional Archives for Integrated iNvestigations) project (Haberzettl et al. 2014, Appendix 12). Based on investigations of terrestrial and marine paleoenvironmental archives in different rainfall zones in South Africa, RAiN assesses the compatibility of the two types of archives in terms of past climate and ecosystem changes and contributes to an improved knowledge of land-ocean interactions by following transport pathways from source to sink (Haberzettl et al. 2014, Appendix 12). Up to now from the year-round rainfall zone sediment cores have been recovered in 2013 from offshore and onshore the Wilderness Coastal Section of the Garden Route National Park. Cores have already been opened and analyzed using a large suite of parameters for paleoenvironmental reconstruction. In terms of paleomagnetic measurements it turned out that marine sediments are unsuited for PSV reconstructions in this area. This might be the consequence of dilution of the sediment by diamagnetic marine carbonates. Lacustrine facies showed a sufficiently high magnetization on sediments from Lakes Eilandvlei and Swartvlei (Haberzettl unpublished data). A similar picture was observed on the West Coast of South Africa, where the top sediments of Lake Verlorenvlei have a sufficiently high magnetization but offshore sediments do not. Paleolimnological investigations at Verlorenvlei just started in 2014 but are very promising.

In Tibet the successful work as also seen in this thesis during the past years within the DFG (German Research Foundation) priority program 1372 TiP (Tibetan Plateau: Formation-Climate-Ecosystems) and the BMBF (German Federal Ministry of Education and Research) funded CAME (Central Asia – Monsoon dynamics and Geo-ecosystems) program encouraged some colleagues including myself to promote a deep drilling effort at Lake Nam Co within the framework of the International Continental Scientific Drilling Program (ICDP). Preliminary seismic investigations revealed a sediment thickness of at least 800 m since no bottom reflector was found down to this depth (Spiess et al. 2014). A conservative age estimation results in an age of 460 to 1,900 ka for this seismically imaged sequence (Spiess et al. 2014). This will result in an enormous amount of paleoenvironmental information from paleoclimatic studies, molecular clock investigations, and tectonic research.

According to the stratigraphic interpretation of the preliminary seismic data, continuous sedimentation at Nam Co occurred during several glacial-interglacial
cycles. Considering the short time coverage of other continuous lacustrine records on
the Tibetan Plateau (<32 ka) this makes Nam Co the perfect site to study large-scale
atmospheric circulation variations (Monsoon and Westerlies) on much longer time
scales. This is of paramount significance since from the whole area information on past
interglacials, especially the ones which are commonly regarded as analogue to the
Holocene like Marine Isotope Stage (MIS) 11 (McManus et al. 2013), are lacking. Nam
Co might provide a unique opportunity to study the internal variability of MIS 11 in
Southeast Asia. Analyses of such analogues could be very valuable for the
understanding of the interactions of climate systems such as Monsoon and Westerlies
enabling better future climate scenarios. Up to now only few terrestrial records covering
this interval have been recovered. However, these are not close to Nam Co (Rousseau
2013).

So far it also remains unclear how the atmospheric circulation systems changed
on the Tibetan Plateau during older glacial-interglacial cycles (or even interstadials).
From the last glacial-interglacial transition it is known that changes from a dry and cold
to a moist and warm environment occurred very fast with a strong moisture pulse in
the early Holocene, i.e., within <1000 years (Kasper et al. 2015, Appendix 17).
However, transitions from interglacial to glacial conditions have not been observed in
this area yet.

Based on dating of ancient lake level terraces around Nam Co, Zhu et al. (2004)
reconstructed an “Ancient Large Lake” on the TP for the period between 115 and
40 ka BP incorporating Nam Co. However, no continuous hydrological information is
available for this interval, inhibiting a detailed investigation of hydrological variations in
this area. The recovery of continuous records would allow to study feedback
mechanisms of a “Pan-Lake” environment to the surrounding area (e.g., vegetation) or
to the climate system itself. Such a large water body would likely cause intensive water
recycling on the Tibetan Plateau in addition to or in contrast to monsoon influence.

From the paleomagnetic perspective the recovery of a long drill core from Nam Co
means that many excursion of the Brunhes chron potentially the Brunhes-Matuyama
transition will be contained in this record in high-resolution since sedimentation rates
at Nam Co can reach up to 2.4 mm a⁻¹ (Kasper et al. 2015, Appendix 17).

Besides the deep drilling of Nam Co another major future aim will be the
construction of a PSV stack for the Tibetan Plateau. Currently eight short lasting
records between 400 and 4,000 years are available although not yet completely processed and more sediment records will be measured in the near future. Once, reliable chronologies are available for the records this task will be addressed. Similar PSV stacks have previously been published for East Asia (Zheng et al. 2014), eastern Canada (Barletta et al. 2010), northeastern United States (King & Peck 2001), Fennoscandia (Snowball et al. 2007; Lougheed et al. 2014), central-northern Great Britain (Turner & Thompson 1981), and the West Eifel (Germany) (Stockhausen 1998). Such a stack for Tibet bears the great potential to be used as a reference curve for dating purposes for a very large region.
The aim of this thesis is to provide new paleolimnological and limnogeological information and develop conceptual approaches from areas of the world where this kind of information is very scarce to (almost) inexistent such as the steppe parts of southern Patagonia (Argentina), the eastern Ecuadorian Andes, the Island of Sulawesi (Indonesia), the epicontinental sea of the Hudson Bay, the Tibetan Plateau, or the different rainfall zones of South Africa. A special emphasis will be on the construction of reliable chronologies using multi-dating approaches. In this context one focus will be on the evaluation of chronologies using PSVs wherever this was possible depending on sediment properties.

For this thesis only internationally published peer-reviewed articles are considered. Although, some contributions are from Laguna Potrok Aike which was the investigated site of my PhD thesis (Haberzettl 2006) all contributions to this habilitation thesis postdate the successful completion of the PhD thesis and were hence compiled independently. Even though the papers are in alphabetical order they can be structured as follows:

1. New conceptual approaches
2. Paleoenvironmental reconstructions using simple magnetostratigraphically not confirmed chronologies since no paleomagnetic secular variation data could be obtained from the sediment and other paleolimnological and limnogeological investigations such as studies on sediment distributions (including one marine study from the epicontinental sea of the Hudson Bay)
3. Paleomagnetic investigations and/or magnetostratigraphic evaluations of chronologies
4. Paleoenvironmental information from magnetostratigraphically corroborated chronologies
5. Other dating approaches
Table 1: List of manuscripts used for this thesis. No. corresponds to the appendix number. Category refers to the categorization given on the previous page.

<table>
<thead>
<tr>
<th>No.</th>
<th>Manuscript</th>
<th>Category</th>
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<tr>
<td>2</td>
<td>Akita L.G., Frenzel P., <strong>Haberzettl T.</strong>, Kasper T., Wang J. &amp; Reichert 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. Palaeogeography, Palaeoclimatology, Palaeoecology 419, 60-74.</td>
<td>1</td>
<td>data acquisition for physical and geochemical sediment properties / comparison to physical and chemical sediment properties / writing manuscript</td>
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<td>5</td>
<td>Brunschön C., <strong>Haberzettl T.</strong> &amp; Behling H. (2010): High-resolution studies on vegetation succession, hydrological variations, anthropogenic impact and genesis of a subrecent lake in southern Ecuador. Vegetation History and Archaeobotany 19(3), 191-206.</td>
<td>2</td>
<td>concept of research approach / data acquisition for geochemical sediment properties / data analysis and interpretation / writing manuscript</td>
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<td>9</td>
<td><strong>Habertzettl T.</strong>, Anselmetti F.S., Bowen S.W., Fey M., Mayr C., Zolitschka B., Ariztegui D., Mauz B., Ohlendorf C., Kastner S., Lücke A., Schäbitz F. &amp; Wille M. (2009): Late Pleistocene dust deposition in the Patagonian steppe - extending and refining the paleoenvironmental and tephrochronological record from Laguna Potrok Aike back to 55 ka. Quaternary Science Reviews 28(25-26), 2927-2939.</td>
<td>1-5</td>
<td>concept of research approach / data assessment / data analysis and interpretation / writing manuscript</td>
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<td>10</td>
<td><strong>Habertzettl T.</strong>, St-Onge G. &amp; Lajeunesse P. (2010): Multi-proxy records of environmental changes in Hudson Bay and Strait since the final outburst flood of Lake Agassiz-Ojibway. Marine Geology 271(1-2), 93-105.</td>
<td>2, 3</td>
<td>concept of research approach / data assessment / data analysis and interpretation / writing manuscript</td>
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<td>17</td>
<td>Kasper T., Haberzettl T., Wang J., Daut G., Doberschütz S., Zhu L. &amp; Mäusbacher R.</td>
<td>Hydrological variations on the Central Tibetan Plateau since the Last Glacial Maximum and their teleconnection to inter-regional and hemispheric climate variations. Journal of Quaternary Science 30(1), 70-78.</td>
<td>2015</td>
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<td>19</td>
<td>Kastner S., Ohlendorf C., Haberzettl T., Lücke A., Mayr C., Maidana N., Schäbitz F. &amp; Zolitschka B.</td>
<td>Southern hemispheric westerlies control the spatial distribution of modern sediments in Laguna Potrok Aike, Argentina. Journal of Paleolimnology 44(4), 887-902.</td>
<td>2010b</td>
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<td>20</td>
<td>Lisé-Pronovost A., St-Onge G., Gogorza C., Haberzettl T., Preda M., Kliem P., Francus P. &amp; Zolitschka B.</td>
<td>High-resolution paleomagnetic secular variations and relative paleointensity since the Late Pleistocene in southern South America. Quaternary Science Reviews 71, 91-108.</td>
<td>2013</td>
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<td>33</td>
<td>Wündsch M., Biagioni S., Behling H., Reinwarth B., Franz S., Bierbaß P., Daut G., Mäusbacher R. &amp; Habertzettl T.</td>
<td>2014</td>
<td>The Holocene 24(12), 1743-1756.</td>
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</table>
References


Since February 2010: Research Associate – Friedrich-Schiller-University Jena (Germany)
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Ehrenwörtliche Erklärung

Ich erkläre hiermit, dass mir die Habilitationsordnung der Friedrich-Schiller-Universität Jena bekannt ist.


Bei der Auswahl und Auswertung folgenden Materials haben mir die nachstehend aufgeführten Personen in der jeweils beschriebenen Weise entgeltlich/unentgeltlich geholfen:

_Siehe Co-Autoren der einzelnen Manuskripte_


Die Arbeit wurde bisher weder im In- noch Ausland in gleicher oder ähnlicher Form einer anderen Prüfungsbehörde vorgelegt.

Ich versichere, dass ich nach bestem Wissen die reine Wahrheit gesagt und nichts verschwiegen habe.

Jena, den 29. Mai 2015

[Unterschrift]