Ostracods as Indicators for Climatic and Environmental Changes on the Tibetan Plateau

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Abstract

The Tibetan Plateau is a vast and elevated plateau in Central Asia with an average elevation measuring more than 4500 meter a.s.l. This region is source area of the most important rivers of China, India and Southeast Asia providing water to more than 1.4 billion people. In this context, reliable predictions about the evolution of water supply from lacustrine and river systems are valuable for the authorities to ensure freshwater availability and environmental disaster prevention, especially in time of global warming.

For this proposal, organisms that provide a proxy record are particularly valuable. Especially ostracods, small bivalved crustaceans, have a large potential in this type of studies and live in practically every aquatic environment. In fact, ostracods allow multi-proxy studies in themselves because (1) their fossil shells provide evidence of past distribution from which palaeoclimate inferences can be drawn via indicator species, transfer function and mutual climatic range approaches; and (2) the biogenic calcite of their shells allows stable isotope and trace element analyses as proxies for temperature and salinity. Recent studies of ostracod assemblages from modern water bodies of the Tibetan Plateau and palaeoenvironmental records provide the basis to assess the environmental and societal impact of recent global change on the Tibetan Plateau, especially with regard to moisture changes and runoff of large rivers in its densely populated eastern and southern foreland and to compare the amplitude and timing of environmental change with those of the pre–industrial history and as proxies for environmental and climatic change on this area. This study wants to contribute to a better understanding and thus improving the ostracods as reliable indicators for the environmental and social impact of Quaternary and recent global change on the Tibetan Plateau.

The first study was conducted on the Taro Co lake system. Its Late Quaternary history was investigated to reconstruct local hydrological conditions and the regional moisture availability. For this aim, ostracod-based water depth and habitat reconstructions combined with OSL and radiocarbon dating were performed to better understand the Taro Co lake system evolution. The results showed a high-stand at 36.1 ka before present which represents the highest lake level since then related to a wet stage and resulting in a merging of Taro Co and its neighbouring lakes Zabuye and Lagkor Co. The lake level then decreased and reached its minimum around 30 ka. After c. 20 ka, the lake rose above the present day level. A minor low-stand, with colder and drier conditions, is documented at 12.5 cal. ka BP. Taro Co, Zabuye and Lagkor Co formed one large lake with a corresponding high-stand during the early Holocene (11.2–9.7 cal. ka BP). After this Holocene lake level maximum, all three lakes shrank, probably related to drier conditions, and the lakes became separated from Taro Co. The accelerating lake-level decrease of Taro Co was interrupted by a short-term lake level rise after

2 ka BP, probably related to minor variations of the monsoonal components. A last minor high-stand occurred at about 0.8 ka before today.

The second study concerned the Tangra Yumco lake system, located about 240 km east of Taro Co in the central–southern part of the Tibetan Plateau. The extension and position of this lake system makes it valuable for reconstructing palaeoclimatic variations through the lake history and to compare both with the adjacent lake systems. We reconstructed Late Quaternary lake level changes based on data from two lacustrine sediment cores. A micropalaeontological analysis focusing on Ostracoda was carried out combined with dating (^{14}C, ^{210}Pb, ^{137}Cs), sedimentology and stable isotope data from bulk sediment. An ostracod-based transfer function for specific conductivity was applied to assess and refine the reconstruction of lake level changes and to compare the results with other reconstructions from the Tibetan Plateau for evaluating inter-regional climatic patterns. The synthesis of ostracod-based environmental reconstruction and chronology for samples from Tangra Yumco reveals the evolution of the lake system during the past 17 ka. A low lake level around 17 cal ka BP is followed by a recovering until a high stand around 8–9 cal ka BP. Subsequently, between 7.7 and 2.5 cal ka BP, the lake level remained relatively stable with a subsequent short-living lowstand–highstand cycle at around 2 ka. Thereafter, the ostracod-based conductivity transfer function shows a decrease of conductivity corresponding to a lake level rising phase at around 0.4 ka. The recorded changes are indicators of past climatic conditions and refine the palaeoclimatic models in this area.

The third study focuses on ostracod associations of the Zhada Basin located in the western Tibetan Plateau. In this area almost no taxonomical studies were carried out so far, and, aiming to a future use of ostracods as palaeoenvironmental proxy for this sector of the Tibetan Plateau, a documentation of several unknown species was performed. This work increases the taxonomical knowledge and sets up a database for further studies on the poorly studied Pleistocene and Neogene sediments, especially in the western part of the Tibetan Plateau. A new species, *Leucocytherella dangeloi* is described.

To compare the obtained results with published records from other lakes, the considered transect was extended with information from articles regarding several water bodies present in different regions of the southern Tibetan Plateau. This database includes the lakes Bangong Co and Tso Moriri in the western part, Nam Co, the already discussed Tangra Yumco and Taro Co lake systems in the central part, Paiku Co, Puma Yumco and Chen Co in the southern part, and Naleng Co in the eastern part. Because of differences in dating, a correlation among the lakes was possible for selected time periods only.

Considering the first stage (40-30 ka), Taro Co shows high lake level followed by a fast decline between 35-30 ka, Paiku Co a general increasing trend probably related to the influence of meltwater in the latter. During the time frame 30-25 ka, Taro Co shows stable conditions followed by a rising of the lake level not in phase with the reconstructions of Paiku Co and Chen Co. This could be related to a bigger influence of the winter westerlies on the region more impacting the western part and a weaker Indian monsoonal component. In the third stage (25-22 ka), Chen Co lake level continued to fall, whilst Paiku Co passed from stable to increasing lake level and Taro Co rose. Following the precedent statement, an intensification of the winter westerlies is a potential explanation. During the fourth stage (22-18 ka), a general increasing trend for almost all the lakes considered is reported. In the following (18-14 ka) the general reconstructed climate conditions were splitted, with the transect from Tso Moriri to Nam Co in the west registering increasing of lake levels, and the eastern and south eastern part almost always with falling lake levels. At 14-10 ka we registered a general increasing trend for all the lakes considered. Almost all records report fluctuations at around 12-11 ka reflecting variations in the intensity of the atmospheric circulation factors at the transition to the Holocene confirmed by the trends of the ostracod assemblages and $\delta^{18}O$ for Taro Co and Tangra Yumco. After this interval, between 10-7, lake levels generally fell after a high stand at around 9-8 ka. In the last stage (7-0.4 ka), the lakes followed a discontinuous decreasing trend. Important fluctuations between 3 and 0.8 ka are reported for several lakes. Considering the uncertainties of the chronological models and the time-lag for this event comparing the two records we assume a synchronous timing. The comparison of all records shows a general homogeneous pattern indicating that the moisture availability evolved almost synchronously on the southern Tibetan Plateau.

The lakes present in the northern part of the Tibetan Plateau are not easily comparable to the southern lakes, because of the influence of the East Asian Summer Monsoon and of the Summer Westerlies. However, the climate reconstruction for lake Kuhai shows the highest lake level during the middle Holocene, about 1-2 ka later compared to the southern lakes, probably due to the influence of the East Asian Summer Monsoon. Anyhow, a strong decline afterwards due to deterioration of precipitation/evaporation balance is also reported, showing the general weakness of influence of the summer monsoonal components.

Especially in the time frame after 18 ka, where more information are available for the southern Tibetan Plateau, our results corresponds with only some time-shift, probably due to different dating or different exposure to the Indian Monsoon and the Westerlies although the lacking of information on tectonic and climate models will be needed to assess the different influence of the circulation patterns for the single lakes.

Kurzfassung

Das tibetische Plateau ist ein ausgedehntes Hochplateau in Zentralasien mit einer durchschnittlichen Höhenlage von mehr als 4500 m über dem Meeresspiegel. Diese Region ist Quellgebiet der wichtigsten Flüsse Chinas, Indiens und Südostasiens, die mehr als 1,4 Milliarden Menschen mit Wasser versorgen. In diesem Zusammenhang sind verlässliche Vorhersagen über die Entwicklung der Wasserversorgung durch die Flusssysteme für die Behörden unerlässlich, um die Verfügbarkeit von Süßwasser und die Verhütung von Umweltkatastrophen zu gewährleisten, insbesondere in Zeiten der globalen Erwärmung. Grundlage solcher Vorhersagen sind nicht nur ein Prozessverständnis und Monitoringdaten, sondern auch eine Rekonstruktion der spätquartären klimatischen Entwicklung auf dem Tibetplateau. Organismen, die als Proxys dienen können, sind für Klimarekonstruktionen besonders wertvoll. Insbesondere Ostracoden, kleine Krebstiere mit einer doppelklappigen, kalzitischen Schale, haben ein großes Potenzial für diese Art von Studien und leben in praktisch allen aquatischen Habitaten. In der Tat stellen Ostracoden an sich einen Multi-Proxy dar, da ihre Fossilien Paläoklima-Rückschlüsse sowohl (1) über Indikatorarten, Transferfunktionen und ökologische Toleranzen erlauben, als auch (2) der biogene Calcit ihrer Schalen stabile Isotopen- und Spurenelementanalysen als Proxys für Temperatur und Salzgehalt ermöglicht. Jüngste Studien über Ostrakodenverbreitungen in modernen Gewässern des tibetischen Hochplateaus und Paläoumweltaufzeichnungen liefern eine Grundlage, um die Auswirkungen des jüngsten globalen Wandels auf die Umwelt und die Gesellschaft des tibetanischen Hochlandes zu bewerten, insbesondere hinsichtlich der Feuchtigkeitsänderung und des Abflusses großer Flüsse in den dicht besiedelten Gebieten des östlichen und südlichen Vorlands und des Vergleichs der Amplitude und zeitlicher Muster der Umweltveränderungen in der vorindustriellen Geschichte. Diese Studie soll dazu beitragen, Ostracoden als verlässliche Indikatoren für die ökologischen und sozialen Auswirkungen des jüngsten globalen Wandels auf dem tibetischen Hochplateau besser zu verstehen und ihre Einsatzmöglichkeiten zu verbessern.

Die erste Studie wurde am Taro Co-Seesystem durchgeführt. Die spätquartäre Geschichte wurde untersucht, um die örtlichen hydrologischen Bedingungen und die regionale Verfügbarkeit von Feuchtigkeit zu rekonstruieren. Zu diesem Zweck wurden Rekonstruktionen von Wassertiefen und Lebensräumen auf der Basis von Ostrakodenanalysen in Kombination mit OSL- und Radiokarbon-Datierungen durchgeführt, um die Entwicklung des Taro Co-Seesystems besser zu verstehen. Die Ergebnisse zeigen einen Hochstand bei 36,1 ka vor der Gegenwart, was den höchsten Seespiegel seither darstellt. Diese relativ feuchte Phase führte zu einer Verschmelzung von Taro Co und den benachbarten Seen Zabuye und Lagkor Co.

Der Seespiegel sank dann ab und erreichte sein Minimum um 30 ka. Nach ca. 20 ka stieg der See wieder über das heutige Niveau. Ein geringer Tiefstand mit kälteren und trockeneren Bedingungen ist bei 12,5 cal ka BP dokumentiert. Taro Co, Zabuye und Lagkor Co verschmolzen während des frühen Holozäns (11,2–9,7 cal. ka BP) zu einem großen See mit einem entsprechend hohen Seespiegelstand. Nach diesem holozänen Maximum schrumpften alle drei Seen, was auf trockenere Bedingungen zurückzuführen war, und die Seen trennten sich vom Taro Co. Das sich beschleunigende Schrumpfen des Taro Co wurde durch einen kurzfristigen Anstieg des Seespiegels nach 2 ka unterbrochen und war wahrscheinlich durch geringfügige Abweichungen der Monsunintensität verursacht. Ein letzter, kleinerer und kurzfristiger Seespiegelhochstand war bei etwa 0,8 ka vor heute.

Die zweite Studie behandelt das Tangra Yumco-Seesystem, das sich etwa 240 km östlich des Taro Co im zentral-südlichen Teil des Tibetischen Plateaus befindet. Die Ausdehnung und Position dieses Seesystems macht es wertvoll, paläoklimatische Veränderungen zu rekonstruieren und mit den benachbarten Seesystemen zu vergleichen. Wir rekonstruieren die Änderungen des späten quartären Seespiegels auf der Grundlage von Daten aus zwei Sedimentkernen. Eine mikropaläontologische Analyse mit Fokus auf Ostracoda wurde in Kombination mit Datierungen (^{14}C, ^{210}Pb, ^{137}Cs), der Sedimentologie und stabilen Isotopendaten aus Bulk-Sediment durchgeführt. Es wurde eine Transferfunktion auf der Basis von Ostracoden für die Rekonstruktion der spezifischen Leitfähigkeit angewendet, um Änderungen des Seespiegels zu bewerten und zu verfeinern und die Ergebnisse mit anderen Rekonstruktionen für Seen des Tibetischen Plateaus für die Bewertung interregionaler Klimamuster zu vergleichen. Die Synthese der Rekonstruktion des Tangra Yumco zeigt die Entwicklung des Seesystems in den letzten 17.000 Jahren. Auf einen niedrigen Seespiegel um 17 cal ka BP folgt ein Anstieg bis zum Erreichen eines Maximums um 8–9 cal ka BP. Anschließend, zwischen 7,7 und 2,5 cal ka BP, blieb der Seespiegel relativ stabil mit einem darauf folgenden, kurzlebigen Tiefstand-Hochstand-Zyklus bei etwa 2 ka. Danach zeigt die auf Ostracoden beruhende Leitfähigkeitstransferfunktion einen Salinitätsabfall, der einer Anstiegsphase des Seespiegels bei etwa 0,4 ka entspricht. Die aufgezeichneten Änderungen der Proxys sind Indikatoren vergangener klimatischer Bedingungen und verfeinern die paläoklimatischen Modelle in diesem Bereich.

Die dritte Studie konzentriert sich auf die Ostrakoden Fauna des Zhada-Beckens im westlichen Tibetischen Plateau. In diesem Bereich wurde bisher fast keine Taxonomie durchgeführt. Um Ostracoden auch für diesen Sektor des Tibetischen Plateaus als Paläoumweltproxy einsetzen zu können, wurde eine taxonomische Dokumentation von mehreren unbekannten Arten durchgeführt. Diese Arbeit zielte darauf ab, das taxonomische Wissen zu erweitern und damit eine Grundlage für weitere Untersuchungen zu Seen und Sedimenten in den schlecht

untersuchten, westlichen Gebieten des Tibetischen Plateaus zu erstellen. Eine neue Art, *Leucocytherella dangeloi*, wird beschrieben.
Um die erzielten Ergebnisse mit publizierten Daten anderer Seen zu vergleichen, wurde der betrachtete Seentransekt mit Informationen aus Artikeln zu Seen aus verschiedenen Zonen des südlichen Tibetischen Plateaus erweitert. Diese Datenbasis umfasst die Seen Bangong Co und Tso Moriri im westlichen Teil, Nam Co, die bereits diskutierten Seesysteme Tangra Yumco und Taro Co im zentralen Teil, Paiku Co, Puma Yumco und Chen Co im südlichen Teil und Naleng Co im östlicher Teil des Tibetischen Plateaus. Aufgrund von Problemen mit den verschiedenen Chronologien wurde die Korrelation zwischen den Seen auf ausgewählte Zeiträume beschränkt
In der ersten Phase (40-30 ka) weist der Taro Co einen hohen Seespiegel auf, gefolgt von einem rapiden Rückgang zwischen 35 und 30 ka. Auch für den Paiku Co ist ein allgemein zunehmender Trend erkennbar, der wahrscheinlich mit dem Einfluss von Schmelzwasser zusammenhängt. Während des Zeitraums von 30-25 ka zeigt der Taro Co stabile Bedingungen, gefolgt von einem Anstieg des Seespiegels, der nicht mit den Rekonstruktionen von Paiku Co und Chen Co übereinstimmt. Dies könnte mit einem größeren Einfluss der winterlichen Westwinde auf die Region zusammenhängen. Sie treffen eher auf den westlichen Teil des tibetischen Plateaus und auf eine schwächere indische Monsunkomponente. In der dritten Phase (25-22 ka) sank der Seespiegel des Chen Co weiter, während der Paiku Co von einem stabilen Zustand zu einem ansteigenden Seespiegel überging und auch der Taro Co anstieg. Eine Zunahme der winterlichen Westwinde ist eine mögliche Erklärung dafür. Während der vierten Phase (22-18 ka) wird für fast alle untersuchten Seen ein allgemein zunehmender Trend dokumentiert. Im Folgenden (18-14 ka) lassen sich die Trends der rekonstruierten Klimabedingungen aufteilen, wobei der Transekt vom Tso Moriri bis zum Nam Co einen Anstieg der Seespiegel verzeichnet und der östliche und südöstliche Teil fast immer fallende Seespiegel aufweisen. Von 14-10 ka verzeichnen wir für alle betrachteten Seen einen allgemein zunehmenden Trend. Nahezu alle Aufzeichnungen berichten von Schwankungen um 12 bis 11 ka, die die schwankende Intensität der atmosphärischen Zirkulationsfaktoren beim Übergang zum Holozän widerspiegeln, was durch die untersuchten Trends der Ostrakodenfaunen und des $\delta^{18}O$ für Taro Co und Tangra Yumco bestätigt wird. Nach diesem Intervall sanken nach einem Hochstand zwischen 9 und 8 ka die Seespiegel im Allgemeinen.
In der letzten Etappe (7-0,4 ka) folgten die Seespiegel einem diskontinuierlichen, negativen Trend. Für einige Seen sind bedeutende Schwankungen zwischen 3 und 0,8 ka erkennbar.
Unter Berücksichtigung der Unsicherheiten der chronologischen Modelle und der Zeitverzögerung für dieses Ereignis beim Vergleich der beiden Datensätze gehen wir von einem möglichen synchronen Timing aus. Der Vergleich aller Datensätze zeigt ein allgemein

homogenes Muster, das darauf hinweist, dass sich die Feuchtigkeitsverfügbarkeit auf dem südlichen Tibetischen Plateau nahezu synchron entwickelte.

Die im nördlichen Teil des Tibetischen Plateaus vorhandenen Seen sind nicht leicht mit den südlichen Seen vergleichbar, was auf den Einfluss des ostasiatischen Sommermonsuns und der sommerlichen Westwinde zurückzuführen ist. Die Rekonstruktion des Klimas für den Kuhai-See zeigt den höchsten Seespiegel im mittleren Holozän, also etwa 1-2 ka später als für die südlichen Seen, wahrscheinlich aufgrund des Einflusses des ostasiatischen Sommermonsuns. Trotzdem wird auch hier ein starker Rückgang infolge eines negativen Niederschlags/Verdunstungsbilanz berichtet, was die allgemeine Schwäche des Einflusses der Monsun-Komponenten des Sommers zeigt.

Insbesondere in der Zeitspanne nach 18 ka, wo mehr Informationen verfügbar sind, entsprechen unsere Ergebnisse nur einer gewissen Zeitverschiebung, wahrscheinlich aufgrund einer unterschiedlichen Exposition gegenüber dem indischen Monsun und den Westwinden, obwohl es an Informationen über Tektonik- und Klimamodelle mangelt. Es ist erforderlich, den unterschiedlichen Einfluss der atmosphärischen Zirkulationsmuster für die einzelnen Seen zu bewerten.

Chapter 1 - Introduction

1.1 *General background*

The Tibetan Plateau (fig. 1) is a vast and elevated plateau in Central Asia covering an area of about 2.5 million km^2 and comprising most of the Tibetan Autonomous Province and Qinghai Province in Western China (75 - 105° E, 27.5 - 37.5° N). The average elevation measures more than 4500 meter a.s.l. (Li *et al*., 1983; Molnar, 1989; Tuttle and Schaeffer, 2013). The plateau is enclosed by the Himalayas and Gangdise Mountains to the south, the Karakoram Range and the Pamirs to the west, the Hengduan Mountains to the east and the Kunlun and Qilian Mountains to the north (Dewey *et al*., 1988; Lehmkuhl and Haselein, 2000; Lehmkuhl and Owen, 2005; Yao *et al*., 2012). The Tibetan Plateau is source area of the most important rivers of China, India and Southeast Asia (Liniger *et al*., 1998; Viviroli *et al*., 2007) and it is obviously a very important hydrological resource, providing water to more than 1.4 billion people (Immerzeel *et al*., 2010). The discharge of these rivers depends mostly on monsoonal rainfall (Wang *et al*., 2006; Jian *et al*., 2009) and snowmelt (Immerzeel *et al*. 2010). Agriculture, freshwater caption and hydropower generation are present activities on the plateau (Mukhopadhyay and Khan 2014). The enhanced human impact (Miao *et al.* 2011), namely growths in water demand due to increasing population (Vörösmarty *et al*. 2000) have been recognized as the main drivers of current or prospective water scarcity (Wang *et al*. 2006, Immerzeel and Bierkens 2012). In this context, reliable predictions about the evolution of water supply from lacustrine and river systems are valuable for the authorities to ensure freshwater availability and environmental disaster prevention, especially in time of global warming (Morril *et al.,* 2003; Jian *et al*., 2009; Mischke *et al*., 2010a).

Concerning this, the past and present processes and variability of moisture availability on the Tibetan Plateau is a central discussion point and its temporal reconstruction through multy proxies approach is urgently needed. Especially lake environments or palaeolakes are among the most sensitive continental recorders of climatic, hydrologic, and environmental changes. Geological studies in this area began in the 1950s as results of petroleum exploration in the northern part of the Tibetan Plateau, but only in recent decades it was monitored to detect possible Quaternary environmental and climatic changes related to global warming, focusing on Asian summer monsoon mainly controlling precipitation (e.g. An *et al*., 2000; Bransod *et al*., 2003; Herzschuh, 2006; Xu *et al*., 2007; Mischke *et al*., 2008; Günther *et al*., 2015; Yan *et al*., 2018). In the last decade, several studies of lacustrine sediments from the Tibetan Plateau identified significant lake level changes during the Late Quaternary that are related to monsoon and westerlies variability, especially in its central-southern part, where the biggest and more stable lakes are present and where the environmental conditions are more comparable

(Mischke and Zhang, 2010; Kasper *et al.*, 2012; Günther *et al.*, 2013; 2015; 2016; Doberschütz *et al.*, 2013; Mishra *et al.*, 2015; Ahlborn *et al.*, 2016; Henkel *et al*. 2016).

Given the increasing attention paid to this type of studies, organisms that provide a proxy record are especially valuable. In particular ostracods, small bivalved crustaceans, have a large potential in this type of studies and live in practically every aquatic environment. In fact, ostracods are multi proxy because their fossil shells provide evidence of past distribution from which palaeoclimate inferences can be drawn via indicator species, transfer function and mutual climatic range approaches. Furthermore, biogenic calcite of their shells allow stable isotope and trace element analyses as proxies for temperature and salinity.

Recent studies of ostracod assemblages from modern water bodies of the Tibetan Plateau and palaeoenvironmental records provide the basis to assess the environmental and societal impact of recent global change on the Tibetan Plateau, especially with regard to moisture changes and runoff of large rivers in its densely populated eastern and southern foreland and to compare the amplitude and timing of environmental change with those of the pre–industrial history (e.g. Mischke *et al.*, 2003; 2006; 2007; 2010a; 2012; Wrozyna *et al.*, 2009a, 2009b, 2010; Frenzel *et al.*, 2010; Li *et al.*, 2010; Akita *et al.*, 2016) and as proxies for environmental and climatic change on this area. This study wants to contribute to a better understanding and improving the ostracods as reliable indicators for palaeoclimatic changes on the Tibetan Plateau.

1.2 *Lacustrine sediments*

To investigate how climatic changes influence the Tibetan Plateau, several types of analysis can be used, e.g. $\delta^{8}O$ of glaciers (e.g. Thompson *et al.*, 2006; Yang *et al.*, 2006), speleothems (e.g. Kotlia *et al.*, 2012; Li *et al.*, 2014a) as well as tree-rings (Qin *et al.*, 2015; Hochreuther *et al.*, 2016). Also the dating of palaeo-shorelines allows to assess moisture availability changes (Kong *et al.*, 2011; Liu *et al.*, 2013; Rades *et al.*, 2015). The big amount of lacustrine records provides sensitive, high-resolution long time palaeoecological and palaeohydrological records, including datasets on lake level changes. In the last decades many scientific works on this topic were published using seismic profiling (e.g. Dietze *et al.*, 2010) sedimentology (e.g. Kasper *et al.*, 2012), palaeomagnetic (e.g. Herb *et al.*, 2013) pollen (e.g. Ma *et al.*, 2014), biomarkers (e.g. Günther *et al.*, 2016) and microfossils (e.g. Akita *et al.*, 2016).

1.3 *Ostracoda*

Ostracoda (Arthropoda) are small crustaceans providing information on environmental processes, biological activities, ecological and sedimentary events, geological and climatic conditions through the presence or abundance of species (Rodriguez-Lazaro and Ruiz-Munoz, 2012). This group has a large fossil record and is present in the marine, brackish and freshwater realm as a consequence of which it is widely employed as a palaeoenvironmental, palaeoclimatic and biostratigraphic indicator. Ostracod studies range into various disciplines such as evolutionary biology, zoology, molecular biology, (palaeo-)ecology, (palaeo-) limnology and (palae-)oceanography.

In terms of crustacean relationships, Horne *et al.* (2005) discuss the validity of palaeontological and neontological criteria in the definition of this group and conclude that ostracods are bivalved arthropods with up to eight pairs of limbs in adults, plus copulatory limbs and a furca all of which are totally enclosed by a bivalved carapace without growth lines. The juvenile ostracods grow by moulting. The calcitic carapace with two valves enclosing the soft body protects ostracods against the potential dangers of the aquatic milieu where they live and also bears the geochemical and isotopic signal of the water at the moment of biomineral precipitation. This carapace has a high potential to be preserved in sediments and as a consequence ostracods have a fossil record extending back at least 450 Ma.

Ostracoda is the oldest fossil arthropod group (Early Ordovician period to the present) with living representatives (Maddocks, 1982; Kempf, 1996; Willams *et al.,* 2008). The global diversity of Ostracoda estimates about 20,000 living species from marine, freshwater and transitional waters (Martens *et al*., 2008) with a total of about 65,000 living and fossil ostracod taxa at or below the species level, including subspecies and synonymies (Ikeya *et al*., 2005).

The success of ostracods in freshwater and brackish habitats is due to efficient osmotic adaptation (calcification in low mineralised waters) providing often wide tolerance to different salinity ranges (Iglikowska, 2014; Iglikowska and Pawlowska, 2015). Ostracods are efficient colonisers of new habitats (Newman, 2005; Iglikowska, 2014). The wide geographical distribution and simultaneous appearance on palaeocontinents indicate their rapid dispersal, reproductive modes and wide environmental tolerance (Willams *et al*., 2008). Ostracods occupy all types of aquatic environments from the oceanic abyss to temporary waters, on aquatic plants and in semi-terrestrial environments (Morgan, 1930; Benzie,1989; Frenzel and Boomer, 2005; Griffiths, 2006; Rodriguez-Lazaro and Ruiz-Munoz, 2012).

The secretion of ostracods shells occurs fairly rapidly, a few hours to a few days, and directly takes up elemental composition from ambient water. The geochemistry (trace-elements and stable isotopes) of ostracod shells is a biomarker of ambient water chemistry at time of secretion (conductivity, dissolved ions and solute compositions) (Forester, 1983; Ito and Forester, 2009; Deocampo, 2010). The geochemical information stored in ostracod shells (e.

g., low Mg/Ca) is commonly used for reconstructing the palaeo-environmental evolution of continental water bodies (Forester, 1986; Holmes, 1996; Börner *et al.*, 2013). The chemical shell composition (Mg, Sr, Na and Ba) is useful for the reconstruction of past water temperature, water balance and salinity (Chivas *et al.*, 1983; 1986; Griffiths and Holmes, 2000; Gouramanis and De Deckker, 2010). The changes in Sr/Ca of ostracod shells are believed to reflect changes in salinity while the changes in Mg/Ca shell do reflect both salinity and water temperature (Forester, 1986; Ito and Forester, 2009). However, new studies demonstrated this relation to be more complex than observed before, with the water chemistry playing a more important role (e.g. Börner *et al.*, 2013).

Ostracod isotopic composition ($\delta^{18}O$ and $\delta^{13}C$) is used to infer past temperature changes in deep lakes, hydroclimatic evolution of the continental waters, productivity changes etc. (von Grafenstein *et al.*, 1999; Schwalb, 2003; Wrozyna *et al.*, 2010; Börner *et al.*, 2013).

Their ecological plasticity based on tolerance to environmental constraints and adaptation to different feeding and reproduction types allow them to occupy most of the ecologic aquatic niches with the exception of that of planktonic in brackish and non-marine waters. Since ostracods have no pelagic larval stage they are dispersed in marine environments by successive occupation of ecosystems represented by water mass (pelagic species) or sediment and water–sediment interface (benthonic species). In the case of non-marine representatives, dispersal is favoured by the resting eggs and desiccation-resistant stages of many of these ostracods, thus intercontinental exchanges can be produced by the dispersal of eggs by prevailing winds, bird migrations, or even by amphibians, insects and, in recent times, by humans (Martens and Horne, 2009). Factors affecting ostracod distribution at different scales are influenced by temporal and physico-chemical stability of the ecosystems where ostracods are living and can be estimated by measuring alpha and beta diversity of the assemblages (Smith and Horne, 2002). In any case, the ecological peculiarities of the ostracods are clues to estimate the potential of these microcrustaceans in palaeoenvironmental interpretations and many authors agree that much work has to be done describing modern ecosystems to complete already existing databases. The NODE (Nonmarine Ostracod Distribution in Europe; Horne *et al.*, 1998) and NANODe (North American Nonmarine Ostracode Database; Forester *et al.*, 2005) databases are excellent examples of this attempt for putting together ostracod distributions for the Recent and Quaternary assemblages of Europe and North America, respectively. Knowledge of modern ostracod diversity is incomplete and variable due to the different intensity of studies of different biogeographical regions. Of c. 20,000 species of ostracods estimated living today, 2000 are non-marine species with irregular geographical distribution, with 400–500 from Palaearctic and Afrotropical regions (Martens and Horne, 2009). Recent work on groundwater faunas (e.g.,

Reeves *et al*., 2007) suggests that future studies in this area are likely to increase substantially the known biodiversity of non-marine ostracods.
Ostracod species show characteristic spatial-temporal patterns of distribution due to varying environmental and climatic parameters (Griffiths, 2006; Walter and Hengeveld, 2014).
An important aspect of this taxon is the worldwide activity of the ostracodologist' community, with more than 400 researchers currently registered in the International Research Group of Ostracoda (IRGO, https://www.ostracoda.net/about-irgo). This community of biological and palaeontological ostracod researchers covers several aspects and geographical regions, providing a large set of scientific publications on this group.

1.3.1 *Ostracoda as (palaeoenvironmental) proxies*

In a geological context, applications of ostracods include relative dating and correlation (biostratigraphy) as well as palaeoenvironmental and palaeoclimatic uses. The ostracod-based biostratigraphy is widely utilised (Colin and Lethiers, 1988; Horne, 1995; Whittaker and Hart, 2009), and integrates especially the sections where planktonic foraminifers and nannoplankton (in marine settings) or diatoms and pollen (in non-marine settings) are scarce. A comparison among living and fossil ostracods needs a good knowledge of potential range of similarity and difference between a living population and the fossil association recovered from a sediment sample, which can range from something close to the original living fauna (thanatocoenosis—if in situ, i.e. autochthonous) to associations that have been subjected to varying degrees of transport with consequent sorting and loss (taphocoenosis). Most taphocoenoses will contain both autochthonous and allochthonous components, and ostracod analysis allows discrimination of both in situ and transported components of the association. Fossil associations, relative and absolute abundances of species, diversity, dominance, the ratios of adult males to females, adults to juveniles, carapaces to valves, etc., all have potential value provided that in situ and transported taxa are discriminated. It follows that fossil associations must be interpreted with care and that recognition of the autochthonous elements is vital for palaeoclimatic analysis, whether the ostracods are being used as an ecological or biogeographical indicator or the shell material is utilised for its chemical or isotopic signals.
Mixtures of fossil and modern ostracod specimens can be recognised and separated by making use of adult to juvenile ratios, proportions of carapaces to valves, abundance of individual species, preservation of the valve morphologic features and presence or absence of soft parts. Taphocoenoses that reflect a mixture of species from various water depths along the gradient of the continental shelf and slope, but which are contemporaneous, can be readily distinguished by examining adult to juvenile ratios, taking advantage of the fact that finer grained particles such as juvenile valves are more readily transported over greater distances; such transported assemblages have a clearly skewed adult to juvenile ratio (Brouwers, 1988).

Ostracods are commonly found in Quaternary deposits of marine, lacustrine and freshwater environments and thus they can be successfully used as palaeoenvironmental and palaeoclimate proxies. Quantitative and qualitative analyses on faunal assemblages and geochemical analyses on their carapaces permit palaeoenvironmental reconstructions by the estimation of past environmental parameters including temperature, salinity, main solute concentrations, productivity, hydrology and oxygenation (e.g. Frenzel and Boomer; 2005; Mischke *et al*., 2007; Börner *et al*., 2013).
Palaeoecological applications of ostracod-based transfer functions have proven to be a useful tool to assess palaeoclimatic conditions (Mischke 2012, Viehberg and Mesquita-Joanes 2012).

1.3.2 *Importance of taxonomy in the western part of the Tibetan Plateau*

Studies of Ostracods from the Tibetan Plateau began in the 1950s at the same time of the petroleum exploration in this area. The reports from this period were mainly published in Chinese language (Sun 1998; Hou and Gou, 2002; 2007), not allowing an easy access for non-Chinese readers. As a result of the economic significance of Quaternary ostracods from the Qaidam Basin for the oil and gas exploration, papers often summarized unpublished reports without a presentation of the detailed original data of ostracod records from individual sites (e.g. Huang, 1964, 1979; Wang and Zhu, 1991). Some of the earlier studies included the investigation of modern ostracods and the relevant habitats of the Tibetan Plateau as a basis for palaeoecological inferences although the majority focused on the stratigraphical use of Quaternary ostracods from the Qaidam Basin (e.g. Huang *et al*., 1985; Yang et al., 1995, 1997). In the last years, with the increasing of palaeontological studies in this region, the quality and availability of ostracod taxonomy became relevantly higher. Unfortunately, the largest amount of works has been mostly concentrated in the most easily accessible northeastern and southeastern part of the Tibetan Plateau (Mischke *et al*., 2012), with only a few works published about the western part (Li *et al*., 1991; Kempf *et al*., 2009; Mishra *et al*., 2015). Among the localities already geologically and environmentally investigated, the Bangong Lake (Li *et al.*, 1991), Tianshuihai lake (Li *et al*., 1997a, 1997b) and South Hongshan (Zhu *et al*., 2007) concern mostly biostratigraphy and most of them are published in Chinese language. The only locality already investigated in more aspects is the Zhada Basin, where studies concerning its tectonical origins (Wang *et al*., 2004; Wang *et al*., 2008; Saylor *et al*., 2010a) and palaeoenvironmental reconstruction (Saylor *et al*., 2010b) were carried out. Kempf *et al*. (2009), which first investigated ostracod assemblages in this area in association with petrographic and sedimentological proxies, found several not identified species, thus further studies are needed.

1.4 *Late Quaternary climate evolution*

The Quaternary period (last 2.6 million years) is characterised by great variability in environments and climate in the Earth history (e.g., continental ice sheets, sea level and lake level fluctuations) (e.g. Bradley, 1985; Anderson *et al*., 2007). The Tibetan Plateau is especially sensitive to global climate change (e.g., temperature rise) during the Quaternary (Mischke and Zhang, 2010; Zhu *et al*., 2015). High lake-water-levels across Africa, Arabia and India (monsoon rains over the Sahara and the Indian subcontinent (between 10,000 and 5000 years B.P., before present) is evidence for a strengthening of monsoon while it was weak during the glacial maximum at 18,000 years BP (Street and Grove, 1979; An, 2000). It is largely accepted that the climate system on the Tibetan Plateau is mostly influenced by the Asian summer monsoon system (e.g. Gasse *et al*., 1991; Liu *et al*., 2009; An *et al*., 2012b, Maussion *et al*., 2014). During the Quaternary, its intensity variations and its interplay with the Indian monsoon and the Westerlies influenced the moisture availability and, as consequence, the evolution of the lake systems on the plateau. These were driven by climatic changes and often also through switches from an open to closed lake basins and vice versa.

Several studies using different approaches on the lakes and their catchments on a southern west-east transect were carried out in the last decades. Among them, there is a general agreement on the climate evolution during the early Holocene, where the conditions were relatively warmer and wetter than in the previous period and, after this, the general trend in the whole region is a progressive drying of the climate, with a consequent lowering of the lake levels (e.g. Fontes *et al*., 1996; Zhu *et al*., 2009; Kasper *et al*., 2015; Ahlborn *et al*., 2017). However, several discrepancies concerning interpretation and time-shifts of the climate-related events are still under discussion.

1.5 *Outline of the thesis*

This PhD thesis is part of the joint research “Lake systems response to Late Quaternary monsoon dynamics on the Tibetan Plateau” funded by the German Research Foundation (Deutsche Forschungsgemeinschaft – DFG) within the Priority Programme 1372; “Tibetan Plateau: Formation – Climate – Ecosystems (TiP)” in cooperation with the Institute of Tibetan Plateau Research of the Chinese Academy of Sciences. The goal was to evaluate the monsoons impact and their past and present evolution, in order to give predictions for the future in this time of strong anthropogenic impact and climatic changes (http://www.tip.unituebingen. de/index.php/de).

Within this project, an additional publication written during this PhD work (Ahlborn, Haberzettl, Wang, Alivernini *et al*., 2015) concerning a multi-proxy sedimentological, geochemical, micropalaeontological, and palynological study of a lacustrine sediment record from the small TT Lake within the catchment of Tangra Yumco (southerncentral Tibetan Plateau) was published. The manuscript was not included in this thesis because of the different field of application and objective.

1.6 *Objectives of the thesis*

On the basis of what has been written above, the objective of this thesis is to improve our palaeoclimatic and palaeoenvironmental knowledge based on late Quaternary ostracods of Tibetan Plateau lakes during the last 40 ka. Moreover, for future researches, it is intended to improve the poor ostracod dataset in Western Tibet. This work is composed by the investigation and reconstruction through a multy-proxy approach of Taro Co and Tangra Yumco lake systems. These two sites were chosen to assess and refine the lake level reconstruction mainly concentrated on ostracods and their related application. Concerning the improvement of taxonomical research in this area, the ostracod fauna from the western Tibetan lakes was poorly studied so far, and the obtained material from the Zhada basin is an opportunity to improve the knowledge for this sector.

More precisely this work aims

1) To reconstruct the evolution of the Taro Co lake system for the last 40 ka especially with respect to changes in lake level variations (Chapter 2) discerning climate change, i.e. shifts of the precipitation/evaporation balance, from lake system changes by investigating all three lakes of the system.

2) To refine and complete the already published Tangra Yumco lake level curve of Ahlborn *et al*. (2016) based on new ostracod data and to reconstruct possible scenarios of the interactions between the basins of the Tangra Yumco system during the past 17 ka using an ostracod-based conductivity reconstruction to discriminate climatic and hydrographic effects (Chapter 3).

3) To characterize the poorly studied ostracod fauna of the Zhada Basin, in order to improve their potential for future (palaeo)environmental reconstruction in Western Tibet (Chapter 4).

4) to answer the question of whether there were synchronous or asynchronous late Quaternary climate shifts along a west-east transect on the southern Tibetan Plateau. The general comparison was carried out based on own results and adding several lakes already investigated by several authors (Tab. 1).

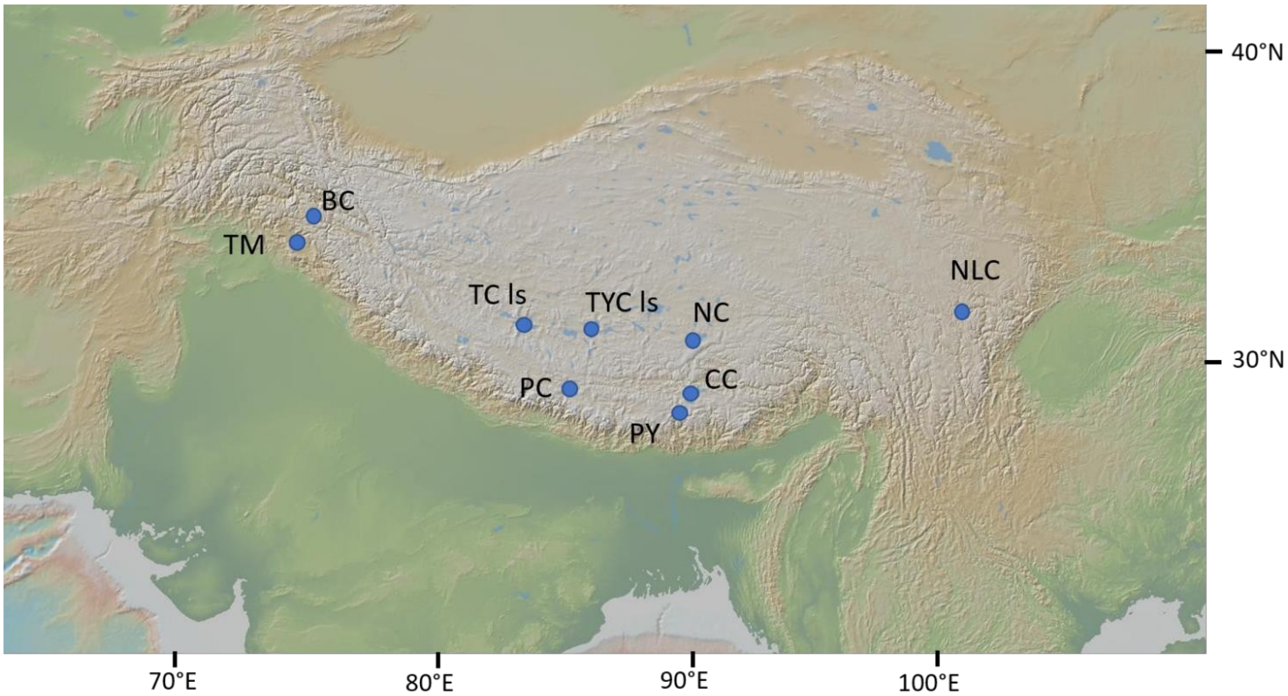

Figure 1: Overview of the Tibetan Plateau with the investigated and compared lakes' locations. TM – Tso Moriri, BC – Bangong Co, TC ls – Taro Co lake system, PC – Paiku Co, TYC ls – Tangra Yumco lake system, NC – Nam Co, CC – Chen Co, PY – Puma Yumco, NLC – Naleng Co

Table 1: Records of the considered lakes from the southern Tibetan Plateau

Lakes	Author(s)
Bangong Co	Fontes *et al*., 1996; Van Campo *et al*., 1996; Wie and Gasse 1999
Tose Moirier	Leipe *et al*., 2014; Mishra *et al*., 2015
Tandra Yumco lake system (inclusive Tangung Co and Xuru Co)	Ahlborn *et al*., 2016; Alivernini *et al*., 2018b (present study)
Taro Co lake system (inclusive Zabuye and Lagkor Co)	Alivernini *et al*., 2018a (present study)
Nam Co	Kasper *et al*., 2015
Puma Yumco	Wang *et al*., 2009; Peng *et al*., 2013; Nishimura *et al*., 2014
Chen Co	Zhu *et al*., 2003;2009
Naleng Co	Kramer *et al*., 2010a;2010b
Paiku Co	Wünnemann *et al*., 2015

Chapter 2 - Late quaternary lake level changes of Taro Co and neighbouring lakes, southwestern Tibetan Plateau, based on OSL dating and ostracod analysis

This chapter appeared as an internationally peer-reviewed article in Global and Planetary Change in 2018: **Alivernini M.**, Lai Z., Frenzel P., Fürstenberg S., Wang J., Guo Y., Peng P., Haberzettl T., Börner N., Mischke S. (2018): *Late Quaternary lake level changes of Taro Co and neighbouring lakes, southwestern Tibetan Plateau, based on OSL dating and ostracod analysis*. Global and Planetary Change 166: 1-18

Alivernini M., Lai Z., Frenzel P., Fürstenberg S., Wang J., Guo Y., Peng P., Haberzettl T., Börner N., Mischke S. (2018): Late Quaternary lake level changes of Taro Co and neighbouring lakes, southwestern Tibetan Plateau, based on OSL dating and ostracod analysis. Global and Planetary Change 166: 1-18										
	Alivernini M.	Lai Z.	Frenzel P.	Fürstenberg S.	Wang J.	Guo Y.	Peng P.	Haberzettl T.	Börner N.	Mischke S.
Conceptual research design	X		X							X
Planning of research activities	X		X							X
Data collection	X	X	X	X			X	X	X	X
Data analyses and interpretation	X	X	X	X				X		X
Manuscript writing	X	X	X	X	X	X	X	X	X	X
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Research article

Late quaternary lake level changes of Taro Co and neighbouring lakes, southwestern Tibetan Plateau, based on OSL dating and ostracod analysis

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ABSTRACT

The Late Quaternary lake history of Taro Co and three neighbouring lakes was investigated to reconstruct lo hydrological conditions and the regional moisture availability. Ostracod-based water depth and habitat reconstructions combined with OSL and radiocarbon dating are performed to better understand the Taro Co la system evolution during the Late Quaternary. A high-stand is observed at 36.1 ka before present which represents the highest lake level since then related to a wet stage and resulting in a merging of Taro Co and it neighbouring lakes Zabuye and Lagkor Co this time. The lake level then decreased and reached its minimum around 30 ka. After c. 20 ka, the lake rose above the present day level. A minor low-stand, with colder and d conditions, is documented at 12.5 cal. ka BP. Taro Co Zabuye and Lagkor Co formed one large lake with a corresponding high-stand during the early Holocene (11.2–9.7 cal. ka BP). After this Holocene lake level max imum, all three lakes shrank, probably related to drier conditions, and Lagkor Co became separated from the Taro Co-Zabuye system at c.7 ka. Subsequently, the lake levels decreased further about 30 m and Taro Co b to separate from Zabuye Lake at around 3.5 ka. The accelerating lake-level decrease of Taro Co was interru by a short-term lake level rise after 2 ka BP, probably related to minor variations of the monsoonal compone A last minor high-stand occurred at about 0.8 ka before today and subsequently the lake level of Taro Co reg isters a slight increase in recent years.

1. Introduction

The climate in several parts of central Asia is controlled primarily by the summer monsoonal circulation, (Molnar et al., 1993; Yu et al., 2001; Wang, 2006), and, understanding of its natural variability and anthropogenic impacts is a crucial question in climate research. Several palaeoenvironment and palaeoclimate studies have shown that the Tibetan Plateau is one of the places most influenced by factors such as the global climate and have demonstrated its high sensitivity to climatic changes (Gasse et al., 1991; Liu and Yang, 2003) making this area of great interest for the atmospheric and environmental sciences (Shen et al., 2005; Morrill et al., 2006; Zhao et al., 2010; Mischke et al., 2012; Nishimura et al., 2014; Ahlborn et al., 2016; Henkel et al., 2016).

Ostracod associations are widely used to deduce information about many palaeoenvironmental parameters archived in lake sediments (Anadòn et al., 1994; Schwalb et al., 2002; Alvarez Zarikian et al., 2005; Mischke et al., 2008). Shell chemistry analysis and the application of ostracod-based transfer functions show that ostracods are in assessing palaeoclimatic conditions (Mischke, 2012). Several palaeoenvironmental investigations using ostracods from Quaternary sediments of the Tibetan Plateau have been conducted in recent years (Mischke et al., 2006; Frenzel et al., 2010; Mischke, 2012; Wrozyna et al., 2012; Ahlborn et al., 2014;). This analysis, combined with the dating of lake levels indicated by beach bars, enables a detailed reconstruction of past lake and climate conditions. Closed lake systems reflect climatically induced water balance changes through lake level variation.

This work analysed several outcrops in the catchments of two adjacent lakes, Taro Co and Zabuye Salt Lake, both located on the southwestern Tibetan Plateau (Fig 1). We used ostracod analysis

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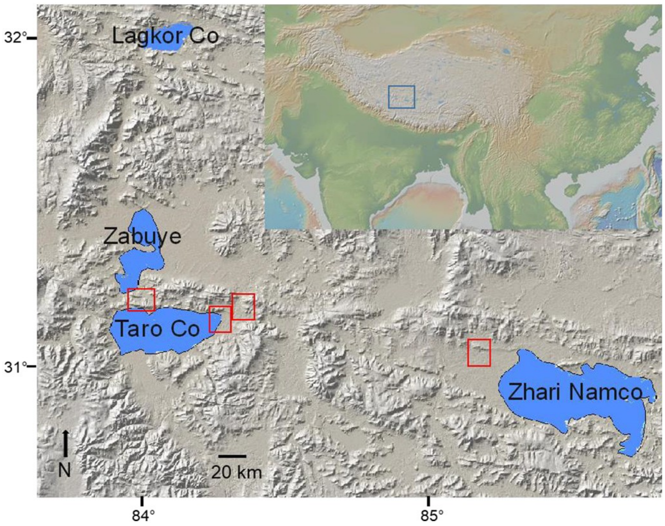


Fig. 1. Location of the Tibetan Plateau in China and position of the four studied sites: three of the Taro Co lake system (Taro Co, Zabuye Salt Lake and Lagkor Co) and Zhari Namco (Geomapapp image modified).

combined with radiocarbon and optically stimulated luminescence (OSL) dating to assess the evolution of this area during the late Quaternary. The evolution of Taro Co's level during this period was almost unknown before but such information is required to estimate the precipitation/evaporation balance to model climate changes in the region. The additional analysis of other closed basin lakes in the neighbourhood of Taro Co enable an investigation of Taro Co as part of a more complex hydrological system, including possible opening/closing scenarios for the basins. A comparison with palaeoclimate records from other large lakes in the region, such as Tangra Yum Co and Nam Co, allows the reconstruction of varying monsoonal impacts and an understanding of hydrological system changes on the southwestern Tibetan Plateau.

We aim to achieve the following objectives: (i) to reconstruct the late Quaternary evolution of the Taro Co lake system, especially with respect to changes in the lake level, (ii) to discern climate change, i.e. shifts of the precipitation/evaporation balance, from lake system changes by investigating all three lakes of the system and (iii) to answer the question of whether there were synchronous or asynchronous primarily late Quaternary climate shifts along a west-east transect on the southern Tibetan Plateau.

2. Study area

Taro Co (31°03′N, 83°55′E) is situated on the northern slope of the Gangdise Mountains, southwestern Tibetan Plateau. The catchment geology is characterised mainly by mudstone, siltstone, conglomerates, marine clastic rocks, siliceous mudstone and marlstone (Bureau of Geology and Mineral Resources of Xizang Autonomous Region, 1993). The elevation of the modern lake level is 4566 m, above sea level (a.s.l.) with a maximum water depth of 132 m (Guo et al., 2016). The area of the modern lake basin is 487.6 km^2, and the catchment area is 6929.4 km^2 (Wang and Dou, 1998). It is mainly fed by the Buduo River, deriving from the glacial melt water of the Gangdise Mountains in the southern part of the catchment (Zheng et al., 1989). When the lake level rises above 4570 m a.s.l., the excess water from Taro Co drains temporarily into the hypersaline Zabuye Salt Lake to its north. Taro Co is a lake of the Ca-Mg-Cl-SO$_4$ type, (Börner et al., 2017) with a mean conductivity of 1.0 mS/cm (salinity 0.8 psu), a pH of 9.4 and an alkalinity of 6.8 mmol/l as measured in September 2011. The basin is located in an alpine, semi-arid region, with a mean annual precipitation of approximately 200 mm and a mean annual temperature of 0–2 °C (Wang and Dou, 1998). The vegetation type is mainly that of the alpine steppe and alpine meadow (Ma et al., 2014).

Zabuye Salt Lake (31°35′N, 84°07′E, 4421 m a.s.l.) has a catchment of 6680 km^2 excluding the drainage basin of Taro Co. The Cretaceous-Eocene bedrock in the catchment of Zabuye is composed of acidic igneous rocks, mudstones and sandstones (Zheng et al., 1989). The presence of lacustrine deposits at elevations above the modern lake level indicates that the level has been higher in the past than it is today (Qi and Zheng,1995; Zheng etal., 1989). The basin is surrounded by mountains with an elevation of about 4600–5200 m a.s.l. The lake has no outflow, but there are two tributaries, one entering from the west and one from the east. The modern lake has an area of 243 km^2, a mean water depth of 0.7 m and a maximum water depth of < 2 m (Zheng et al., 1989, cited in Yu et al., 2001). The salinity of the Na-Cl-HCO$_3$ dominated lake water is very high at 360–410 psu.

Lagkor Co (32°01′N, 84°06′E) is situated north of Zabuye Salt Lake at an altitude of 4472 m, i.e. distinctively below that of Taro Co but 49 m above the present-day lake level of Zabuye. It is surrounded by a diverse rock association, from limestone to ultramafic rocks. A zone of amphibolite > 9 km in length crops out on the north shore of the lake, while mainly sandstones and limestones occur on the other margins of the lake (Lee et al., 2009). It has an area of 95.6 km^2 and a catchment of 4294 km^2. Lagkor Co is fed primarily by two perennial tributaries from south-east and south-south-west (Lee et al., 2009). The lake water is a Na-SO$_4$-Cl type, with a salinity of 60 psu (Zheng et al., 1989). A narrow and currently dry valley connects the catchments of Lagkor Co and Zabuye Salt Lake with a threshold at 4579 m a.s.l.

Zhari Namco (30°55′N, 85°37′E) is situated at 4617 m a.s.l. about 80 km east of Taro Co. The lake is surrounded, in particular in the west and east, by carbonaceous lake sediments and shorelines up to an altitude of 4757 m a.s.l. A few sandy palaeo-shore levees are distributed near the lake, the highest reported by Wang and Dou (1998) being 119 m above the recent lake level. The western shallower lake area consists of a gently alluvial fan influenced by several large inflowing rivers (Wang et al., 2010). Zhari Namco is one of the largest lakes on the Tibetan Plateau covering 1073 km^2, with a catchment of 18,407 km^2 (Hudson and Quade, 2013). The catchment area borders directly on this lake and on Tangra Yumco in the east, one of the few lakes in this region with an already existing Holocene lake-level reconstruction (Ahlborn et al., 2016). The north and south catchments of Zhari Namco constitute a fault zone within low hills of no > 500 m a.s.l., almost in parallel along the lake bank. The deepest part of the lake is located in the eastern area, at a water depth of 71 m.

3. Material and methods

3.1. Fieldwork

All samples were taken in September 2011 and 2014 during two field campaigns to the Taro Co area. Ancient shorelines and lake sediments were mapped east, north and north-east of Taro Co and in a broad valley in the southern catchment of Zabuye Salt Lake. Sediment sections and the relative positions of shorelines were documented using a hand-held GPS device with a horizontal error of 3–6 m, while their altitude differences and distances were measured using a Leica Disto D8 laser distance meter. Selected sediment profiles were documented and sampled for ostracods. Altitude values from GPS measurements were corrected by calculated elevation differences and Google Earth. Samples were preferentially collected from horizons immediately below assumed lake sediments or at their base for dating and micropalaeontological analysis in order to reconstruct the trends of palaeoenvironmental change at these sites.

OSL samples were taken using iron tubes of about 7 cm diameter and 30 cm length hammered into the cleaned vertical surfaces of the sediment units. A piece of fabric covered the proximal end of the tube to control penetration and provide light sealing. The other tube end was

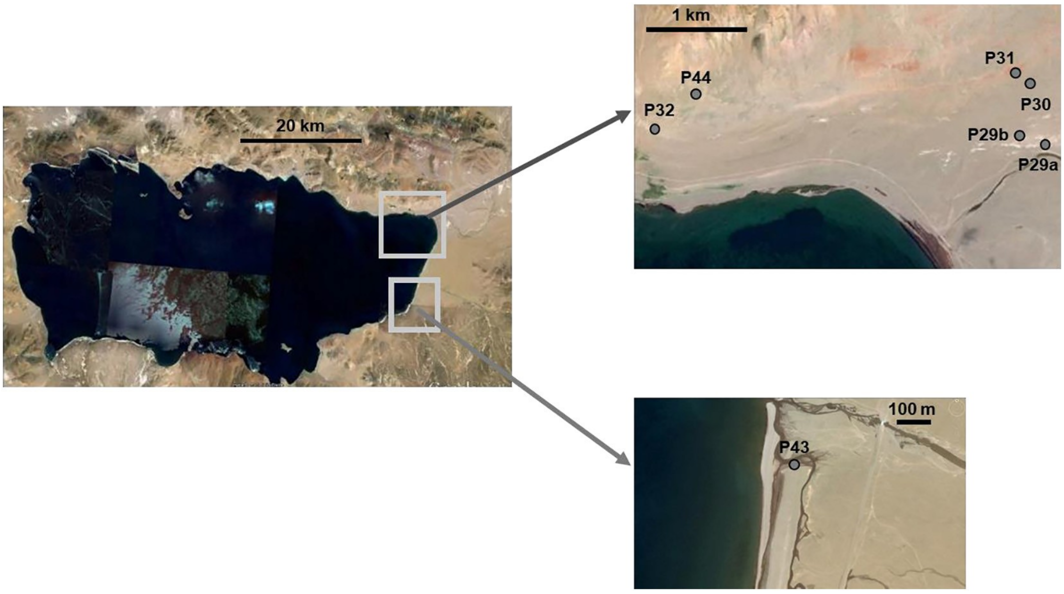


Fig. 2. Localization of the profiles from the Taro Co catchment. Satellite images by Google Earth (date of acquisition: 26/12/2004).

immediately sealed after extraction of the tube and the whole sample was wrapped in black lightproof plastic bags. One adjacent NAA (neutron activation analysis) sample and one water content sample to 20 cm around the OSL sample were taken within every sedimentary unit selected for OSL dating.

In total, four sectors of outcrops where sampled within the Taro Co-Zabuye lake system: one immediately to the east of Taro Co, the second located close to Taro Co’s north-eastern shore, the third in the south-eastern part of Zabuye Salt Lake's catchment and the fourth in Zabuye's southern part, situated at the potential outflow of Taro Co (Figs. 2, 5, 6).

One additional sample from the Zhari Namco catchment was collected in 2011 from exposed lake sediments in the northern outskirts of the city of Coqen, immediately below an ancient carbonaceous lake sediment horizon (Fig. 7). This sample was taken at an altitude of 4684 m (67 m above the modern lake level).

3.2. OSL dating

Fourteen OSL samples from outcrops were dated, and three were also radiocarbon dated for comparison. The water content of the samples accompanying the OSL dating samples was measured a few days after sampling in the Lhasa Branch of the Institute of Tibetan Plateau Research, Chinese Academy of Sciences. A water content of 5% was used for the higher values. This water content originally existed at some localities and then diminished as the sediment dried up. OSL sample preparation was carried out in the Luminescence Dating Laboratory of the Qinghai Institute of Salt Lakes (Chinese Academy of Sciences) under red safe lights. Raw samples were first treated with 30% H_2O_2 and 10% HCl to remove organic materials and carbonates. Since the samples were quite coarse, grains between 90 and 200 μm were dry sieved. To extract quartz these grains were then treated with 35% H_2SiF_6 acid for about two weeks to remove feldspars. The purity of the quartz was checked with infrared stimulation, then, the quartz grains were mounted in a 7 mm central circle on stainless steel discs (10 mm diameter), using silicone oil. OSL measurements were carried out using an automated Risø TL/OSL DA-20 reader. Stimulation was from blue LEDs (λ470 ± 20 nm) with 90% LED power. The OSL signal was detected through a 7.5 mm Hoya U-340 filter, with a peak transmission at 340 nm. Equivalent doses (De) were determined using the single-aliquot regenerative-dose (SAR) protocol for quartz (Murray and Wintle, 2000). Laboratory irradiation used a 90Sr/90Y beta source. OSL stimulation was carried out for 40 s at 130 °C. Signals from the initial 0.64 s stimulation were integrated for growth curve construction after subtraction of the last 10 s of signals. Lithogenic radionuclide activity concentrations were determined from measurements of U, Th and K concentrations using neutron activation analysis (NAA) of dried and ground bulk samples. NAA data were measured at the Chinese Atomic Energy Institute in Beijing. The cosmic-ray dose was estimated for each sample as a function of depth, altitude and geomagnetic latitude (Prescott and Hutton, 1994). For the analysis we selected preheat conditions at 260 °C for 10 s for the regenerative dose and we cut the heat 220 °C test dose OSL measurements, after a preheat plateau test and a dose recovery test (measured/given dose is 0.93). Quartz OSL signals are fast-component dominant, and in general, recuperation is within 10%. Quartz grains are quite bright when it comes to OSL sensitivity. The growth curves and shine-down curves of a typical sample are shown in Fig.4. Due to the using of quartz, unaffected by anomalous fading (Duller, 2004), fading test were not performed.

3.3. Radiocarbon dating

In total, seven sediment samples were used for radiocarbon dating, three from profile TiP14-P, single samples from three other profiles and one from the sandy base of the 10.4 m long core TR 14-3 which had been taken from Taro Co at about a 132 m water depth in 2014. The sandy base of this core, representative of the lowermost 50 cm of the sediment core is considered to represent the shallowest known lake level for Taro Co. Except for the sample from the core, all samples, consisting of carbonaceous bulk sediment, were dated by Beta Analytics (Miami, U.S.) using the < 180 μm size fraction without chemical pre-treatments. As Haberzettl et al. (2015) determined a reservoir effect of 120 ± 30 years for the late Holocene sediments from Taro Co which accords with paleomagnetic secular variation stratigraphic investigations have been constant through time. We applied this reservoir age to the conventional radiocarbon ages in this study before calibration by Calib 7.0 (Stuiver et al., 2017) and the IntCal13 curve (http://calib.qub.ac.uk/calib/) (Reimer et al., 2013). Reversed ages and those significantly older than the accompanying OSL ages were excluded from the chronologies assuming contamination by reworked material.

3.4. Micropalaeontological analysis

Micropalaeontological work was done mainly using ostracod valves.

Table 1
Counted valves of ostracod species and adult/juvenile ratio in sediment samples taken from the Taro Co, Zabuye and Zhari Namco catchments in Septemb
2014. Samples without ostracod valves are omitted.

Sample TiP11#	L. sinensis	L. dorsotuberosa	T. gyirongensis	F. gyirongensis	C. xizangensis	L. inopinata	L. postilirata	Ilyocypris sp.	H. salina	Adults	Juvenile	Total
Taro Co												
P29 b/8	5	1	0	0	0	0	0	0	0	4	2	6
P29-7	217	211	8	41	16	0	17	0	0	196	314	510
P30-2	131	11	0	1	0	0	0	0	0	62	81	143
P31-2	30	6	0	0	0	0	0	0	0	7	29	36
P10	518	24	0	6	81	0	7	1	0	222	414	637
P9	289	7	0	2	4	0	0	0	0	55	247	302
P8	249	15	0	7	3	0	4	16	8	71	231	302
P7	275	5	0	10	2	0	0	5	0	66	231	297
P6	252	7	0	24	25	1	0	2	0	63	248	311
P5	242	13	0	35	7	0	0	1	4	73	229	302
P4	235	11	0	49	15	0	0	0	0	106	204	310
P3	251	2	0	18	13	0	1	4	0	54	235	289
P2	291	8	0	13	2	0	1	4	0	55	264	319
P1	306	6	0	4	17	0	1	2	0	60	276	336
Zabuye												
P37/2	8	0	0	0	0	0	0	0	0	8	7	15
P37-3	122	8	0	0	2	1	4	0	0	137	179	316
P37-4	126	9	0	0	3	0	3	0	0	141	160	301
P37-5	24	0	0	0	0	0	0	0	0	24	37	61
P40-2	1	0	0	0	0	0	0	0	0	1	4	5
Zhari Namco												
P28-1	31	5	0	3	4	0	1	0	0	44	64	108

In total, 41 samples containing valves were analysed, of which 21 were from the catchment of Taro Co, 19 from the catchment of Zabuye Salt Lake and one from old exposed lake sediments of Zhari Namco. The samples were treated with H_2O_2 (ca. 5–10% for about 1–2 h) to separate aggregates of mud and they were subsequently sieved with water through a 200 μm-sieve to enrich the valves. Depending on the grain size of the sediment, about 3–10 g were prepared for fine-grained sediment and up to 200 g for sand and gravels. For quantitative ostracod analysis, the samples were split into sub-samples using a microsplitter and valves from subsequent splits were counted until 300–500 individuals were reached. The species proportions and the total ostracod abundance were calculated. For ostracod abundance we considered all ontogenetic stages (juvenile and adult valves). In order to assess water turbulence (Boomer et al., 2009) and to check for the possible removal of thinner juvenile valves by dissolution, the adult/juvenile ratio was determined. Identification was performed primarily with a low-power binocular microscope and was occasionally supported by a Scanning Electron Microscope (SEM). Counted valves of ostracod species and their adult/juvenile ratio is showed in Table 1.

A modern training set of ostracod distributions from Taro Co and its catchment was also set up from the 34 samples reported by Guo et al. (2016), complemented by sixteen new ostracod samples from ponds, streams, wetlands and shallow water in and around Taro Co. Eight of the new samples added to the Guo et al. (2016) data set were used to build up an improved ostracod-based transfer function for the water depth in Taro Co. The dataset of Guo et al. (2016) was restricted to the lake and contained only a few shallow water samples. Thus, we added all the new samples from the Taro Co itself to the existing data set. All training-set samples represented the uppermost 1–2 cm of surface sediment taken with a box corer in 2011. A minimum of 100 valves were picked and identified in a manner similar to that of the ones in Guo et al. (2016)'s data set. The new ostracod-based water depth transfer function was intended to estimate the palaeo-water depth for fossil samples; the program C2 (Juggins 2003) as well as Weighted Averaging Partial Least Squares (WAPLS) regression were used, in accordance with several other authors (Mischke et al., 2007; 2010a; Guo et al., 2016). The water depth was log10-transformed before analysis. A Google Earth file of all modern sampling positions is provided as electronic supplementary material (supplementary online material).

A Hierarchical Cluster Analysis (WARD method) of the relative ostracod abundance of all samples with at least 50 valves was applied to reveal similarities between recent and fossil associations as a proxy for habitat similarity.

The calculations estimations of lake level elevations, reconstructed environments and water depths are presented in Appendix A.

3.5. Modelling of lake system stages

Digital elevation models were built with MATLAB® using SRTM-data covering 30°N-33°N and 83°E-85°E at a resolution of 90 m (USGS, 2004). The lake area was computed in 1 m steps for all altitudes from recent lake levels to the high-stands. The lake volume was calculated as the integral of the single lake areas. The catchment was tracked and calculated by observation on Google Earth. To better understand the relative water inflow and the importance of the evaporation in the lakes, variations of the catchment/area ratio were calculated.

4. Results

4.1. Sediment profiles

The profile TiP14-P, in the south-eastern part of the Zabuye Salt Lake's catchment is located at an altitude of 4586 m a.s.l., close to Taro Co's recent temporary outflow. This profile is 90 cm long (Fig. 6). Fine brownish banded sand occurs between its base and 48 cm above the base. On top, the sediment gradually becomes finer, always containing root remains. Between 78 cm and the top, the sediment is predominantly composed of silt, penetrated by sub-recent roots and mottled with brown rust patches (Fig. 6).

The lithology of the profiles of Taro Co's north-eastern sector (Figs. 2, 3b) is dominated by sandy sediments with some gravels. Profile P32 consists of a 12.2 m thick sequence often characterised by cross and horizontal bedding.

Sediments in the profiles in the eastern sector are mainly sandy with coarse gravels. Unconsolidated lacustrine limestones and marls containing shells of the gastropod Radix sp. were found in P29a-b of Taro Co and in samples P30-1 and P31-1 (Figs. 2, 3b). The sandy sediments of the Zabuye catchment contain gravels, often with horizontal and

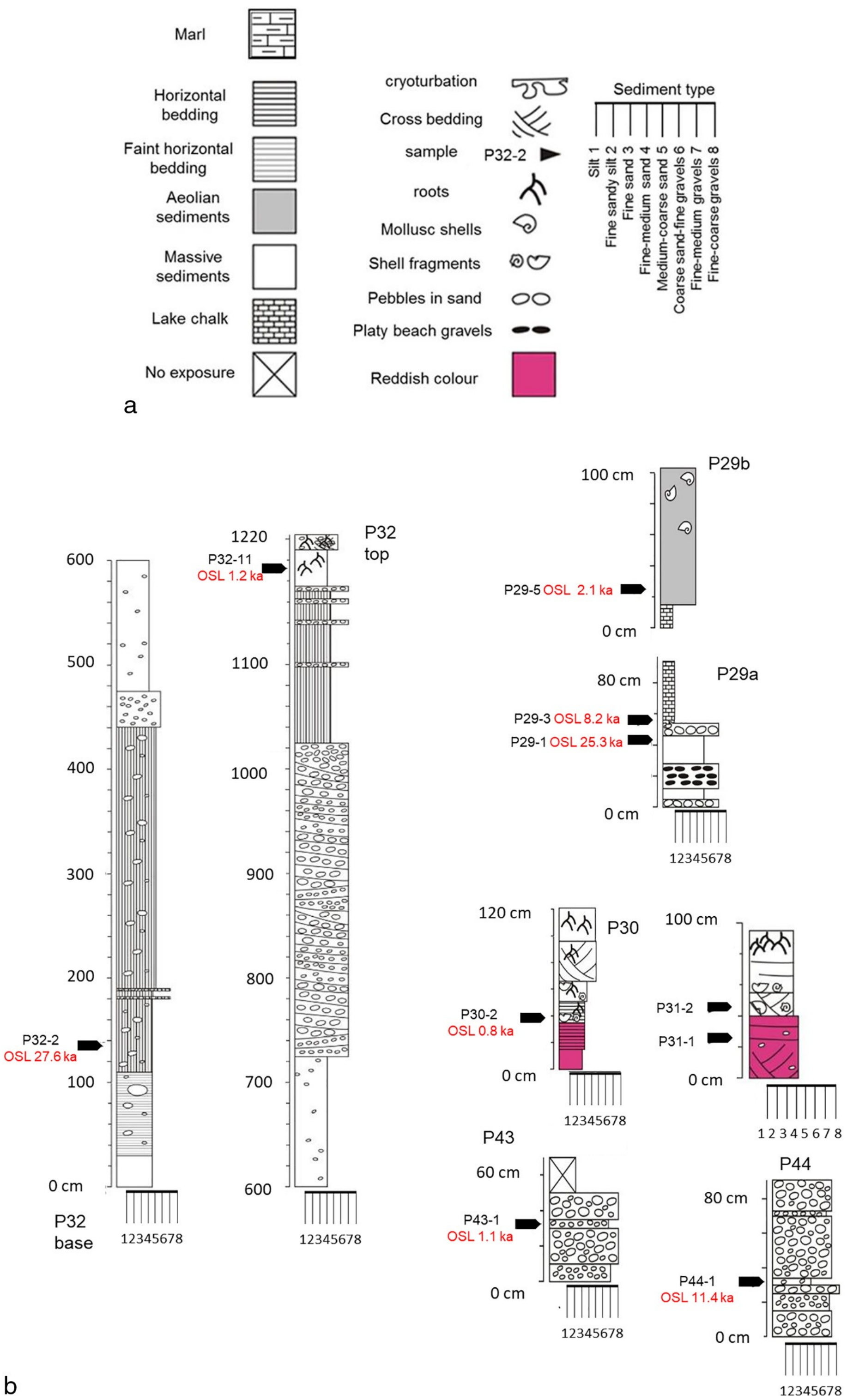


Fig. 3. (a) Legend for the Figs. 3b, 5, 6, 7. (b) Profiles from the Taro Co catchment. P29a is situated stratigraphically slightly lower than P29b, both togethe a continuous succession.

low-angle cross-bedding. Some gastropod shells were found in profile P37.

The sediment profile from Zhari Namco has a thickness of 25 cm (Fig. 7). The profile consists of a whitish marl with thin sandy layers and only a few small gravels at 5 cm above base.

4.2. Chronology

In the Taro Co catchment, OSL-dating of sediment samples yielded ages between 27.6 ka and 0.8 ka. In the Zabuye catchment, five sample were dated with ages between 36.1 and 3.0 ka. The sample TiP11P28-1 from Zhari Namco dated by OSL had an age of 4.2 ± 0.4 ka (Table 2).

The samples from profiles TiP14-P, TiP11-29 and TiP11-30 provided radiocarbon ages between 16.0 and 3.8 cal. ka BP (Table 3).

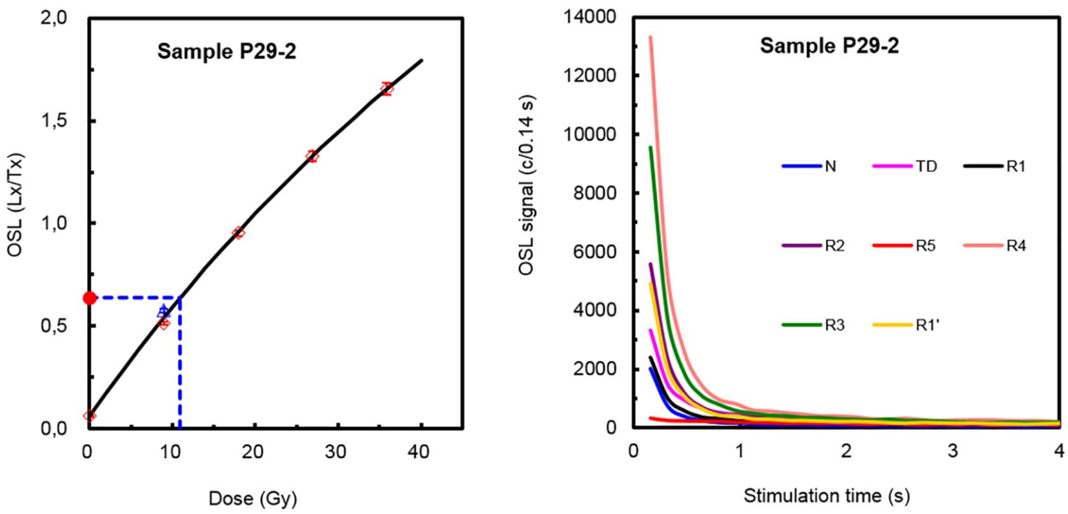


Fig. 4. Growth curve and shine-down curves of a typical sample of Taro Co.

The sample from the sandy base of the core was collected from Taro Co at 143 m below its present water level and yielded an age of 30.3 ± 3 ka BP.

4.3. Results of micropalaeontological analysis

4.3.1. Ostracod record and performance of transfer function

In total, nine ostracod species were detected within 41 fossil-bearing sediment samples. The abundance of these species varied between 0 (for 25 barren samples) and 43.3 valves/g. The highest abundance was recorded in the Zabuye catchment. In profile TiP14-P, ostracod valves were present in each sample with a mean abundance of 19.5 valves/g. In the other two sectors located north-east and east of the Taro Co catchment, the distribution of ostracods was discontinuous due to the high number of barren samples. Most valves were found as single valves and adult valves were dominant.

Leucocytherella sinensis dominated the assemblage with an abundance between 27% and 92%. Other frequently occurring species were Candona xizangensis, Leucocythere? dorsotuberosa and Fabaeformiscandona gyirongensis. Tonnacypris gyirongensis, Ilyocypris s. Heterocypris salina and Limnocythere inopinata, only occurred in a few samples and at low percentages (0.2–3%) (Fig. 8).

Surface sediment samples from Taro Co and its catchment contained the same species as the fossil samples, but Bradleystrandesia reticulata (Zaddach, 1844), Candona candida (O.F. Müller, 1776), Eucypris sp., Heterocypris incongruens (Ramdohr, 1808) and Potamocypris villosa (Jurine, 1820) were also found (Table 6). All additional species derived from small water bodies.

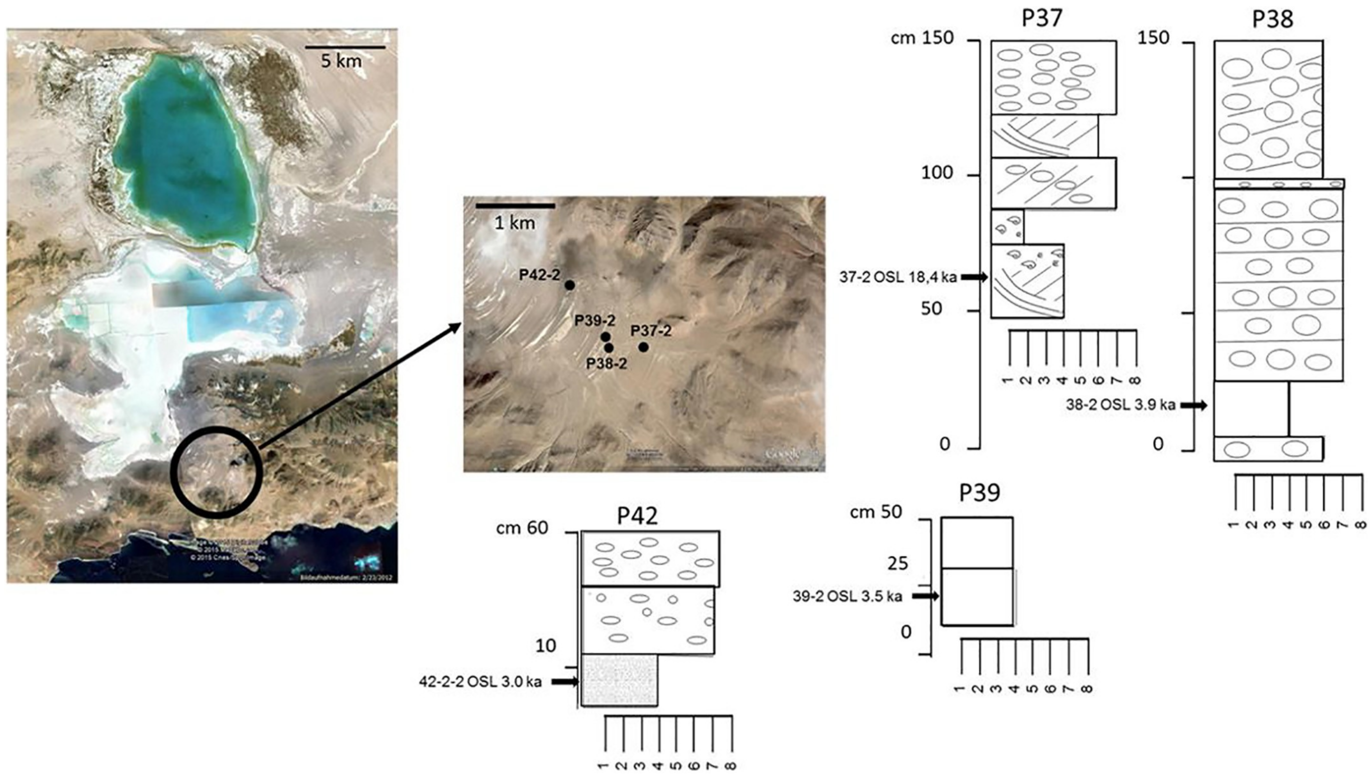
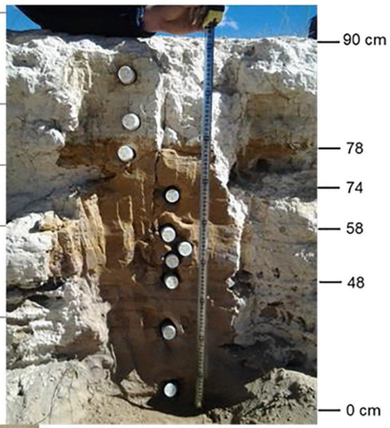


Fig. 5. Zabuye catchment lithology. Satellite images by Google Earth (date of acquisition: 26/12/2004).

Silt light gray with less brown rust. strong root penetration. Th: 22 cm	TIP14-P10 (11.01 ka cal BP); TIP14-P9
Silt with brown rust and root remains. Th: 4 cm	TIP14-P8
Fine sand. brown rust and root remains. Th.: 16 cm	TIP14-P7
Silt with fine brownish banded sand and root remains. Th.: 10cm	TIP14-P6; TIP14-P5 (19.01 ka cal BP); TIP14-P4
Fine brownish banded sand Th.: 38 cm	TIP14-P3; TIP14-P2; TIP14-P1 (12.91 ka cal BP)



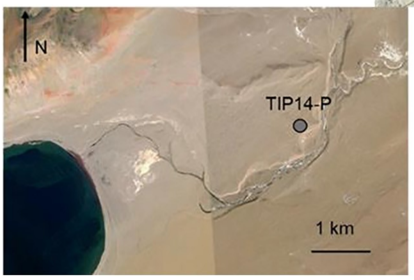


Fig. 6. Location and lithology of profile TiP14-P (N31.19812°; E084.37550°). Satellite images by Google Earth (date of acquisition: 25/8/2011). The tubes present in the picture were inserted to take the sediment samples.

The performance of the extended ostracod-based water-depth transfer function is indicated with $R^2 = 0.64$ and RMSEP = 0.28 (Fig. 9).

4.3.2. Profile TiP14-P

The ostracod record of profile TiP 14-P was relatively continuous in terms of abundance (Fig. 10). The dominant species in all samples were L. sinensis, always with percentages higher than 75%. Other abundant ostracods were C. xizangensis, F. gyirongensis and L.? dorsotuberosa, including its variant, f. postilirata sensu Pang (1985). Limnocythere inopinata, H. salina and Ilyocypris sp. were poorly represented, with an abundance between 0.3% and 5%. The ostracod fauna showed a slight increase of C. xizangensis and F. gyirongensis, respectively in samples P10 and P4. The adult/juvenile ratio was relatively low with juvenile individuals always more abundant than adults.

4.3.3. Other profiles in the Taro co catchment

Ostracod valves were present in only a few samples (Fig. 11). Ostracod valves were abundant in samples TiP11P29b-7 and TiP11P30-2, with the dominant species being L. sinensis with an abundance between 42% and 91% as well as L.? dorsotuberosa (7–41%). The other valves were classified as T. gyirongensis, F. gyirongensis, C. xizangensis and L.? dorsotuberosa f. postilirata. The highest degree of diversity is present in sample TiP11P29b-7.

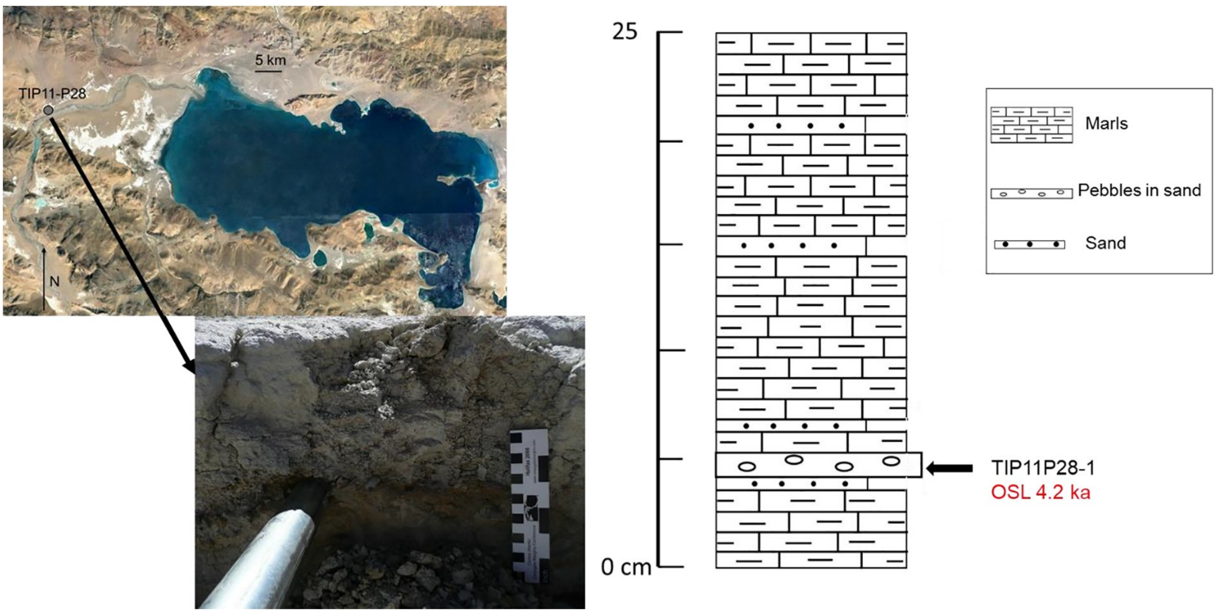


Fig. 7. Sediment section TiP11P28-1 from Zhari Nam Co at an altitude of 4684 m a.s.l. (date of acquisition: 8/8/2013).

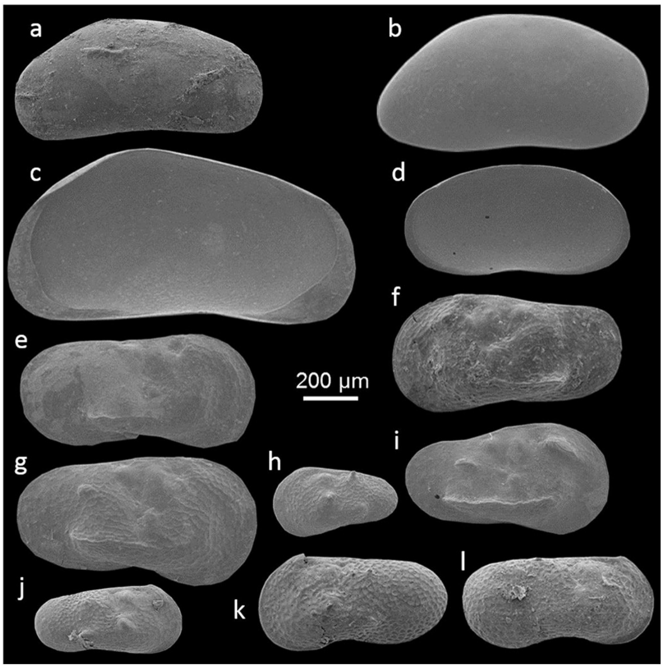


Fig. 8. SEM pictures of ostracod species found in recent and fossil samples from the Taro Co lake system: a) Fabaeformiscandona gyirongensis (Huang, 1982), female, RV; b) Candona xizangensis Huang, 1982, female, RV; c) F. gyirongensis, female, LV; d) C. xizangensis, juvenile, RV; e) Leucocythere? dorsotuberosa Huang, 1982 f. postilirata, male, RV; f) L.? dorsotuberosa f. postilirata, female, LV. g) L.? dorsotuberosa (Huang, 1982), adult female, RV; h) Leucocytherella sinensis (Huang, 1982), juvenile, LV; i) L.? dorsotuberosa, juvenile, RV; j) L. sinensis, juvenile, RV; k) L. sinensis, adult female, LV; l) L. sinensis (Huang, 1982), adult male, RV.

In TiP11P29b-7 and TiP11P29b-8 the valves were not translucent as in the other samples but were often encrusted. The adult/juvenile ratio was low with more adult than juvenile valves found have only in sample TiP11P29b-8.

Seventeen samples in the catchment of Taro Co were ostracod-barren but contained low quantities of head capsules of chironomid larvae, shells of gastropods (Radix), plant remains and invertebrate eggs.

4.3.4. Zabuye catchment

Ostracod valves were found in this area in four samples only (Fig. 12). The ostracod associations of low abundance were characterised by the almost 100% the dominance of L. sinensis, while the other species are extremely rare with a relative abundance between 0.3% and 5%. The juvenile valves were more abundant than the adult valves with sample TiP11-P37/2 being the only exception. In addition to the ostracod fauna, five shells of the gastropod Radix sp. were found in sample TiP11-P37/3. The rare L.? dorsotuberosa valves showed traces of erosion.

4.3.5. Zhari Namco

The ostracod fauna from sample TiP11P-28-1 were dominated by L. sinensis with proportions of c. 10% L.? dorsotuberosa and C. xizangensis and low numbers of F. gyirongensis.

4.4. Lake system stages

The lake system changes in altitude, volume, area, catchment/area ratio and lost volume were calculated and are represented in Tables 4, 5 and compared in Fig13. To confirm the merging of the three lakes, some closed shorelines and some shorelines higher than the present-day threshold separating the catchment were found. These shorelines have not been yet dated so far, but they can be used as indicators of higher lake levels. Fig. 16 shows a possible scenario of the merging of the three lakes and the present-day visible shorelines.

5. Interpretation and discussion

5.1. Water depth transfer function

The R^2 value of 0.64 determined for the new water depth transfer function is significantly lower than the R^2 of 0.86 calculated by Guo et al. (2016) for the smaller data set. However, the RMSEP of our new transfer function is significantly lower and represents an error of only 1.9 m at a 1 m water depth compared to 13.3 m in Guo et al. (2016). In shallow waters, the improved accuracy of the new transfer function results from the filling in of the gaps of the previously established water-depth training set by new samples (Fig. 9).

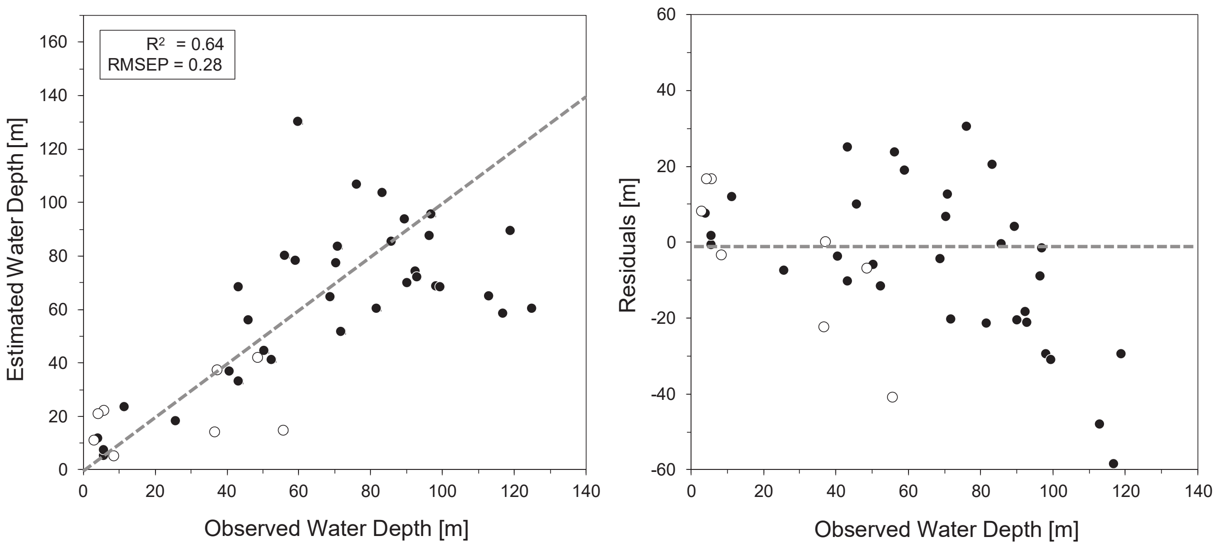


Fig. 9. Performance of the extended ostracod-based water depth transfer function. Samples added to the already published training set by Guo et al. (2016) are indicated by hollow circles. The extreme outlier of sample TiP11-91 from 60.1 m water depth and estimated as 363.6 m is outside the figured range of the

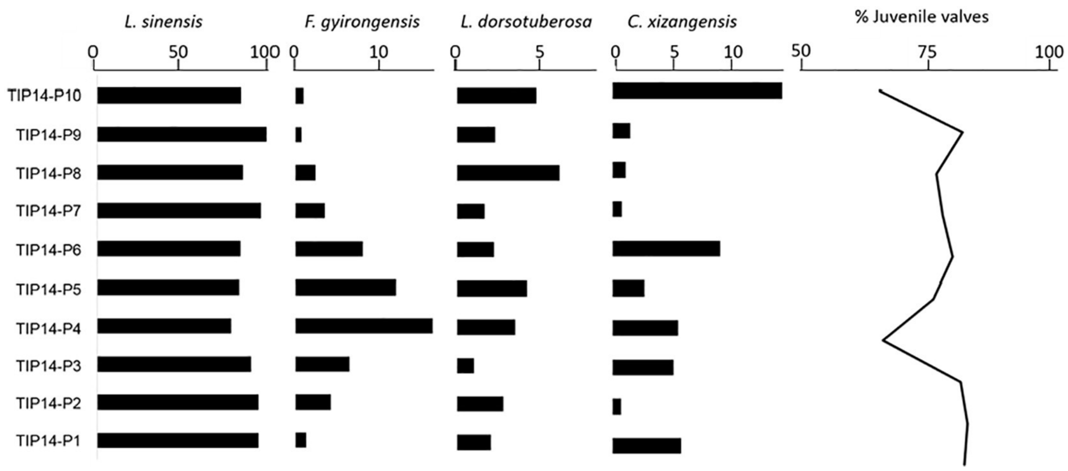


Fig. 10. Relative abundances and Adult/Juvenile ratio of the ostracod valves in profile TiP14-P. For these parameters only the most abundant ostracod spe considered.

5.2. Taro Co and south-eastern Zabuye catchments

Considering the much younger OSL dates many of the radiocarbon data for the profiles of the south-eastern sector of the Zabuye catchment were apparently influenced by reworking, the only exception being sample TiP29-3 (Table 2, 3). Additionally, TiP14P-5 included an inverse age within the profile. These reworked samples were not considered for further analysis. Comparison of OSL and radiocarbon data for sample TiP11P29-3 indicated a low reservoir effect of close to 120 ± 30 years, reported by Haberzettl et al. (2015). We therefore assume reservoir effects to be constant over the studied period and applied this reservoir correction for all radiocarbon dates, in accordance with the investigations by Haberzettl et al. (2015) for the late Holocene.

The oldest age of the Taro Co catchment was obtained from profile TiP11-P32 at 27.6 ka (OSL). This catchment is located about 1.4 m above the base of a fluvial sequence 53 m higher than the present-day lake level. The medium to coarse sandy sediments with gravels and without macro- or microfauna remains indicate that a fluvial system well above the modern lake level existed at this time. The following suite of cross-bedded gravels and sand mirrors (between 702 and 1020 cm, Fig. 3b) the changing fluvial and colluvial conditions near the lake. The sample close to the top of the profile at 4639 m a.s.l. indicates that the lake level never reached the elevation of the profile between 27.6 ka and 1.2 ka limiting the maximum potential lake level to 4639 m a.s.l. for the last 28 ka.

Samples from profile TiP-P29 yielded ages between 25.3 ka (OSL, sample P29-1), and 2 ka (OSL, sample P29-5). This profile is located 6 m above the present-day lake level. The older OSL sample represents a unit of sandy-silty sediments without faunal remains which indicates a shallow fluvial system and sediment accumulation above the lake level. Subsequently, the presence of lacustrine calcareous sediment combined with the palaeoecology of the ostracod fauna suggests a deep lake environment dated to 8.2 ka. In the upper part of this profile, the depositional setting becomes shallower again as indicated by shells of the pulmonate gastropod Radix.

The core base sample from Taro Co (TR 14-3) indicates the lowest documented lake level at about 4423 m a.s.l. (about 143 m below present day lake level) for the Taro Co catchment at 30.3 cal. ka BP. The coarse sediment directly below a continuous succession of lacustrine silts is assumed to reflect a lake level low-stand.

Profile TiP11-P44 is situated at an ancient shoreline and can be correlated to profile TiP11-P32. Sample P44-1 provided an age of 11.4 ka (OSL) and is located 27 m above the present-day lake level. This sample indicates the highest point reached by the lake during the Holocene.

The ostracod fauna in profile TiP14-P contains stable, low-diversity

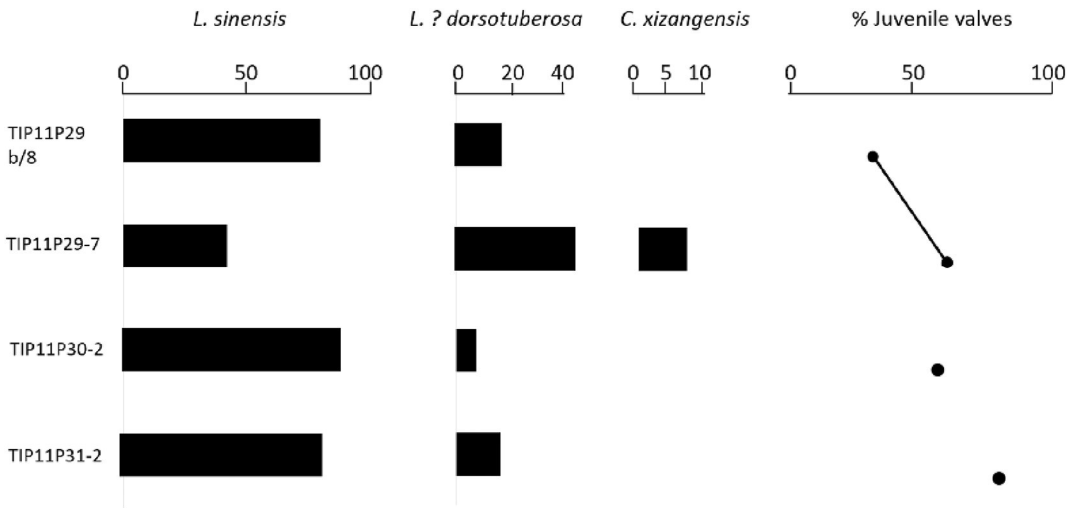


Fig. 11. Relative abundances of ostracod valves and juvenile ratio in profiles of the north-eastern sector of the Taro Co catchment.

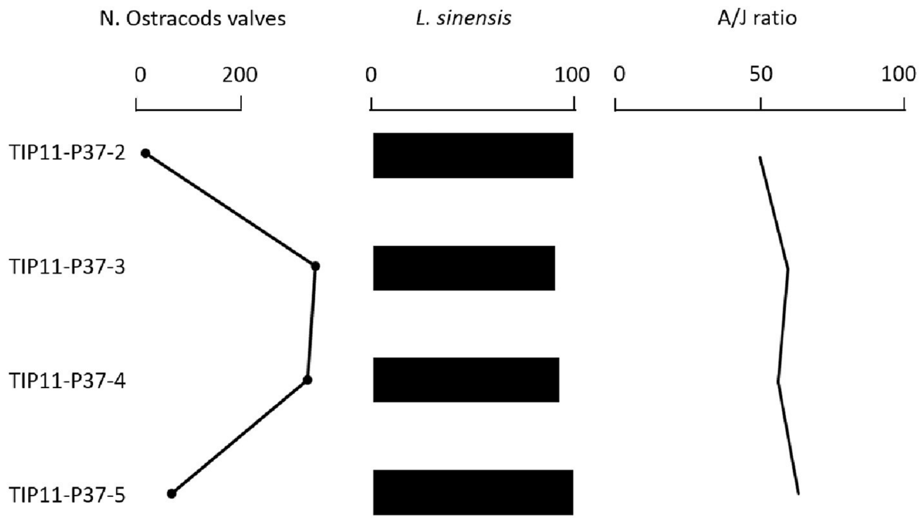


Fig. 12. Relative abundances of ostracod valves and juvenile ratio in profiles of the Zabuye catchment.

lacustrine fauna with nine species. Ecologically stable conditions are assumed from similar percentages of the species over the profile, with a dominance of L. sinensis typical of shallow lacustrine conditions and low proportions of L.? dorsotuberosa typical of deeper water (Akita et al., 2016). Only the proportion of F. gyirongensis documents a gradual change of increasing and, later, of decreasing water depth (Akita et al., 2016). A comparison with present day ostracod associations of Taro Co and its catchment reveals the greatest similarities, with associations from the lake's epilimnion and upper hypolimnion. Water depth estimation based on the ostracod-based transfer function indicates depths between 20 and 39 m with only slight variations.

Profiles TiP11-P30 and TiP11-P31 consist of grey sediments with L. sinensis indicating aquatic deposition. The second profile is located stratigraphically higher than the first one and is related to an ancient shoreline. The corresponding ostracod associations of TiP11–P30 can be found in a shallow lacustrine habitat or in small water bodies bound to the present-day outflow area.

5.3. Southern Zabuye catchment

The valley in the southern catchment of Lake Zabuye contains a series of distinct ancient shorelines. The OSL ages of these shorelines show an increasing trend in elevation, except sample TiP11-P41-2 (Fig. 14). This sample is taken from lake sediments, not from a shoreline, and it therefore indicates deeper water conditions. However, because the lacking of ostracods, a water depth estimation is not possible. We assume a more or less continuous regressive trend between samples TiP11-P39 and TiP11-P42, reflecting the shrinking of Zabuye Salt Lake (Fig. 15).

Ostracods are missing in most of the samples from Zabuye's southern catchment because gravelly beach bars were preferentially sampled. Another reason for ostracod-barren samples is potentially a high salinity which may have existed in the Zabuye Lake during its recessional stages. Ostracods are present in profile TiP11-P37 only. The associations are dominated by L. sinensis indicating a shallow water environment by comparison with recent samples, which is in good agreement with an ostracod-based water depth estimation of

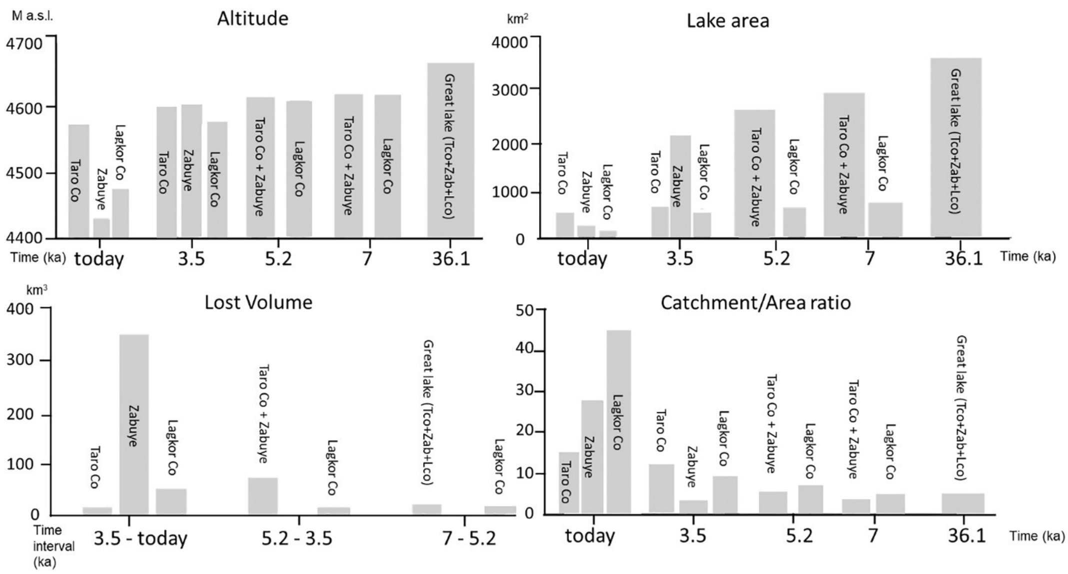


Fig. 13. Variations of altitude, lake area, lost lake volume and catchment/area ratio of the Taro Co lake system divided into time phases.

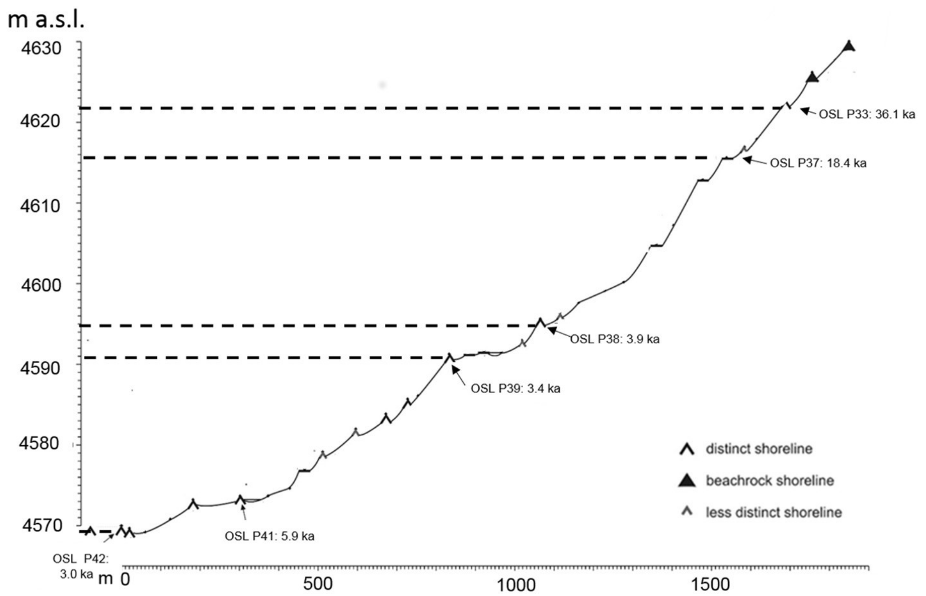


Fig. 14. Cross-Profile through shorelines of the southern Zabuye Salt Lake catchment. The dashed lines indicate the lake level during the correspondent ag samples.

about 20 m, except for beach bar sample TiP11P37–2, the oldest sample of the profile.

5.4. Lake level changes to the Taro co lake system

The reconstruction of the lake level (Fig. 15) is based on chronological, geomorphological, sedimentological and palaeoecological data. A synthesis for the Taro Co lake system covering the last 36.1 ka was carried out by adding OSL data from Lee et al. (2009) for Lagkor Co to our data set. Unfortunately, no micropalaeontological data are available from this older study. Lee et al. (2009) documented that about 5.2 ka ago the lake level of Lagkor Co was 130 m higher than the present one. The lake level dropped rapidly by 25 m between 5.2 ka and 3.7 ka. Lake shrinkage further accelerated between 3.7 ka and 3.2 ka before the present day where the lake level was 74 m above the present surface of Lagkor Co (Fig. 15).

The oldest maximum lake level documented in our study was found at 36.1 ka (4632 m a.s.l.). After that, a relatively fast lake decline in the level was recorded at 30.3 ka. In this part of the lake several samples indicate a lower lake level related to the altitude of the sampling points. An elevation of 4423 m a.s.l., i.e. 143 m below the present-day lake level of Taro Co, is given by the core base of TR 14-3 and indicates the presence of a shallow water body. However, it is not clear whether Taro Co became a small and very shallow salt lake.

At 18 ka, the lake level had already recovered and reached 4626 m a.s.l., as indicated by the position of sample TiP11P37-2, indicating a shoreline deposit. This is > 50 m above the thresholds among the three lakes, implying the possibility that the three present lakes, Taro Co, Zabuye Salt Lake and Lagkor Co, merged and formed a single vast lake. To confirm this statement, however, further sampling will be needed in the future. After this high-stand, the water depth estimations based on ostracod data from lake

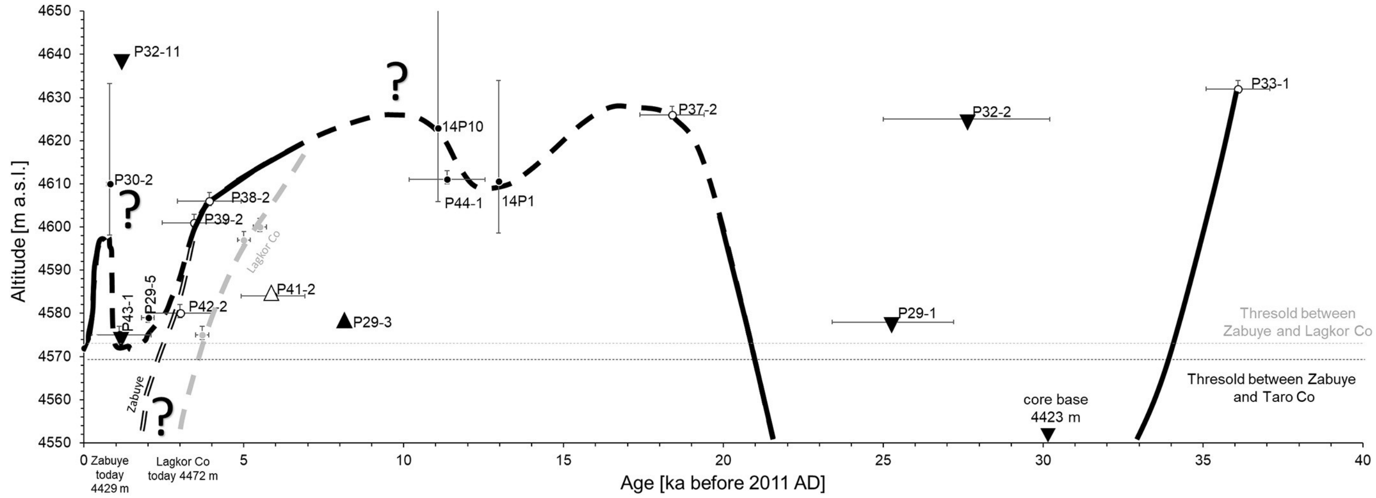


Fig. 15. Reconstructed lake level curve for the Taro Co lake system. Black (Taro Co), grey (Zabuye Salt Lake) and white (Lagkor Co) circles indicate former either by beach bare dating directly or by ostracod-based water depth estimation (transfer function) indirectly. Discontinuous lines indicate uncertainties i level evolution. Error bars indicate vertically performance of the used water depth transfer function and are set at +2 m respectively −1 m for beach bars horizontally age uncertainties of dating. Radiocarbon dating produce small errors and OSL dating larger ones. Triangles indicate lake levels below them if downwards (fluvial or wetland deposits) and above them if pointing upwards (lake deposits without ostracod-based water depth estimation). Question mar for minimum lake levels during highstands. Threshold elevations of lake separation are given based on today's swells between catchments.

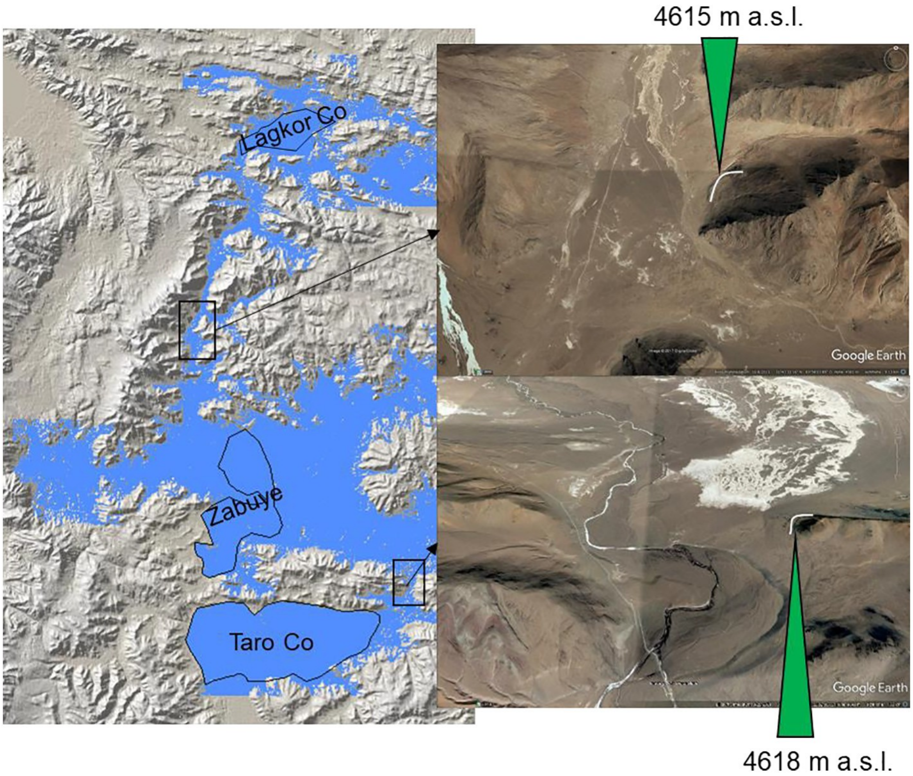


Fig. 16. Possible scenario of the high stand phases (around 36.1, 18.0 and 12.5 ka) of Taro Co lake system, when the three lakes were merged together. The rectangles indicate the present-day visible shorelines close to the catchment's borders of the three lakes. The altitudes of the shorelines are higher than the present day thresold connecting the three catchments. Google Earth images; date of acquisition: 12/2/2011 (above); 9/9/2004 (below).

sediments of profile TiP14-P in the south-eastern part of Zabuye Salt Lake's catchment point to a slight regression during the Pleistocene-Holocene transition. The maximum Holocene lake level reached an altitude between 4623 m and 4639 a.s.l. (Fig. 15) during the early Holocene (between 51 and 67 m above today's lake level of Taro Co), as indicated by samples TiP14-P10 and TiP11P32-11. This maximum was followed by a long trend of decrease in the lake level causing the separation of Lagkor Co from the system about 7 ka ago (Lee et al., 2009) and of Zabuye Salt Lake from Taro Co between 3.5 and 3.0 ka. The degree of water loss during this drier period is determined by the catchment/area ratio of the lakes, a higher ratio implies relatively more water inflow or less deficiency by evaporation than does a lower one. Lagkor Co had a higher catchment/area ratio than the merged Taro Co and Zabuye lakes between 7 and 3.5 ka, implying a relatively smaller loss of water as indicated by the volume difference over this time span. Lagkor Co yielded a much smaller water volume, an even smaller loss of water that in Taro Co-Zabuye lake resulting in a quickly dropping lake level in Lagkor Co. After 3.5 ka, Zabuye had a much lower catchment/area ratio than the other two lakes and it decreased much more quickly in water volume and area until it reached a higher ratio. The separations happened well before the lake level fell to the present-day thresholds between the catchments. This indicates either a limited water outflow through the narrow valleys and/or an erosion of these swells by a cutting of the rivers flowing out of Lagkor Co and Taro Co into Zabuye Salt Lake. A lower lake level phase of 4579 m a.s.l. is documented for Taro Co at 2.0 ka BP. It followed the maximum lake level between 1.1 and 0.8 ka. A subsequent fast decline caused the present-day lake level of Taro Co, the lowest of the entire Holocene (4570 m a.s.l.). Today, the three lakes are separated, and water only temporarily and occasionally flows out of Taro Co into the Zabuye catchment.

5.5. Lake level changes in Zhari Namco

The ostracod assemblage in the single sample (TiP11-P28–1) from Zhari Namco, with an OSL age of 4.2 ka, resembles those of the upper hypolimnion of Taro Co today. An ostracod-based water depth estimation indicates a water depth of about 42 m. Hence, the reconstructed water depth reflects a lake level 109 m higher (4726 m a.s.l.) at 4.2 ka than today. The highest shoreline recognizable in Google Earth images in the western catchment of Zhari Nam Co is situated at an altitude of 4757 m a.s.l., thus only 31 m below the ostracod-based estimation of the palaeo-lake level for 4.2 ka. The shoreline of Zhari Namco analysed by Liu et al. (2013) is located ca. 80 m above the present day lake level and dated at about 4.7 ka, close to the present-work interpretation.

6. Palaeoclimatic implications

6.1. Previous studies

The pollen record of a 3.1 m-long sediment core from Taro Co was published by Ma et al. (2014). Their chronology relies on a model assuming a reservoir effect of 3223 years for the upper 20 cm of the core and of 3483 years below. Based on a reservoir correction of 120 ^{14}C years as introduced by Haberzettl et al. (2015) we modelled the chronology for the core studied by Ma et al. (2014) for the sake of comparison. The pollen record, combined with the corrected age model, implies that the climate was wetter at c. 15 cal. ka BP and that it was drier at the Pleistocene-Early Holocene transition, probably due to a weakening of the Indian monsoon. After the transition, the climate was cooler and wetter between 11.7 and 7.7 cal. ka BP. During the middle Holocene, the climate was cold and dry, related to the influence of the westerlies. Ma et al. (2014) also assumed several minor cold spells during the Holocene, placed in the re-calculated chronology at c. 10.2–9.0, 8.2–7.9,

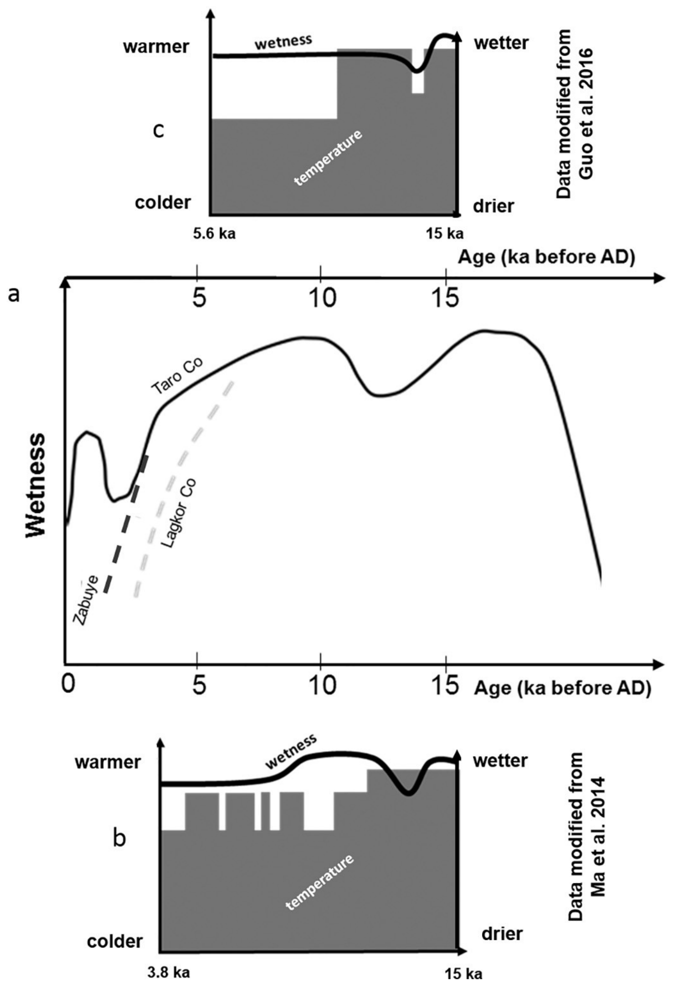


Fig. 17. Comparison between the present work (a) and the results with the modified age of Ma et al. (2014) (c) based on pollen analysis and Guo et al. (2016) (b) based on ostracod analysis, regarding temperature and precipitation of the Taro Co lake system.

7.5–7.1, 6.2–5.8 and 4.9–3.8 cal. ka BP. Guo et al. (2016) analysed the ostracod fauna from the same core and recorded the opportunistic Leucocytherella sinensis as the dominant species, accompanied by four other species (Leucocythere? dorsotuberosa,

Table 3
Radiocarbon dating results of sediment samples from the Taro Co catchment. Dates with a star are regarded as representing reworked material and are discarded from our age models.

Radiocarbon sample	Measured radiocarbon age [^{14}C ka BP]	Calibrated radiocarbon age [cal. ka BP] with reservoir correction
TiP-14P-1	11.23 ± 0.04	12.91 ± 0.09
TiP-14P-5*	16.04 ± 0.05	19.10 ± 0.11
TiP-14P-10	9.67 ± 0.04	11.01 ± 0.06
P29-3	7.43 ± 0.03	8.12 ± 0.04
P29-5*	14.36 ± 0.05	17.25 ± 0.14
P30-2*	3.83 ± 0.03	4.06 ± 0.02
TR 14-3 core base	26.97 ± 0.10	30.30 ± 0.17

Fabaeformiscandona gyirongensis, Candona xizangensis and Ilyocypris sp.) in low abundance. Because the chronology of Guo et al. (2016) relies on the same age model published by Ma et al. (2014), we present their results here with the remodelled chronology. Guo et al. (2016) support the conclusion of Ma et al. (2014) between 15 cal. ka BP and c. 13.4 cal. ka BP. After this, the climate tended to be wetter. In general, the reconstructions by Ma et al. (2014) and Guo et al. (2016) are similar, but the pollen record gives a more detailed temperature estimation and documents a decrease in precipitation around 9 cal. ka BP. A comparison of the present work with Ma et al. (2014) and Guo et al. (2016) is represented in Fig. 17. Zabuye Salt Lake was investigated by Wang et al. (2002), reconstructing the glacial-interglacial cycles using carbon and oxygen isotopes in a sediment core for the last 30 ka in low temporal resolution. The results indicated that climatic changes led to a drastic negative shift of stable isotopic ratios at 16.2 cal. ka BP and to a fast positive shift at the Pleistocene–Holocene transition (10.6 cal. ka BP). After this period, the stable isotope results indicate a drastic climate warming until the Early–Middle Holocene characterised by unstable climatic conditions. The last phase marked by the formation of a hypersaline lake is dated after 5 cal. ka BP, with a clear negative water balance from 3.8 cal. ka BP until present.

6.2. Climatic and lake system changes

The evolution of the Taro Co lake system was driven by climatic and system changes causing switches from an open to a closed lake basin and vice versa. A high-stand observed at 36 ka ago represents the highest lake level since then. In a review of dated ancient shorelines of several lakes located on the north-western and south-eastern part of the Tibetan Plateau, Li and Zhu (2001) assumed for

Table 2
OSL dating results of sediments from Taro Co and Zhari Namco lake systems. Water content of the wet sediment is 5%. Studied grain sizes lie between 90 for all samples.

Sample ID	P28-1	P29-1	P29-3	P29-5	P30-2	P32-2	P32-11	P33-1	P37-2	P38-2	P39-2	P41-2	P42-2	P43-1	P44-1
Altitude	4684	4578	4578	4578	4586	4625	4626	4632	4626	4606	4601	4584	4580	4587	4605
Age (ka)	4.2	25.3	8.2	2.1	0.8	27.6	1.2	36.1	18.4	3.9	3.4	5.9	3.0	1.1	11.4
Error (ka)	0.4	1.9	0.6	0.2	0.1	2.6	0.1	3.3	1.7	0.4	0.3	0.6	0.3	0.1	1.2
De (Gy)	21	67	34	10.2	3.4	119	5.1	125	62	12	14.3	17.5	10.4	3.7	54
Uncertainty	1.5	1.9	0.8	0.2	0.5	7	0.4	7	3.4	1	0.8	1.1	0.8	0.4	4
Aliquot #	24	30	23	23	30	23	28	24	29	24	24	24	30	27	23
% K	2.66	1.08	2.23	2.70	1.84	2.40	2.57	2.19	2.26	2.12	2.49	1.94	2.29	1.99	2.65
Error (%K)	0.07	0.04	0.06	0.08	0.06	0.07	0.07	0.07	0.06	0.06	0.07	0.06	0.07	0.06	0.07
Th (ppm)	16.00	7.01	14.00	17.10	8.77	15.20	12.10	9.12	7.53	6.76	13.00	6.33	5.94	10.60	17.90
Error (ppm)	0.38	0.22	0.35	0.41	0.25	0.38	0.33	0.26	0.24	0.24	0.34	0.22	0.21	0.30	0.43
U (ppm)	5.26	3.95	3.74	4.06	2.36	3.51	3.02	2.39	2.16	1.66	3.13	2.09	2.90	2.14	3.72
Error (ppm)	0.18	0.16	0.17	0.18	0.14	0.15	0.14	0.15	0.13	0.13	0.15	0.13	0.15	0.15	0.17
Total dose rate. (Gy/ka)	5.01	2.65	4.13	4.84	4.18	4.32	4.16	3.46	3.37	3.06	4.15	2.96	3.44	3.30	4.76
Error	0.37	0.19	0.30	0.36	0.25	0.32	0.31	0.25	0.25	0.23	0.30	0.22	0.26	0.24	0.35

Table 4
Temporal variation in altitude, catchment and area of the Taro Co lake system.

Period	Lake	Altitude	Catchment	Area	Catchment/area ratio
today	Taro Co	4572 m a.s.l.	6929 km^3	489 km^2	14.2
	Zabuye	4429 m a.s.l.	6680 km^3	143 km^2	27.5
	Lagkor Co	4472 m a.s.l.	4294 km^3	96 km^2	44.9
3.5 ka	Taro Co	4601 m a.s.l.	6929 km^3	613 km^2	11.3
	Zabuye	4601 m a.s.l.	6680 km^3	2060 km^2	3.2
	Lagkor Co	4574 m a.s.l.	4294 km^3	486 km^2	8.8
5.2 ka	Taro Co + Zabuye	4620 m a.s.l.	13609.4 km^3	2630 km^2	5.2
	Lagkor Co	4610 m a.s.l.	4294 km^3	576 km^2	7.5
7.0 ka	Taro Co + Zabuye	4620 m a.s.l.	13609.4 km^3	2880 km^2	4.7
	Lagkor Co	4620 m a.s.l.	4294 km^3	676 km^2	6.3
36.1 ka	Great Lake (Taro Co+Zabuye+Lagkor Co)	4632 m a.s.l.	17903 km^3	3739 km^2	4.8

Table 5
Lost lake volume during the separation of Lagkor Co from the system (5.2–7.0 ka), during the separation of Zabuye from Taro Co (5.2–3.5 ka), and during the onset of modern conditions (3.5 ka – today).

Lake	7.0–5.2 ka	5.2–3.5 ka	3.5 ka–today
Taro Co	–	–	14.7 km^3
Zabuye	–	–	344.1 km^3
Lagkor Co	13.5 km^3	14.4 km^3	49.6 km^3
Taro Co + Zabuye	20.2 km^3	15.8 km^3	–

this period a relatively high precipitation in the entire region. But concerning the three lakes in the present study, the only one documented in Li and Zhu (2001) is Zabuye, where the highest lake level is supposed to have occurred before 29 ka, with a corresponding merging with the other lakes. If we consider the neighbouring regions, lake Paiku Co reached its highest lake level prior to 25 cal. ka BP (Wünnemann et al., 2015). This finding contradicts this study, but always Wünnemann et al. (2015) hypothesized that Paiku Co was mainly controlled by the contribution of meltwater from the next glaciers of the Himalaya Region, implying a higher meltwater flux in the basin. This could have caused a switch in time with the Taro Co lake system, where there was only a partial contribution from the glaciers (Guo et al. 2016).

After this lake level high-stand, it decreased and reached a minimum around 30 cal. ka BP with the corresponding separation of the three lakes. Wang and Zheng (1998) postulate a warm, interglacial phase for Zabuye between 30 and 20 cal. ka BP. However, our data suggest a very low lake level for Zabuye Salt Lake during this period. Relatively high water temperatures during the summer supporting warm-water phytoplankton were documented by Wang and Zheng (1998), but this would not be a proof of interglacial temperatures, because a very shallow lake would have been heated more quickly than one with a larger water volume.

The lake rose above the present-day level after 20 cal. ka BP. Other lakes close to the Taro Co lake system indicate a similar trend. Kasper et al. (2015) detected a rising lake level for Nam Co at about 20 cal. ka BP. A minor low-stand around 12.5 cal. ka BP was detected by a dating of sample TiP14-P1 and was confirmed by the trend of the ostracod fauna. During the early Holocene (11.2–9.7 ka), the three lakes in this study formed one large lake at an altitude probably between 4625 m and 4630 m a.s.l. Our inferences are validated by the re-assessed pollen record of Ma et al. (2014) which confirms the presence of colder and drier conditions around 12.5 cal. ka BP and warmer and wetter climate for the subsequent period. In addition, Guo et al. (2016) recorded a drier phase around 12.5 cal. ka BP.

The exact date of the Holocene lake level maximum remains uncertain. However, it occurred sometime after 11.0 cal. ka BP, the last water depth estimation before 3.9 ka, when the lake level was about 20 m lower. Ma et al. (2014) and Guo et al. (2016) both suggested wetter conditions for the early Holocene and detected a switch to a drier climate at 7.7 cal. ka BP. An early Holocene lake level maximum around 9 ka is recorded for many lakes of the southern Tibetan Plateau (Kasper et al., 2015; Ahlborn et al., 2016). Concerning lakes seated west of Taro Co, Tso Moriri shows this maximum as well. Mishraa et al. (2015) depict maximum Ti concentrations in a sediment core indicating increased inflow for this time. This confirms a similar influence at this time of Indian Summer monsoon and westerlies in this area. Concerning the most southern part of the Tibetan Plateau, a high lake level also appeared in Paiku Co also during the late glacial/early Holocene period between 11.9 and 9.5 cal. ka BP (Wünnemann et al., 2015), probably for the already cited stronger control of meltwater in its basin. After the lake level maximum, all three lakes of the present study decreased in size and at 3.5 ka Lagkor Co was completely separated

Table 6
Relative abundance [%] of ostracod species in surface sediment samples taken from Taro Co and its catchment in September 2011. The lowest counted number in a sample is 92 valves.

Sample (TiP11-#)	Water type	Water depth [m]	Leucocytherella sinensis	Leucocythere dorsotuberosa	Candona xizangensis	Fabaeformiscandona gyirongensis	Ilyocypris sp.	Tonnacypris gyirongensis	Candona candida	Limnocythere inopinata	Eucypris sp.	Heterocypris salina	Potamocypris cf. villosa	Bradleystrandesia reticulata	Heterocypris incongruens
81	Open lake	3.0	85.1	-	-	11.9	-	3.0	-	-	-	-	-	-	-
82	Open lake	5.7	100.0	-	-	-	-	-	-	-	-	-	-	-	-
83	Open lake	8.5	85.2	0.5	2.3	6.7	0.2	5.1	-	-	-	-	-	-	-
84	Pond	0.2	-	-	-	-	-	-	-	0.4	3.9	70.3	-	25.5	-
87	Open lake	36.7	68.1	0.8	-	31.0	-	-	-	-	-	-	-	-	-
88	Open lake	48.7	67.2	9.8	4.9	14.8	3.3	-	-	-	-	-	-	-	-
89	Open lake	55.8	100.0	-	-	-	-	-	-	-	-	-	-	-	-
91	Open lake	60.1	31.2	23.4	42.7	2.6	-	-	-	-	-	-	-	-	-
93	Bay	4.3	99.2	0.1	-	0.4	-	0.1	-	0.1	-	-	-	-	-
95	Bay	37.3	68.2	6.4	1.7	17.9	5.6	-	-	-	-	0.2	-	-	-
96	Inflow	0.8	0.2	-	-	7.6	-	85.0	6.7	-	-	0.5	-	-	-
97	Pond	0.3	0.9	-	-	0.9	0.9	91.5	5.5	-	-	0.4	-	-	-
99	River mouth	0.2	-	-	-	-	-	3.5	3.5	-	-	1.8	-	-	91.2
101	Inflow	0.3	-	-	-	5.0	-	92.0	2.0	-	-	1.0	-	-	-
105	Peatbog	0.5	-	-	-	-	-	69.4	1.0	-	-	-	29.5	-	-
106	Peatbog	0.01	-	-	-	-	30.4	55.4	-	-	-	1.1	13.0	-	-

from the Taro Co-Zabuye system. Subsequently (3.5–1.1 ka), the lake levels decreased further, and Taro Co became separated from Zabuye Salt Lake. Another low-stand is recorded around 2 ka ago, as Ahlborn et al. (2016) lake-level curve which was also reported for Tangra Yumco, a large lake east of Taro Co. This low-stand at 2 ka before the present day was followed by an increase in the lake level, as was likewise observed for Tangra Yumco and Nam Co further east. This sequence is probably related to minor variations in monsoonal components (Kasper et al., 2012; Ahlborn et al., 2016). The last recorded high-stand for Taro Co at about 0.8 ka is not reported in other works, but the position and presence/absence of fauna in the TiP11-30P and TiP43-1 samples suggest a lake level between 4580 and 4600 m a.s.l. Due to missing data, we were not able to determine whether Zabuye followed also this tendency. Subsequent to this period the lake level of Taro Co decreased as modern conditions began to prevail, with a slight increase in recent years.

7. Conclusion

According to the multi-proxy approach used in this work, the evolution of the lake level of the Taro Co lake system can be divided into five main phases:

1) The results indicate, at about 36 ka BP, the presence of a Late Pleistocene high stand, with a corresponding positive water balance with the three lakes merged together.
2) Since then, a rapid decline in lake level during a dry phase was recorded for the period between 35 and 23 ka before the present day. We do not know exactly when and at which elevation this low stand occurred, but the presence of coarse lake sediment in core TR 14-3 from Taro Co suggests that its level was slightly above 4423 m a.s.l.
3) The three lake basins were combined into one large lake during the early and middle Holocene. The lake reached its highest level of the entire Holocene during c. 11.2–9.7 ka cal BP.
4) Lagkor Co was separated from Taro Co at around 7 ka and Zabuye Lake was separated at around 3.5 ka.
5) A last minor high stand occurred at about 0.8 ka before the present.
6) The levels of the three lakes decreased, setting up the modern conditions, with only a little rise for Taro Co in recent years.

Comparing the evolution of this system with the other basins already investigated along a west-east transect, a synchronicity for almost all the events which occurred is recognizable. However, it is still difficult to interpret the phase after 3.5 ka BP, where the results indicate different reactions of other lakes within the E-W transect, probably due to a different exposure to the westerlies and the summer monsoon. A possible explanation could be a differing influence of the westerlies at about 2 ka, which impacted Taro Co more than Nam Co and Tangra Yum Co but less than Tso Moriri, causing a time lag in reaction between them.

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Appendix A. Ages, lake level calculation and reconstructed palaeoenvironments for analysed samples from the Taro Co lake system and Zhari Namco. Reconstructed water depths rely on the ostracod-based transfer function. The ages given with "*" are relative to radiocarbon ages and they are considered as cal ka BP

Sample	Age [ka]	Error [ka]	Altitude [m a.s.l.]	Water depth [m]	Error+ [m]	Error− [m]	Lake level [m a.s.l.]	Inferred depositional setting
Taro Co								
Today	0.00	0.00	4572	0	0	0	4572	Shore line
P29-1	25.30	1.90	4578	–	0	0	< 4578	Colluvial?
P29-3	8.18	0.04	4578	–	0	0	> 4578	Lake
P29-5	2.00	0.20	4579	–	1	1	?4579	Shallow lake or wetland
P29b-7	–	–	4580	84	82	42	4664	Lake, hypolimnion
P29b-8	–	–	4581	–	–	–	?4581	Shallow lake or wetland
P29c-9	–	–	4581	–	–	–	?4581	Shallow lake or wetland
P30-1	–	–	4586	–	–	–	max4586	Shallow lake or wetland at outflow
P30-2	0.80	0.10	4586	24	23	12	4610	Lake, epilimnion
P30-4	–	–	4587	–	–	–	max4587	Shallow lake or wetland at outflow
P31-1	–	–	4606	–	–	–	< 4606	Alluvial fan
P31-2	–	–	4606	0	0	0	max4606	Shallow lake or wetland at outflow
P32-1	–	–	4624	–	–	–	< 4624	Alluvial fan
P32-4	–	–	4625	–	–	–	< 4625	Alluvial fan
P32-2	27.60	2.60	4625	–	0	0	< 4625	Alluvial fan
P32-5	–	–	4626	–	–	–	< 4626	Alluvial fan
P32-6	–	–	4627	–	–	–	< 4627	Alluvial fan
P32-7	–	–	4628	–	–	–	< 4628	Alluvial fan
P32-8	–	–	4630	–	–	–	< 4630	Alluvial fan
P32-9	–	–	4633	–	–	–	< 4633	Alluvial fan
P32-11	1.20	0.10	4639	–	0	0	< 4639	Alluvial fan
P43-1	1.10	0.10	4575	0	2	1	4575	Beach bar
P44-1	11.40	1.19	4611	0	2	1	4611	Beach bar
14P-1	12.91*	0.09	4586	25	23	12	4611	Lake, epilimnion
14P-2	–	–	4586	23	21	11	4609	Lake, epilimnion
14P-3	–	–	4586	25	23	12	4611	Lake, epilimnion
14P-4	–	–	4586	29	26	14	4615	Lake, epilimnion
14P-5	–	–	4586	28	25	13	4614	Lake, epilimnion
14P-6	–	–	4586	28	25	13	4614	Lake, upper hypolimnion
14P-7	–	–	4586	22	21	11	4608	Lake, epilimnion
14P-8	–	–	4587	39	37	19	4626	Lake, upper hypolimnion
14P-9	–	–	4587	20	21	10	4607	Lake, epilimnion
14P-10	11.01*	0.06	4587	36	32	17	4623	Lake, upper hypolimnion
Core base	30.30*	0.17	4432	0	0	0	< 4432	Just before transgression
Lake Zabuye								
Today	0.00	0.00	4429	0	0	0	4429	Shore line
P33-1	36.10	3.33	4632	0	2	1	4632	Beach bar
P36	–	–	4614	0	–	–	4614	Beach bar
P37-2	18.40	1.68	4626	0	2	1	4626	Beach bar
P37-3	–	–	4626	24	23	12	4650	Lake, epilimnion
P37-4	–	–	4626	23	23	12	4649	Lake, epilimnion
P37-5	–	–	4626	18	18	9	4644	Lake
P38-2	3.90	0.44	4606	0	2	1	4606	Beach bar
P39-2	3.40	0.32	4601	0	2	1	4601	Beach bar
P40-2	–	–	4592	0	–	–	?4592	Beach bar?
P41-2	5.90	0.57	4584	–	0	0	? > 4584	Lake?
P42-2	3.00	0.30	4580	0	2	1	4580	Beach bar
Lagkor Co								
Today	0.00	0.00	4472	0	0	0	4472	Shore line
Lee 2008	5.50	0.20	4600	0	2	1	4600	Beach bar
Lee 2008	5.00	0.20	4597	0	2	1	4597	Beach bar
Lee 2008	3.70	0.20	4575	0	2	1	4575	Beach bar
Lee 2008	3.30	0.10	4544	0	2	1	4544	Beach bar

Zhari Namco								
P28-1	4.20	0.40	4684	42	36	19	4726	Lake, upper hypolimnion

Appendix B. Supplementary data

Supplementary data associated with this article can be found in the online version, at https://doi.org/10.1016/j.gloplacha.2018.03.016. Th data include the Google map of the most important areas described in this article.

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Chapter 3 - Ostracod-based reconstruction of Late Quaternary lake level changes within the Tangra Yumco lake system (southern Tibetan Plateau)

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	Alivernini M.	Akita L.G.	Ahlborn M.	Börner N.	Haberzettl T.	Kasper T.	Plessen B.	Peng P.	Schwalb A.	Wang J.	Frenzel P.
Conceptual research design	X										X
Planning of research activities	X	X									X
Data Collection	X	X	X		X	X		X	X		X
Data analyses and interpretation	X	X	X	X	X	X	X	X			X
Manuscript writing	X		X	X	X	X			X	X	X
Suggested publication equivalence value	1.0	n.a.	n.a.	n.a.	n.a	n.a	n.a	n.a	n.a	n.a	n.a.

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JQS Journal of Quaternary Science QRA Quaternary Research Association

Ostracod-based reconstruction of Late Quaternary lake level chang within the Tangra Yumco lake system (southern Tibetan Plateau)

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ABSTRACT: Tangra Yumco, a large saline lake located in the central–southern part of the Tibetan Plateau, lies in a hydrologically closed basin and is part of a cascade lake system including Tangqung Co, Tangra Yumco and Xuru Co. The extension and position of this lake system makes it valuable for reconstructing palaeoclimatic variations through the lake history and to compare both with the adjacent systems. We reconstructed Late Quaternary lake level changes based on data from two lacustrine sediment cores. A micropalaeontological analysis focusing on Ostracoda was carried out combined with dating (^{14}C, ^{210}Pb, ^{137}Cs), sedimentology and stable isotope data from bulk sediment. Ostracod analysis involves the quantitative documentation of associations. An ostracod-based transfer function for specific conductivity was applied to assess and refine lake level changes and to compare the results with other lake level reconstructions from the Tibetan Plateau for evaluating inter-regional climatic patterns. Seven ostracod species were detected, with *Leucocytherella sinensis* dominating the associations followed by *Leucocythere? dorsotuberosa*, *Limnocythere inopinata* and *Tonnacypris gyirongensis*. *Fabaeformiscandona gyirongensis*, *Candona candida* and *Candona xizangensis* were found in only a few samples and at low percentages. The synthesis of ostracod-based environmental reconstruction and chronology for samples from Tangra Yumco reveals the evolution of the lake system during the past 17 ka. A low lake level around 17 cal ka BP is followed by a recovering until the reaching of a high stand around 8–9 cal ka BP. Subsequently, between 7.7 and 2.5 cal ka BP, it remained relatively stable with a subsequent short-living lowstand–highstand cycle around 2 ka. Thereafter, the ostracod-based conductivity transfer function shows an increase of conductivity corresponding to a lake level rising phase at around 0.4 ka. The recorded changes are indicators of past climatic conditions and refine the palaeoclimatic models in this area.
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KEYWORDS: conductivity; Late Quaternary; micropalaeontology; palaeoclimate; Tangra Yumco.

Introduction

In the last decade, several studies of lacustrine sediments from the Tibetan Plateau identified significant lake level changes during the Late Quaternary that are related to monsoon and westerlies variability (Mischke and Zhang, 2010; Kasper et al., 2012; Günther et al., 2013, 2015, 2016; Mishra et al., 2015; Ahlborn et al., 2016; Henkel et al., 2016). Due to the role of this area as origin of many large rivers of south-eastern Asia, the climate variations in this area force environmental, social and economic consequences for millions of people and their better understanding is urgently needed to offer indications of future scenarios.

A multi-proxy approach, integrating chemical, physical and palaeontological data, was applied in this study to reconstruct the lake level variations of Tangra Yumco in detail. In such a context, ostracods have already been widely used as palaeoenvironmental indicators on the Tibetan Plateau (e.g. Mischke et al., 2006; Frenzel et al., 2010; Wrozyna et al., 2010, 2012; Mischke, 2012; Ahlborn et al., 2015; Akita et al., 2015; Alivernini et al., 2018).

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Palaeoecological applications of ostracod-based transfer functions have proven to be a useful tool to assess palaeoclimatic conditions (Mischke, 2012; Viehberg and Mesquita-Joanes, 2012). Such approaches have generally been used to reconstruct relative lake level changes on the Tibetan Plateau, identifying the timing of past moisture availability and evaporation intensity.

This work focuses on the lake Tangra Yumco, which is part of a cascade lake system including Tangqung Co, Tangra Yumco and Xuru Co (Fig. 1), located on the southern–central Tibetan Plateau. Tangra Yumco has been investigated in several studies in recent years to assess lake level changes during the Late Quaternary (Long et al., 2012; Rades et al., 2013; Miehe et al., 2014; Ahlborn et al., 2016, 2017; Günther et al., 2016; Henkel et al., 2016). Akita et al. (2016) provided a dataset of the ecology of recent Ostracoda of Tangra Yumco as a groundwork for palaeoecological applications. In Ahlborn et al. (2016) an analysis on surface samples was carried out and a lake level curve of Tangra Yumco was reconstructed. We compared these with the results of this study to have a continuous dataset to refine their results. For the present study, an 11.5-m-long piston core (31°13.93′N, 86°43.25′E, 217 m water depth) and a gravity core (31°15.15′N, 86°

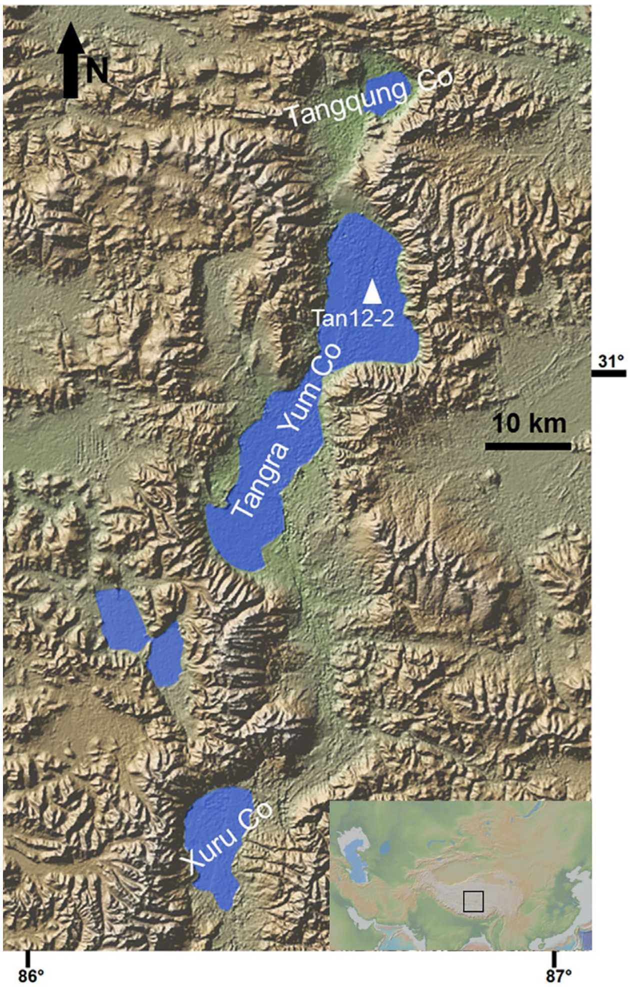

Figure 1. Location of the three studied lakes of the Tangra Yum Co lake system (with elevation, area and salinity): Tangqung Co (4475 m a.s.l.; 57 km^2; ca. 100‰), Tangra Yum Co (4595 m a.s.l.; 818 km^2; 8.3‰) and Xuru Co (4720 m a.s.l.; 206 km^2; 3.2‰). Source: www.geomapapp.org. Lake Monco Bunnyi was not part of the Tangra Yum Co lake system during the investigated time frame. The position of sediment core TAN12-2 is indicated by the white triangle.

43.37′E, 223 m water depth) located close-by were micropalaeontologically analysed, dated by ^{14}C, and for the piston core the resulting chronology was confirmed by palaeomagnetic secular variation stratigraphy (Haberzettl et al., 2015; Henkel et al., 2016).

Tangra Yumco together with other large lakes improves our understanding of hydrological system changes on the southern–central Tibetan Plateau and the varying monsoonal impact. Estimation of the specific conductivity is valuable tool in reconstructing lake level changes and switches from open to closed lake basins or vice versa, allowing a comparison with neighbouring lakes and other basins on the Tibetan Plateau.

This work aims (i) to reconstruct the Late Quaternary evolution of the Tangra Yumco lake system by refining and integrating the work of several authors (Ahlborn et al., 2016, 2017; Henkel et al., 2016), (ii) to assess possible scenarios of the interactions between the basins of the Tangra Yumco system during the past 17 ka using an ostracod-based conductivity reconstruction to discriminate climatic and hydrographic effects and (iii) to contribute to a holistic picture by comparing with other lakes in order to detect climate shifts along an east–west transect on the southern Tibetan Plateau during the Late Quaternary.

Study area

Tangra Yumco (30°41°22′N, 86°23′39°49′E; Fig. 1) is a terminal lake located on the central-southern Tibetan Plateau at an elevation of 4545 m a.s.l. (Rades et al., 2013) with a catchment size of 8219 km^2 and a salinity of 8.3‰ (Long et al., 2012). Tangra Yumco is the second deepest (230 m m) lake in China (Wang et al., 2010) and third largest lake on the Tibetan Plateau. The population in the Tangra Yumco area is sparse and human impact is mainly restricted to pastoralism (Miehe et al., 2014). Precipitation at Tangra Yumco is mainly dominated by the Indian summer monsoon originating from the south (Miehe et al., 2014) and westerly winds during the winter months (Maussion et al., 2014). Today, the lake system comprises three lakes: Tangra Yumco, Tangqung Co and Xuru Co located in a 300-km-long and 40-km-wide graben (Akita et al., 2016). Tangra Yumco and adjoining lakes are covered with ice in winter but do not completely freeze in some years due to the high salinity of their waters (Kropacek et al., 2013). The cold arid climate supports alpine meadow with Kobresia and steppe vegetation with Artemisia (Miehe et al., 2014). Tangra Yumco is an endorheic lake formed by active tectonic movement in a north–south-trending graben (Zhu et al., 2004; Kong et al., 2011). Whereas the southern Tibetan Plateau is dominated by Palaeozoic–Mesozoic carbonate and clastic sedimentary rocks (Galy and France-Lanord, 1999), the flank of the rift of Tangra Yumco is mainly composed of volcanic rocks, granitoid intrusions and potassic lavas (Gao et al., 2010). During the middle Pleistocene, the three water bodies formed one large lake and lacustrine deposits are well preserved between Tangqung Co and Tangra Yumco (Kong et al., 2011). The three lakes are arranged as on a staircase, with Xuru Co seated at the highest position (4720 m a.s.l.) and the other basins subsequently lower. Tangra Yumco has two large rivers entering from the south-east and west but no outflow. Due to its terminal character, lake level variations of Tangra Yumco are mainly controlled by precipitation and the contribution of glacial meltwater is negligible (Biskop et al., 2015). Quaternary palaeo-shorelines and lake terraces are located up to 200 m above the present-day lake level of Tangra Yumco (Rades et al., 2013), indicating a Holocene shrinkage of a larger ancient lake (Long et al., 2012; Liu et al., 2013; Ahlborn et al., 2017). The large lake was divided gradually into independent smaller waterbodies during the Early and Late Holocene due to an extensive drop of water level (Zhang, 2000; Zhu et al., 2004; Liu et al., 2013). However, the presence of submerged lake level terraces (Akita et al., 2015) indicates significantly lower lake levels in the past. Additionally, beach rocks formed by precipitation of secondary carbonates, Holocene stromatolites and tufa can be found in the northern part of the Tangqung Co catchment (Akita et al., 2015).

Material and methods

Sedimentological analysis

The composite profile consists of the 1.62-m-long gravity core TAN 10/4 and the 11.5-m-long piston core TAN12-2 (Henkel et al., 2016). The complete record with lamination of different thickness (sub-mm to cm) consists of interbedded silty sediments and blackish sandy layers (Fig. 2). The cores were subsequently sampled every centimetre. For further details, see Henkel et al. (2016). In Tangra Yumco radiocarbon dating on the cores yielded ages from 17.4 cal ka BP to today, for a total of 29 dated samples (Ahlborn et al., 2017).

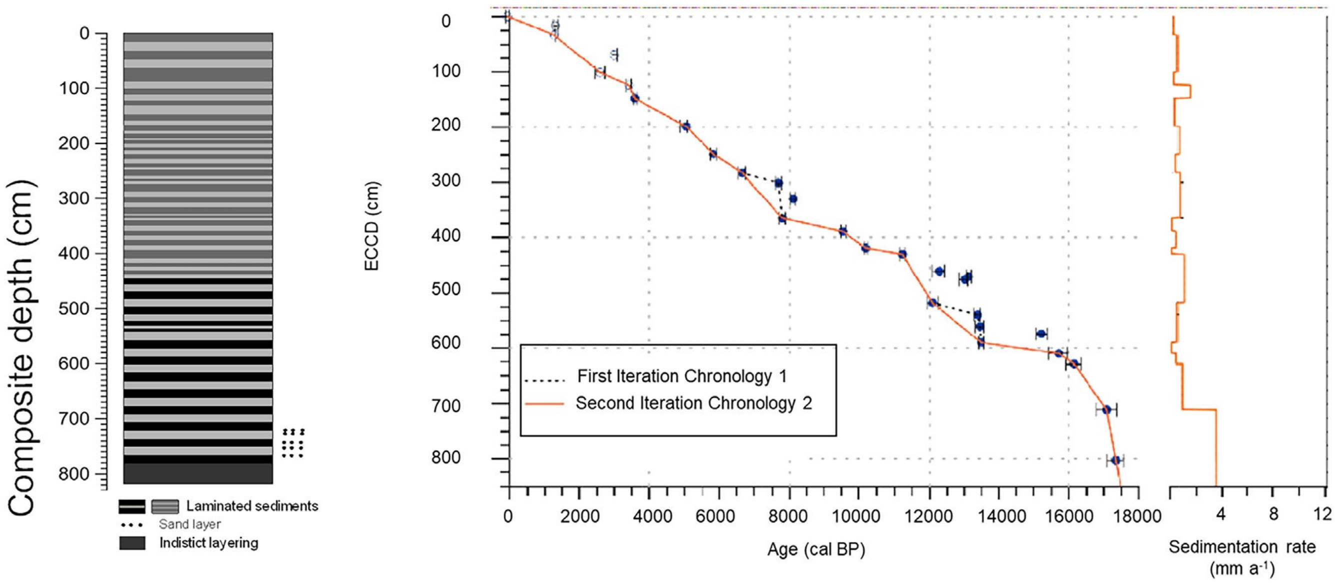

Figure 2. Composite profile (without turbiditic layers) of the two cores with age–depth model and sedimentation rates as published by Henkel et al. (2016).

Micropalaeontology

In total, 168 samples containing mostly disarticulated ostracod valves were taken every 10 cm, and shorter intervals if valves were not found within selected samples. The results from the pilot core TAN 10/4 (126 sub-samples) were integrated in the piston's core dataset to complete the record for the most recent past. Species percentages and total ostracod abundance were calculated. For ostracod abundance, juvenile and adult stages were counted separately. The adult/juvenile ratio was determined to assess water turbulence (Boomer et al., 2009) and to check for possible removal of thinner juvenile valves by dissolution. Samples were treated with H_2O_2 (ca. 5% for about 1–3 h) and subsequently sieved with water through a 200-mm sieve to enrich the valves. In addition, the sieve residues were split into sub-samples using a microsplitter to perform a more indicative quantitative analysis with a large number of valves. Identification was mainly done with a low-power binocular microscope and occasionally supported by a scanning electron microscope as well as a Keyence Digital Microscope and the ostracods were classified on the basis of previous taxonomical works in this geographical area (e.g. Mischke, 2012; Wrozyna et al., 2010). Valves were subsequently counted to 300–500 individuals for every sample. If the number of 50 valves in a single sample was not reached, the samples were combined with the subsequent samples to achieve the required minimum number of valves (>50), within 0.1-ka intervals. For a complete overview of the grouped samples and the ostracod species see the Supporting Information (https://doi.pangaea.de/10.1594/PANGAEA.890591).

An ostracod-based transfer function for the reconstruction of past conductivity values was applied (Peng et al., 2016) to trace lake level and system changes. The modern training set of Peng et al. (2016) covers 34 lakes of the southern and western Tibetan Plateau with a total of 75 samples and conductivity ranging from 0.3 to 18 mS cm^{-1}. The program C2 (Juggins, 2003) and Weighted Averaging Partial Least Squares (WAPLS) regression were used (Mischke et al., 2007; Guo et al., 2016) to develop quantitative relationships between environmental variables and ostracod assemblages. The conductivity values were $\log_{10}$ transformed before calculation. The performance of the ostracod-based conductivity transfer function is indicated by a correlation of R^2 ¼ 0.77 between observed and estimated values and an error (RMSEP) of 0.25 (Peng et al., 2016).

Stable oxygen isotope analysis

For stable isotope analysis, the cores TAN 10/4 and TAN12-2 were sampled at intervals of 1 cm, and bulk sediment was freeze-dried and ground. The analysis of stable oxygen isotopes was carried out at Helmholtz-Zentrum Potsdam, Deutsches Geoforschungszentrum (GFZ, Germany), using a Finnigan GasBench-II with carbonate-option connected to a DELTAplus XL isotope ratio mass spectrometer (IRMS). Before analysis sediment samples were reacted with 100% H_3PO_4 at 75 °C for 60 min, and each sample was analysed nine-fold. Results are expressed in the standard delta notation in per mil relative to VPDB (Vienna Pee Dee Belemnite). Standardization was done using international reference materials IAEA-NBS18 and NBS19, as well as laboratory internal standards CO1 and C1 (calibrated against VPDB). Analytical precision was better than 0.07‰ for $\delta^{18}O$.

Results

Micropalaeontological analysis

The composite profile comprising the short and the long core covers about 18 ka. Total abundances vary between 32 and 602 valves g^{-1} with a mean value of 109 valves g^{-1} for both cores (Fig. 3). Most valves were disarticulated and juvenile valves were dominant. Ostracods were lacking in the oldest part of the core, i.e. between 18 and 17 cal ka BP. After this, Limnocythere inopinata (Baird, 1843) was dominant until ca. 16.0 cal ka BP and, from 16.0 to 12 cal ka BP Leucocythere? dorsotuberosa (Huang, 1982) became the most frequent species. Between ca. 12 and 10 cal ka bp, three dominant species were detected in different intervals. The most prominent species is the opportunistic Leucocytherella sinensis (Huang, 1982), which often occurs in association with Leucocythere? dorsotuberosa. Fabaeformiscandona gyirongensis (Huang, 1982) was prominent at around 10.1 cal ka BP. After this interval, L.? dorsotuberosa returned to be dominant until 5 cal ka BP. Concerning the final period, Leucocytherella sinensis and L.? dorsotuberosa were alternately dominating from 1.8 cal ka BP until today, but they are largely replaced by L. inopinata for the period between 1.8 cal ka BP and 400 bp

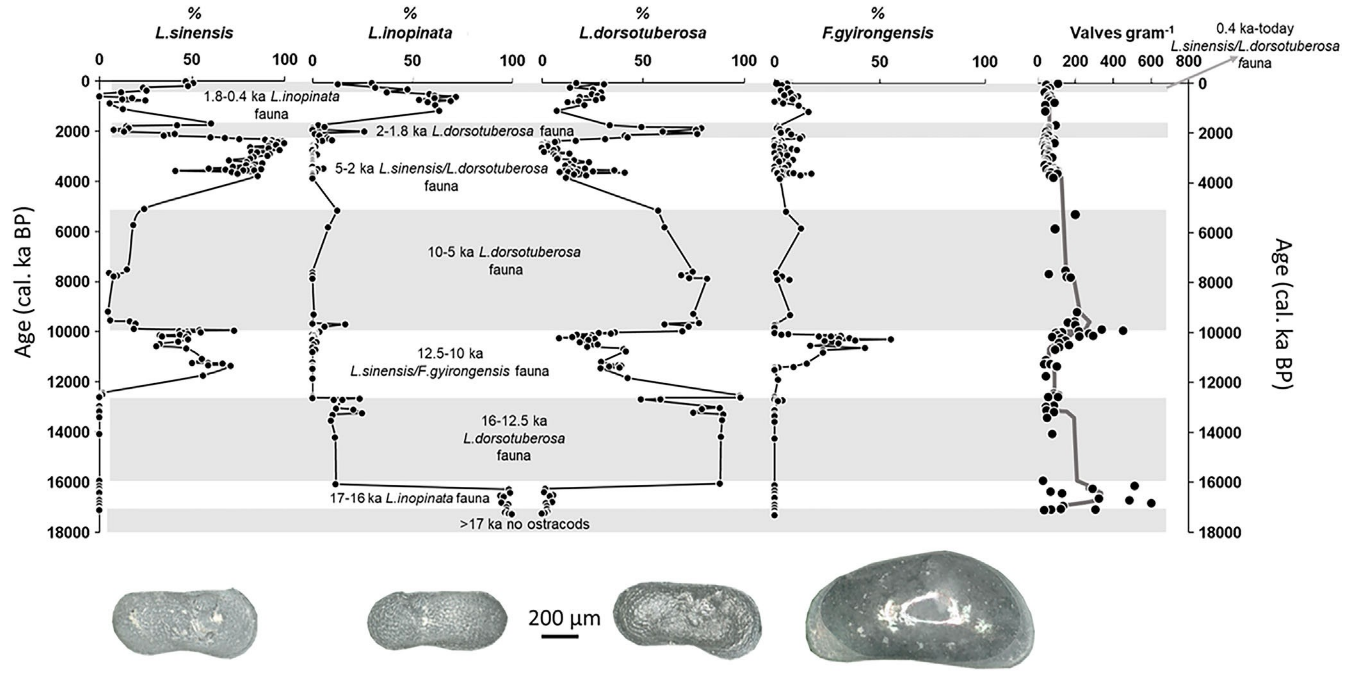

Figure 3. Relative abundances and valves/weight ratio of the ostracods. For relative abundances only the most abundant species were considered. From left to right, L. sinensis adult male, RV, ext., L. inopinata adult male, LV ext., L.? dorsotuberosa adult male, LV ext., F. gyirongensis adult female, RV, int.

cal ka BP. Candona xizangensis (Huang, 1982), Tonnacypris gyirongensis (Yang, 1982) and Candona candida (O.F. Müller, 1776) were also found but in very small percentages along the cores. The relative abundances of the most abundant ostracods are shown in Fig. 3.

Conductivity reconstruction

The conductivity transfer function shows the highest value of 13.6 mS cm^{-1} close to the bottom of the composite core TAN12-2 at 17.1–16.1 cal ka BP (Fig. 4). Thereafter, the conductivity follows a general decreasing trend, reaching its minimum value (0.6 mS cm^{-1}) around 10.1 cal ka BP. Subsequently, conductivity increases again until 9.6 cal ka bp (3.3 mS cm^{-1}). Thereafter, values decrease until 1.7 cal ka BP, ranging between 2.8 and 1.2 mS cm^{-1} with the exception of a single peak of 4.3 mS cm^{-1} around 1.9 cal ka BP. For the last 1.1 ka, values range between 5.2 and 8.2 mS cm^{-1} and, close to the top of the core, are ca. 0.4 cal ka BP, until today, conductivity generally shows a decrease, with values between 5.1 and 2.1 mS cm^{-1}.

Stable oxygen isotopes

The d^{18}O record from Tangra Yumco shows high values at around 17.0 cal ka BP. After this there is a general decrease until about 11.0 cal ka BP. Thereafter the curve follows a positive trend towards higher values until about 0.4 cal ka BP, where a new negative trend until today was observed.

Discussion and interpretation

Lake level changes of the Tangra Yumco lake system

A possible explanation for the lack of ostracods between 18 and 17 cal ka BP could be high salinity as indicated by high d^{18}O values of the bulk sediment (Fig. 4) and a high sedimentation rate due to a pronounced low lake level stand. This hypothesis is also supported by the reconstructed conditions of the lake level between 17 and 16 cal ka BP, with a dominance of L. inopinata. This species indicates a low lake level and meso- to polyhaline conditions in the southern part of the Tibetan Plateau (Akita et al., 2016). At the same time L.? dorsotuberosa confirms the presence of a lacustrine water body. The maximum conductivity reached during this period is 13.6 mS cm^{-1}. Until about 12 cal ka BP, the dominance of L.? dorsotuberosa indicates a rising lake level (Akita et al., 2016) with a correspondingly decreasing conductivity and negative d^{18}O trend. Based on the increased relative abundance of L. sinensis and lower numbers of the deep water species L.? dorsotuberosa, there was a slight increase in water depth during this period, although the conductivity transfer function does not show a clear trend. This alternation could be due to temporary variations of the lake level or variations to the inflow/outflow of the system. The switch in dominance from L.? dorsotuberosa to the opportunistic L. sinensis and shallow-water taxon L. inopinata (Akita et al., 2016) between 9.8 and 7.5 cal ka BP indicates a slow and progressive lowering of the lake level with a corresponding slight increase in conductivity. This trend is also confirmed by d^{18}O analysis, indicating an enrichment in heavy ^{18}O isotopes within the sediments after 8.5 cal ka BP, which can be assumed to be directly related to the lake water, reflecting a decrease in effective moisture and thus a slow, long-term reduction in lake water volume typical of large terminal lakes (Leng and Marshall, 2004). These d^{18}O-based lake volume reconstructions are supported by a quantitative lake level reconstruction from Tangra Yumco based on optically stimulated luminescence (OSL) ages of exposed lacustrine sediments (Ahlborn et al., 2016) showing a very similar pattern (Fig. 4).

During the period 7.5–3.7 cal ka BP the evolution of the lake could not be reconstructed based on the ostracod assemblage as only two samples dated to 5.7 and 5 cal ka BP are available. Nevertheless, the bulk sediment oxygen isotopes show a gradual increase, indicating a high but gradually falling lake level accompanied by slowly increasing conductivity.

For the last 3.7 cal ka BP, it is possible to distinguish four phases (Fig. 3). The first, with L. sinensis as the dominant species,

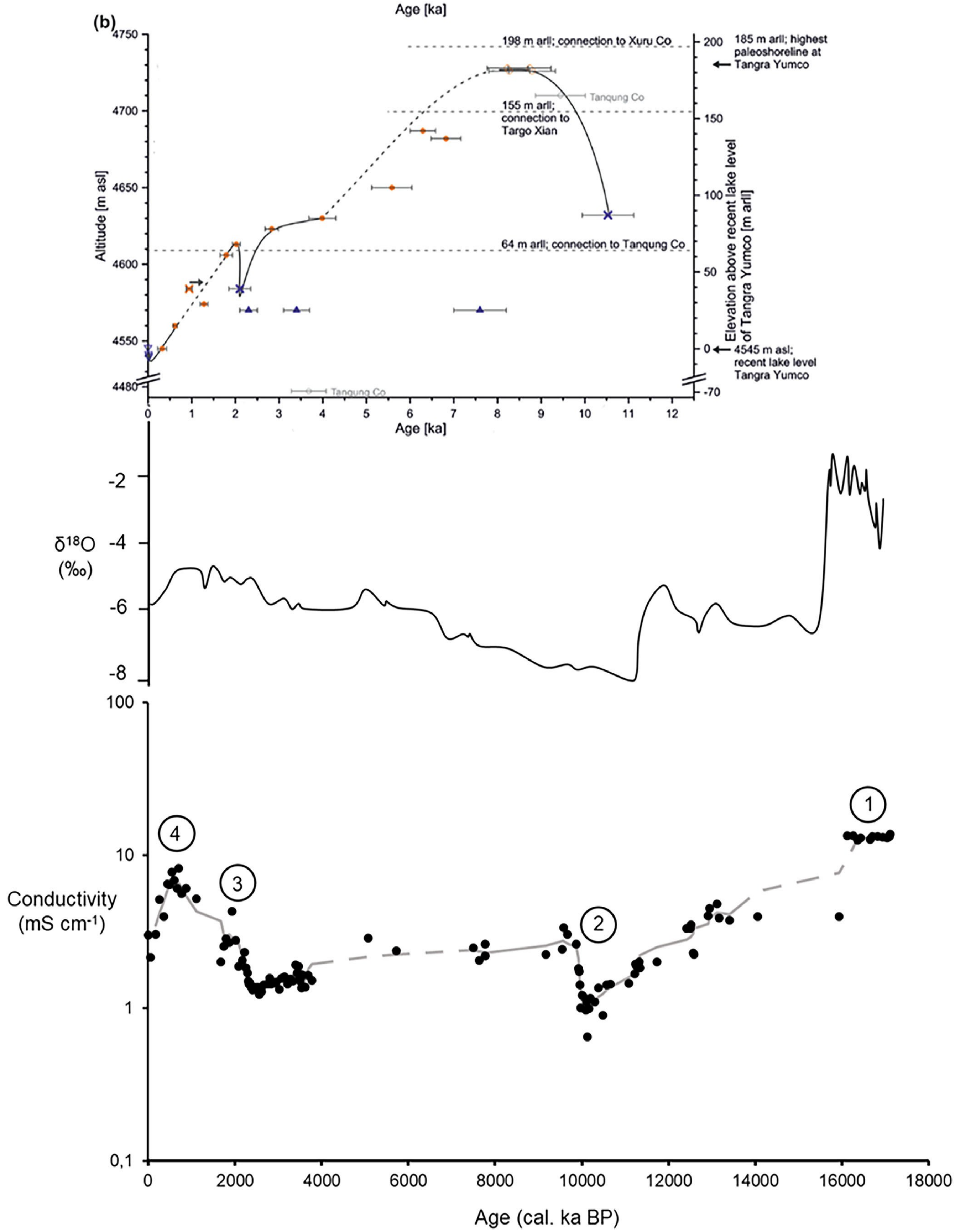

Figure 4. Comparison of the lake level curve of Ahlborn et al. (2016; upper diagram), changes in bulk d^{18}O and ostracod-based conductivity estimation. The black points are calculated values and the grey line indicates the 5-point average (the broken line indicates uncertainties due to a lack of samples). In the oldest stage (1) at 17–10.5 ka cal BP, the conductivity decreases. (2) An increase is recorded, followed by a decrease, in contrast to Ahlborn et al.'s record. Good agreement with Ahlborn et al.'s (2016) curve is recognizable around 2 ka (3) and by the fast switch of decreasing and later increasing lake level reported in the conductivity curve. Subsequently (4), the two curves agree until 0.4 ka cal BP where the conductivity starts to decrease earlier than the rise of the lake assumed by Ahlborn et al. (2016).

indicates a relatively stable lake level with low conductivity and corresponding oligohaline conditions. Around 2 cal ka BP, a switch in dominance between L. sinensis and the two species L.? dorsotuberosa and L. inopinata suggests a fast lake level decline and a subsequent fast rise. The dominance of the halotolerant species L. inopinata between 1.1 and 0.2 cal ka BP indicates mesohaline conditions and a falling lake level. In the uppermost six samples, L. sinensis reappears, probably due to a recovery of the lake level as also confirmed by $\delta^{18}O$ analysis revealing a negative trend during this period.

Comparison with previous studies and regional comparison

Tangra Yumco sediments have already been investigated for palaeoecological and palaeoclimatic purposes in the recent years (Long et al., 2012; Rades et al., 2013; Miehe et al., 2014; Ahlborn et al., 2016, 2017; Akita et al., 2016; Ehner et al., 2016; Henkel et al., 2016). Ahlborn et al. (2016) reconstructed the lake level history based on OSL dating (Fig. 4) of massive carbonate banks in the catchment of Tangra Yumco integrating similar datasets from several authors (Kong et al., 2011; Long et al., 2012; Rades et al., 2013, 2015). In addition of this, we match our micropalaeontological data with datasets presented by Ahlborn et al. (2017), who compared lithological and geochemical analysis on the cores of Tangra Yumco with similar records from other water bodies on the southern part of the Tibetan Plateau, and with the results of the $\delta^{18}O$ analysis data from Tangra Yumco. Regarding the whole system, neotectonics probably had only a minor role in the interaction between the lakes, given the dramatic lake level fluctuations and the relatively low impact of tectonics in this region (Armijo et al., 1986).

Akita et al. (2016) demonstrated small and temporary water bodies were populated by different ostracod assemblages compated with large lakes, but the distribution of lacustrine ostracods is mainly driven by salinity. This observation was made by Mischke et al. (2007) as well and supports the reliability of ostracod-based conductivity transfer functions for lakes of the Tibetan Plateau.

The results show low conductivity values, probably related to a shallow lake level around 17 ka, also confirmed by Ahlborn et al. (2017). After this, merging of the lake Tangqung Co in Tangra Yumco, forming one large lake at around 10.5 cal ka, is recorded (Ahlborn et al., 2016). Subsequently to this period, a highstand of 181–183 m above the present lake level is recorded and Tangra Yumco reached its highest elevation during the entire Holocene between 9 and 8 cal ka BP (Ahlborn et al., 2016). A comparison of the lake level reconstruction of Ahlborn et al. (2016) with the ostracod-based conductivity of the present study shows a generally similar pattern, especially concerning the first phase of increasing lake level (10.5 cal ka BP) and the phase between 4 and 0.4 cal ka BP, where the lake level shows lowstand–highstand switches followed by a new decrease, before stabilizing. However, some differences are observed (Fig. 4). At about 10 cal ka, conductivity shows an increase, despite a postulated lake level rise. A possible explanation could be that before this event, Tangra Yumco was integrated to Tangqung Co with a decrease of conductivity due to over-flowing into the latter. With a further rise of the lake Tangqung Co at about 10.2 ka, the latter reached the water level of Tangra Yumco, mixing with its more saline waters and leading to a subsequent increase in conductivity. The results indicate, at about 9.8 cal ka BP, a decrease in conductivity as result of the further rise of the lake level. The general lack of data for the period 7.5–3.7 cal ka BP for the ostracod dataset and for the OSL samples does not allow a more precise reconstruction, although a moderate trend of increasing conductivity is conceivable.

The documented conductivity reconstruction based on ostracods shows a rapid highstand–lowstand around 2 cal ka BP (Fig. 4), documented also in the OSL-based reconstruction of Ahlborn et al. (2016). Although not shown in the isotope data, the slight increase is probably compounded by the short-term mixing with Tangqung Co water. So our proxy would show this minor variation best. In the youngest part of the record the conductivity increase is confirmed by the lake level trend documented by Ahlborn et al. (2016). After ca. 0.4 cal ka BP, decreasing conductivity, as suggested by the ostracod conductivity transfer function, is in contrast to a falling lake level indicated by the OSL-based reconstruction. However, this result agrees with the $\delta^{18}O$ ratio dataset from the same core where a negative trend of isotopes for the

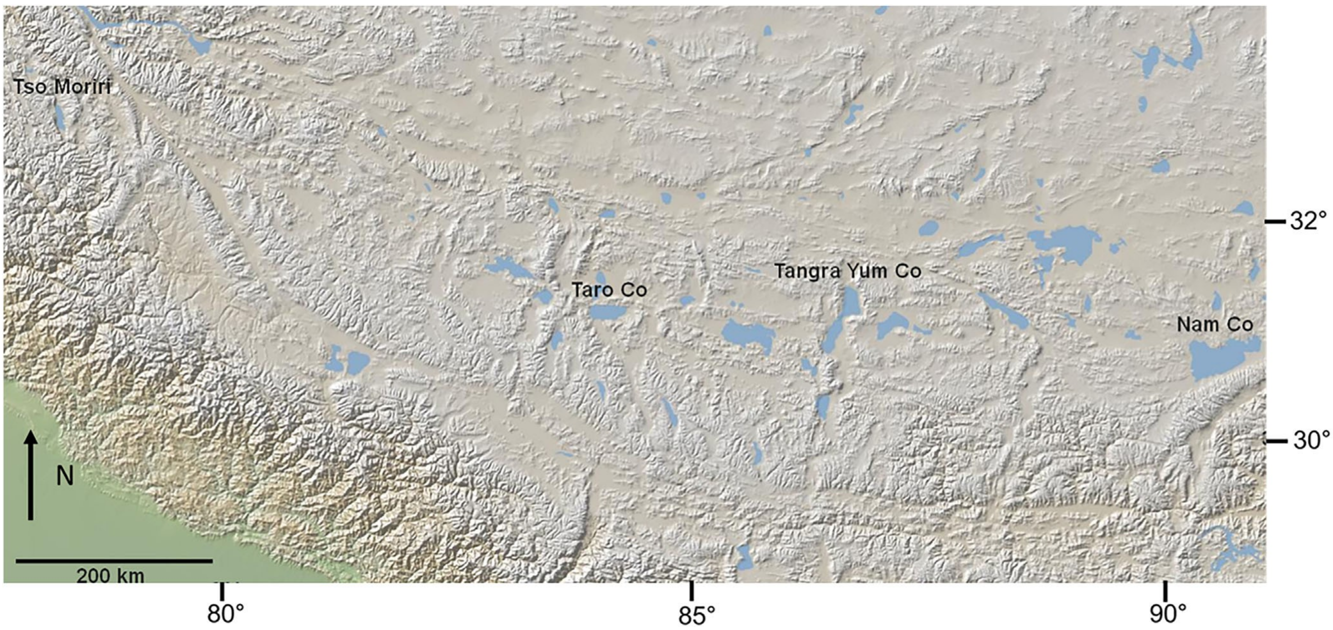

Figure 5. Location of the four lakes considered for the lake system comparison on the southern Tibetan Plateau. Source: www.geomapapp

last 0.5 cal ka BP is recorded. The lake level possibly rose slightly earlier than previously reported by Ahlborn et al. (2016), also given the chronology's uncertainty (0.3 ka).

As Ahlborn et al. (2017) reported, we also note the first synchronous development between 17 and 16 ka where relatively low lake level conditions switch with the start of deglaciation to an increasing lake level registered in Taro Co (Alivernini et al., 2018), Nam Co (Kasper et al., 2015) and Tso Moriri (Mishra et al., 2015) along an east–west transect on the Tibetan Plateau (Fig. 5).

After this shift, between 12 and 8.5 ka, an increase in moisture availability and temperature at the transition to the Holocene and a general precipitation decrease thereafter is reported for Taro Co (Alivernini et al., 2018), Tso Moriri (Mishra et al., 2015) and Nam Co (Kasper et al., 2015), showing a similar pattern with Tangra Yumco. A lowstand recorded around 2 ka ago followed by an increase in lake level was also reported by Kasper et al. (2015) for Nam Co to the east and by Alivernini et al. (2018) for Taro Co to the west. For lake Tso Moriri, Leipe et al. (2014) registered, during the general trend of decreasing humidity after 9 ka, an increase in moisture availability between 1.1 and 0.4 ka. Considering the uncertainties of the chronological model for the Tso Moriri core (Leipe et al., 2014) and the time lag for this event when comparing the two records, we assume a possible synchronous timing. This last sequence is probably related to minor variations of the monsoonal components in the lakes studied (Kasper et al., 2012; Ahlborn et al., 2016).

Conclusions

According to the ostracod-based approach used here and the comparison with other datasets, the lake level evolution of the Tangra Yumco lake system as refined with the ostracod-based transfer function and the d^{18}O analysis can be divided into six main phases.

- In the oldest stage (17–10.5 ka) conductivity and d^{18}O generally decrease from relatively high values, in phase with the general increasing levels of the other considered Tibetan lakes.
- At around 10 ka, a decrease of conductivity in contrast to Ahlborn et al.'s (2016) curve is recorded. The different trend in the ostracod-based transfer function can be explained by a switch from an open to a closed lake basin and a mix of saltier water from Tangqung Co with oligohaline water from Tangra Yumco.
- Between 9.8 and 7.5 cal ka BP the ostracod fauna and conductivity based on it indicate a slow and progressive lowering of the lake level. This trend is also confirmed by d^{18}O analysis.
- During the period 7.5–3.7 cal ka BP the general lack of data for both for the ostracod dataset and for the OSL samples does not allow a more precise reconstruction, although the moderate trend of increasing of d^{18}O could be related to a decrease of the lake level.
- After this, the conductivity is in general in good agreement with Ahlborn et al.'s (2016) lake level curve, especially around 2 ka, where the fast switch of decreasing and later increasing lake level is synchronously mirrored by the conductivity curve.
- Thereafter, the conductivity, d^{18}O and lake level curve agree until 0.4 ka, where the conductivity starts to decrease earlier than the rise of the lake level and the positive shift of the d^{18}O.

Comparison of the evolution of the Tangra Yumco lake system with the adjacent basins along an east–west transect shows synchronism for almost all the events recognizable at Tangra Yumco. However, the ostracod-based transfer function has proven to be a valuable tool for refining lake level curves, discriminating climatic and hydrographic effects such as switching between closed and open lakes.

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Abbreviation. OSL, optically stimulated luminescence.

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Chapter 4 - Plio-Pleistocene Ostracoda from the Zhada Basin (Western Tibetan Plateau)

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Abstract:	We present a list of Ostracoda (Crustacea) from profiles from Zhada Basin, Western Tibetan Plateau. In this area almost no taxonomical studies were carried out so far, and, aiming to a future use of ostracods as palaeoenvironmental proxy for this sector of the Tibetan Plateau, a documentation of several unknown species was performed. The taxa Leucocytherella sinensis (Huang, 1982), ?Leucocythere dorsotuberosa (Huang, 1982), Leucocythere postilirata (Pang, 1985), Ilyocypris spp., Eucypris cf. zandaensis Yang, 1982, ?Trajancypris sp., Paraeucypris sp. and Leucocytherella dangeloi (Alivernini, sp. nov.) were found and classified. The new species Leucocytherella dangeloi shows a higher rounding in the posterior part and a general weaker ornamentation than in Leucocytherella sinensis. It was possible to classify it as distinct species. Ilyocypris spp belong probably to three different species, although for the complexity of the taxonomical classification of this genus, further work is needed as well as for the species in open nomenclature: Ilyocypris spp., Paraeucypris sp., Eucypris cf. zandaensis and ?Trajancypris sp. The taxa from the Zhada Basin are mainly lacustrine species indicating lake sediments for most samples. Based on the taxonomical analysis and more sample material a quantitative palaeoecological analysis of ostracod faunas from the Plio-Pleistocene Zhada Basin will enable new palaeoenvironmental and palaeoclimatic reconstructions.
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	Ping Peng pengping@itpcas.ac.cn Dr. Peng worked on the Ostracoda of the Tibetan Plateau for a long time and she has a good experience on their taxonomy. Her knowledge could be a great value to improve and review the manuscript

Plio-Pleistocene Ostracoda from the Zhada Basin (Western Tibetan Plateau)

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Keywords: Ostracoda; Species; Western Tibetan Plateau; Zhada Basin; Plio-Pleistocene; taxonomy

Abstract

We present a list of Ostracoda (Crustacea) from profiles from Zhada Basin, Western Tibetan Plateau. In this area almost no taxonomical studies were carried out so far, and, aiming to a future use of ostracods as palaeoenvironmental proxy for this sector of the Tibetan Plateau, a documentation of several unknown species was performed. The taxa *Leucocytherella sinensis* (Huang, 1982), ?*Leucocythere dorsotuberosa* (Huang, 1982), *Leucocythere postilirata* (Pang, 1985), *Ilyocypris* spp., *Eucypris* cf. *zandaensis* Yang, 1982, ?*Trajancypris* sp., *Paraeucypris* sp. and *Leucocytherella dangeloi* (Alivernini, sp. nov.) were found and classified. The new species *Leucocytherella dangeloi* shows a higher rounding in the posterior part and a general weaker ornamentation than in Leucocytherella sinensis. It was possible to classify it as distinct species. *Ilyocypris* spp belong probably to three different species, although for the complexity of the taxonomical classification of this genus, further work is needed as well as for the species in open nomenclature: *Ilyocypris* spp., *Paraeucypris* sp., *Eucypris* cf. *zandaensis* and ?*Trajancypris* sp. The taxa from the Zhada Basin are mainly lacustrine species indicating lake sediments for most samples. Based on the taxonomical analysis and more sample material a quantitative palaeoecological analysis of ostracod faunas from the Plio-Pleistocene Zhada Basin will enable new palaeoenvironmental and palaeoclimatic reconstructions.

1 Introduction

There are many examples for the prominent role of Ostracoda (Crustacea) in different fields of geosciences and their use as palaeoenvironmental, palaeoclimatic and biostratigraphic indicators. Their sensitivity to environmental changes and their wide distribution in all types of water bodies make their good documentation also in less studied areas desirable. In contrast to the large number of geological and palaeontological studies on the Tibetan Plateau, research on ostracods in this area is rather rare and improved only in the last decade (e.g. Wrozyna *et al*., 2009; Frenzel *et* *al.*, 2010; Mischke, 2012). Investigations were mainly conducted in the more easily accessible northern and eastern part of the plateau, and only a few studies (e.g. Li *et al.*, 1991; Zhu *et al.*, 2010) improved the available knowledge of the local ostracod fauna of its central and western part. Furthermore, ostracod studies in the central and southern parts of the Tibetan Plateau focussed on Holocene and Late Pleistocene faunas whereas the precursors of these partly endemic species are not known. Investigations on Plio-Pleistocene ostracods from the Tibetan Plateau are restricted to the Qaidam Basin so far (e.g. Sun *et al.*, 1988; Yang *et al.*, 1997; Mischke *et al.*, 2006, 2010) where they are a valuable tool for biostratigraphy in hydrocarbon exploration.

This work focuses on Plio-Pleistocene ostracods of the Zhada Basin located in the western Tibetan Plateau. Previous works carried out in this area concern its tectonic origins (Wang *et al.*, 2004; 2008; Saylor *et al.*, 2010b) and palaeoenvironmental reconstruction (Saylor *et al.*, 2010a) using mostly pollen records and sedimentological analyses. Kempf *et al.* (2009), who investigated petrographic and sedimentological properties, were the first to describe also elements of the ostracod fauna in this area. They found some typical endemic taxa like *Leucocytherella sinensis* and several not identified species. In this work we present the Plio-Pleistocene ostracod assemblage recovered from 105 sub-samples of Joel Saylor's stratigraphic "South Zhada" ("SZ") section, localised in the southern part of the Zhada Basin and already sedimentologically analysed and dated by Saylor (2008) in order to improve the taxonomic data base on ostracods of this area for future palaeoecological and potentially stratigraphical studies.

2 Study area

The Zhada Basin is the largest late Cenozoic sedimentary basin in the Tibet Autonomous Region. It is located north of the high Himalayan ridge crest in the western part of the orogen (~32°N, 82°E; Fig. 1). The basin is at least 150 km long and 60 km wide, and the current outcrop extent of the basin fill covers at least 9000 km ^{2} (Saylor *et al.*, 2010b). It is bounded by the South Tibetan detachment system to the southwest, the Indus suture to the northeast, and the Leo Pargil and Gurla Mandhata gneiss domes to the northwest and southeast, respectively (Saylor *et al.*, 2010a). The Zhada Basin contains a thick sequence of late Neogene fluvial and lacustrine deposits (Kempf *et al.*, 2009) which allows the reconstruction of long term climate history.

3 Material and methods

3.1 Fieldwork

A total of 124 sediment samples were collected from Saylor's "South Zhada" section (Saylor, 2008). Seven prominent lake beds distributed more or less evenly over the 820 m thick sediment sequence were selected to enable the comparison of ostracods from stagnant water deposits formed over the last ca. 8 Ma (Saylor *et al*., 2010b). Sediment samples from individual lake beds were collected at ca. 0.5 m intervals. The seven selected lake beds are located between 31.46538 °N and 79.72865 °E as the lowermost and northernmost position and 31.36556 °N and 79.75152 °E as the uppermost and southernmost position, and centred at 114, 232, 325, 377, 422, 631 and 771 m above the base of the "South Zhada" section (Saylor *et al*., 2010b).

3.2 Micropalaeontological analysis

All 124 sediment samples were treated for micropalaeontological analysis. The samples were treated with H_2O_2 (ca. 5-10 % for about 1-2 hours) to separate aggregates of mud, and they were subsequently sieved with water through a 200 µm-sieve to remove fine-grained particles. In total, 105 samples contained ostracod valves. For quantitative ostracod analysis, the sieve residues were split into sub-samples using a microsplitter. The species proportions and the relative ostracod abundances were calculated considering all ontogenetic stages (juvenile and adult valves). In order to assess water turbulence (Boomer *et al*., 2009) and the possible removal of thinner and smaller juvenile valves by dissolution, the adult/juvenile ratio was determined. Identification was performed primarily with a low-power binocular microscope and was occasionally supported by a Scanning Electron Microscope (SEM) as well as a Keyence Digital Microscope. The valves were classified and taxonomically attributed, where possible by comparison with previous studies about the ostracods of the Tibetan Plateau (e.g. Mischke, 2010; Wrozyna *et al*., 2009, 2010; Akita *et al*., 2016) and using Chinese literature (Huang, 1982; Hou *et al*., 2002; Hou and Gou, 2007). In addition to this, an amended description of the shells, where they present differences from the original description, was added.

4 Results

4.3 Micropalaeontological analysis

4.3.1 Preservation

The samples contain 6722 ostracod valves and the abundances fluctuate considerably, 19 samples did not contain ostracods. Most valves were disarticulated and adult valves were dominant. Especially in presence of alluvial sediment, deformations on juvenile valves are recorded. Beside ostracods, gyrogonites of charophytes and molluscs, mostly fragments of Gastropoda, were found frequently within the samples.

4.3.2 Taxonomy

We found at least eight ostracod species in the 124 samples from the Zhada Basin. The most abundant species is *Leucocytherella sinensis* (Huang, 1982) which often occurs in association with ?*Leucocythere dorsotuberosa* and its morphotype *L. postilirata* (Tab.1). Other abundant taxa are *Paraeucypris* sp., *Leucocytherella dangeloi* (spec.nov) and the genus *Ilyocypris*.

A systematic overview on the ostracod taxa of the Zhada Basin follows below. The synonymy lists contain first description, emendations and other taxonomically important references. The systematic is adopted from Martin and Davis (2001) and Fürstenberg *et al*. (2015)

Classis Ostracoda Latreille, 1802

Order Podocopida Müller, 1894

Superfamily Cytheroidea Baird, 1845

Family Limnocytheridae Klie, 1938

Subfamiliy *Limnocytherinae* Klie, 1938

Genus *Leucocytherella*, Huang, 1982

Leucocytherella sinensis (Huang, 1982)

Fig.1, 1-2

*1982 *Leucocytherella sinensis* Huang gen. et sp. nov. — Huang *et al.*, p. 341-342, text-fig. 23-26, pl. 12, figs. 1-8; pl. 13, figs. 1–7 [type species of *Leucocytherella* Huang, 1982]

2015 *Leucocytherella sinensis* Huang — Fürstenberg *et al.*, p. 67-70, fig. 6, figs. 10-12 [comprehensive synonymy list]

2016 *Leucocytherella sinensis* Huang — Akita *et al.*, p. 7, figs. 3/6-10

2016 *Leucocytherella sinensis* Huang — Guo *et al.*, fig. 2 [upper left valve]

2018 *Leucocytherella sinensis* Huang — Alivernini *et al.*, fig. 8/1

Material: 2714 valves (females, males, juveniles, including carapaces specimens)

Size: 0.64-0.72mm (adults)

Original Description (Huang, 1982; plate 12): Valve of female rectangular in lateral view, anterior end higher than posterior, two transverse sulci anterodorsally, radial pore canal zone moderately broad, with slender, straight and sparse radial pore canals. Hinge of left valve consists of an anterior small reniform tooth, posterior small triangular one and middle shallow groove. Valve of male rather long, both ends nearly equivalently high. Valve of larva rather short, anterior end higher than posterior.

For the general description of the valves of recent specimens (males, females, juveniles) on the Tibetan Plateau see Fürstenberg *et al.* (2015).

Ecology and distribution: *Leucocytherella sinensis* is ubiquitous and endemic on the Tibetan Plateau above 4000 m a.s.l. (Akita *et al*., 2016). Valves of *L. sinensis* were found in lakes, ponds, rivers, and lagoon-like and estuary-like water bodies at lake shores in salinities of 0.08–12.81 psu. It lives on mud, sand, sandy gravel and in phytal habitats in permanent fresh to brackish-lacustrine waters, dominating in Ca^{2+} depleted waters. The nodes on the calcitic valves in low salinity can be used as a proxy for palaeosalinity (Fürstenberg *et al*., 2015).

Fossil record. From Miocene to recent (Huang, 1985)

Leucocytherella dangeloi Alivernini, sp. nov.

Fig.5, 1-7

Material examined. 129 valves (females, males, juveniles, including carapaces specimens)

Size. 0.58-0.72 mm (adults)

Diagnosis: Typical *Leucocytherella* species but with smooth surface and with posterior part higher compared to anterior part than in *L. sinensis* more evident in the left valve. Lophodont hinge.

Holotype: A female right valve (0.70 mm). Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences

Locus typicus: Zhada Basin, sample Z068.

Description: Carapace nearly rectangular. The posterior part of *L. dangeloi*, as well as of *L. sinensis*, is more rounded and higher than the anterior one, but in *L. dangeloi* this difference is more pronounced with an even higher rounding. Valves smooth and less pitted than in *L. sinensis*. Weak dorsomedian sulcus at half-length of carapace. Protuberance in the anterodorsal part of the carapace. Valves are un-noded or weakly noded. Four adductor muscular scars in an almost vertical and slightly inclined row are shifted slightly anteriorly from the centre of the valve. Marginal pore canals thin, from weakly inclined to straight and not numerous. Weak ornamentation of the hinge. Similar to *L. sinensis*, the hinge of the right valve consists of a pit on both ends and a ridge in between; the hinge of left valve presents an anterior small rounded tooth, posterior a small triangular one and a shallow groove in between. Inner posterior lamella broad. Dorsal carapace sexually dimorphic, males are larger and more expanded posteriorly than females.

Derivatio nominis: The name “*dangeloi*” was given to commemorate the death of Fabio D'Angelo, a young micropalaeontologist at the beginning of his academic career who died in 2012.

Genus Leucocythere Kaufmann, 1892

?*Leucocythere dorsotuberosa* (Huang, 1982)

Fig. 6-8

*1982 *Leucocythere dorsotuberosa* Huang — Huang *et al*., p. 335-336, plate 10, figs. 10-17

pars 2009 ?*Leucocythere dorsotuberosa*, Huang — Wrozyna *et al.*, p. 668-669, plate 2, fig. 2, 4-9, 11 [non p. 670-671, plate 2, fig. 1, 3, 10, 12-13 = ?*Leucocythere postilirata* which is considered as forma of ?*L. dorsotuberosa* by Wrozyna *et al.* (2009) who provide a comprehensive synonymy list]

2010 *Leucocythere dorsotuberosa* f. *parasculpta* — Zhu *et al*., fig. 3/5

2010 *Leucocythere dorsotuberosa* f. *typica* — Zhu *et al*., fig. 3/7

pars 2010 ?*Leucocythere dorsotuberosa* Huang — Wrozyna *et al*., fig. 3/1-3 [non fig. 3/4 = ?*L. postilirata*]

non 2011 *Leucocythere dorsotuberosa* Huang — Wu *et al*., p. 64, plate 3, fig. 10 [= juvenile *Cyprideis torosa*]

2010 *Leucocythere dorsotuberosa*, Huang — Mischke, fig. 15.3/16-17

2016 ?*Leucocythere dorsotuberosa* Huang — Guo *et al*., fig. 2 [middle row right]

2016 *Leucocythere*? *dorsotuberosa* Huang — Akita *et al*., p. 32 + 33, figs. 3/1-5

non 2017 *Leucocythere dorsotuberosa* — Song *et al*., fig. 5/7

2018a *Leucocythere*? *dorsotuberosa* Huang — Alivernini *et al*., fig. 8e-g + 8i

2018b *Leucocythere*? *dorsotuberosa* Huang — Alivernini *et al*., fig. 3 [3rd from left]

Material examinated: 1061 valves (females, males, juveniles, including double-valved specimens)

Size: 0.65-0.77 mm

Original Description: (Huang, 1982, p. 335): Male valve rectangular, anterior end higher than posterior, dorsal margin nearly straight, ventral margin distinctly concave in the middle. Valves with reticulation. Two transverse sulci anterodorsally, and an alar protuberance extending posteroventral to medioventral, and a tubercle in posterodorsal position. Marginal pore-canal zone broad, comprising 10%-11% of the length of carapace, marginal pore-canals slender, not numerous, several are furcated, anterior with nineteen marginal pore-canals. Hinge of the left valve consists of sockets in both sides and a shallow ridge in between; hinge of the right valve consists of elongated teeth in both ends and a groove in between.
Valve of male is longer than female, posterior bulgy. Juvenile valve short, anterior broadly rounded, dorsal margin slightly rounded. Hinge of male, female and juvenile are similar. Valves are transparent. Carapaces sub-rectangular in lateral view.
Further description: Wrozyna *et al*. (2009) observed on recent valves that female carapaces are more triangular, the posterior to anteriomedian region bears protuberances interrupted by a mediodorsal sulcus partly divided by a central node. In

dorsal view anterior and posterior ends are pointed. Right valve overlaps left valve anteroventral and posterior in a lobe-like protrusion. (modified from Wrozyna *et al*., 2009)

Remarks: The found valves of ?*L. dorsotuberosa* present a lophodont hinge. Wrozyna *et al.* (2009) and Danielopol *et al.* (1989) doubted that *L. dorsotuberosa* belongs to the genus *Leucocythere* because of the different hinge, lophodont in ?*L. dorsotuberosa* instead of the typically anterior significantly smaller tooth of the genus *Leucocythere*.

Ecology and distribution: Living ?*L. dorsotuberosa* occur mainly in brackish lakes (phytal and muddy substrate) and its marginal lagoon-like water bodies. Living individuals have also been found in freshwater, but in low numbers only. Empty valves of ?*L. dorsotuberosa* were found in higher proportions at deeper water depth (Akita et al., 2016).

Fossil record: Pliocene to recent (Huang, 1982)

Leucocythere postilirata (Pang, 1985)

Fig.2, 3-5

*1985 *Leucocythere postilirata* sp. n. — Pang, p. 257, plate 2, fig. 13-16

2009 ?*Leucocythere dorsotuberosa* f. *postilirata* Pang — Wrozyna *et al*., p. 670-671, plate 2, fig. 1, 3, 10, 12-13

2010 ?*Leucocythere dorsotuberosa* f. *postilirata* Pang — Wrozyna *et al*., fig. 3/4

2016 ?*Leucocythere dorsotuberosa* f. *postilirata* Pang — Akita *et al*., fig. 2

2018 ?*Leucocythere dorsotuberosa* f. *postilirata,* Pang — Alivernini *et al*., fig. 8/e-f

Material examinated: 457 valves (females, males, juveniles, including double-valved specimens)

Size: size 0.78-0.92 mm

Original description (Pang, 1985, p. 257): Elongated carapace. Valve of male of elongated kidney-shape. Anterior slightly higher and / or has the same height as posterior. Both ends curved. Dorsal margin is elongated and almost straight, mediodorsal slightly curved. Anteromediodorsal is obviously compressed. Two transverse sulci anterodorsally, the more anterior sulcus shorter than the more posterior one. A rounded node is located between the sulci, another more obvious bulge behind the posterior sulcus and a third at the end of both sulci. A distinctive anterodorsal carina occurs where the dorsal margin meets the anterior one, another carina runs along the central ventral side below the sulci. A third carina lays posteriorly and protrudes the valve outline. The ventral and posterior carinae are not connected to each other. The maximum width lies at ¼ length of the valve. Valve not curved so much, ornamented with a net of large alveoles. Valves of female shorter than male, kidney-shaped. Anterior higher than posterior. Posterior carina and ventral carina weak. (modified from Wrozyna *et al*., 2009)

Further description: As already observed by Wrozyna *et al.* (2009) the valves present a typical sharp carina running parallel to the ventral margin; more distinct on the right valve. Another more or less developed carina runs parallel to the anteroventral margin. Additionally, a margin parallel posterior carina following the curvature of the margin can be more or less developed, separated from or fused with the ventral carina. The valves are strongly reticulated.

Remarks: Wrozyna *et al*. (2009) and Frenzel *et al.* (2010) regard *L. postilirata* as morphotype of *?L. dorsotuberosa* with most pronounced medio-ventral and anterior and often posterior carinae as protruding foldings of the shell.

Ecology and distribution. Living *?Leucocythere postilirata* occur where *Leucocythere dorsotuberosa* is present. Following Wrozyna *et al*. (2009) for Nam Co, ?*L*. *postilirata* shows a higher salinity tolerance (max. 8-10 psu) than ?*L. dorsotuberosa*, and is limited to water below the thermocline (20-30 m) and increases in number and relative abundance with water depth.

Fossil record. Recent from Nam Co and Pumoyong Co; Early Holocene of Peiku Co (Peng, 1997), Pleistocene of Kunlun mountains (Pang, 1985), Late Pleistocene of Bangong lake (Li *et al*., 1991), Cenozoic of Siling and Bangkok lakes (Pang, 1985), Tertiary of the Qaidam Basin (Sun *et al.*,1988)

Suborder Cypridocopina Jones 1901

Superfamily Cypridoidea Baird 1845

Family Ilyocyprididae Kaufmann 1900

Ilyocypris spp.

Fig.4, 1-8

Material: 676 valves (juveniles and adults, including double-valved specimens)

Remarks: The species of the genus *Ilyocypris* are often hard to discriminate relying on hard parts only, even in well studied regions as Central Europe (Meisch, 2000). Hou *et al.* (2002) list eleven *Ilyocypris* species for the Tibetan Plateau but many of them are of dubious taxonomic state. The partly poor preservation of our material and impossible attribution of most juvenile valves to adult stages makes it difficult to discriminate and identify *Ilyocypris* species from the Zhada Basin.

All documented valves bear the typical characters of the genus – a rectangular carapace in side view, about 1 mm long, with pitted to smooth surface and two conspicuous transverse dorsolateral sulci; the left valve overlaps the right one.

Based on outline and ornamentation three morphotypes, probably different species, are recognisable: a) well rounded anterior and posterior end in side view, surface weakly or not pitted, no tubercles; b) well rounded anterior and posterior end in side view, surface weakly pitted, five distinct tubercles similar to *Qinghaicypris subpentanoda* Yang, 1982; c) side view with truncated posterior end similar to *Ilyocypris inermis* Kaufmann, 1900, surface pitted, no tubercles. Left valves of the two well rounded morphotypes (a and b) show distinct marginal ripplets on the inner lamella of both ends. This character resembles *Ilyocypris bradyi* Sars, 1890 and *Ilyocypris decipiens* Masi, 1905 (Mazzini *et al.*, 2014) but the ripplets are more numerous and can be found at the anterior end as well.

Family Cyprididae Baird, 1845

Subfamily Eucypridinae Baird, 1845

Eucypris cf. zandaensis Yang, 1982

Fig.3, 1-2

**1982 Eucypris zandaensis Yang sp. nov. — Yang in Huang et al.: 330, pl. 2, fig. 1-9*

2002 Eucypris zandaensis Yang, 1982 — Hou et al.: 169, pl. 19, fig. 5-10

Material found: 59 valves

Size. 0.78-1.1 mm

Original description (Hou *et al*., 2002): Valves big, female elliptical in side view, dorsal margin straight and short inclining to the posterior part in side view, ventrally slightly concave, highest point at 2/5 of length, network of lines on the valve, marginal pore channels thick and numerous, central muscle scars with four in front of two others, oviduct traces, male valve longer, traces of four loops of testes recognisable.

Remarks: Our material differs from the holotype in having a slightly more trapezoidal outline of the right valve and being slightly smaller.

Distribution: Plio-Pleistocene of Zanda, Zhada Basin (Hou *et al*. 2002)

?*Trajancypris* sp.

Fig.3, 7-8

Material examined: 5 valves (only juveniles)

Size: 0.78-1.00mm

Description: Valves rounded triangular with highest point at about a third of length, anterior margin broadly rounded, posterior end more pointed, dorsal margin only very weakly curved over the hinge, ventral side slightly concave. Surface of valves smooth. No lists recognisable on inner lamella of the juvenile valves. Central muscle scars paw-like, marginal pore channels straight and numerous.

Remarks: No adult valves were available for description.

Paraeucypris sp.

Fig. 3, 3-6

Material examined: 756 juvenile valves

Size: 0.86-1.3 mm

Description: Valves elongated elliptical in side view, both ends well rounded, highest point well in front of mid-length, posterior part of right valves slenderer than anterior one, dorsal margin along the hinge straight and distinctively inclined towards posterior, ventral margin slightly concave. Surface of valves smooth. Lists on inner lamella not recognisable on juvenile valves. Hinge with a simple groove in the left valve and a smooth bar in the right valve. Central muscle scars of the typical cypridid paw-like pattern.

Remarks: Adult valves are needed for a comprehensive description of this species.

6 Discussion and Conclusion

Our list of ostracod taxa from the Zhada Basin contains at least eight species, several of them are already described for the Tibetan Plateau. Among them, the opportunistic and ubiquitous *L. sinensis* is the most abundant species. *Leucocytherella sinensis* is often observed together with ?*L. dorsotuberosa* and *L. postilirata* as it is known for recent faunas (Wrozyna *et al.*, 2009, Akita *et al.*, 2016). Kempf *et al.*, 2009 lists only five species from the Zhada Basin. One of them, *Candona xizangensis* Huang, 1982, was not found in our study. Adding it to our list we get a minimum of nine species, a low diversity for the studied area and time. Akita *et al*. (2016) found eleven species inthe recent Tangra Yumco lake system, a number comparable to our count from the Zhada Basin. We assume the harsh environmental conditions of the high elevation to be the cause for the low diversity observed.

The taxa from the Zhada Basin and also known from the recent ostracod fauna of the Tibetan Plateau are mainly lacustrine species indicating lake conditions for most samples. The ostracod-based palaeoenvironment of the sediment varies from river mouth to moderately deep lacustrine water

The newly described species *Leucocytherella dangeloi* sp. nov. is very interesting for the evolution of the genus *Leucocytherella* Huang, 1982 endemic to the Tibetan Plateau. All specimens of the genus described so far and studied by Fürstenberg *et al*. (2015) belong to *Leucocytherella sinensis* Huang, 1982. The association of *L. dangeloi* with lacustrine species points to a lacustrine habitat of the new species as well.

Based on the taxonomical analysis and more sample material a quantitative palaeoecological analysis of ostracod faunas from the Plio-Pleistocene Zhada Basin will enable new palaeoenvironmental and palaeoclimatic reconstructions.

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ZHADA BASIN	*Ilyocypris* spp	*L. sinensis*	*L. dorsotuberosa*	*L. postilirata*	*Paraeucypris* sp	?*Trajancypris* juv	*L. dangeloi*	*Eucypris* cf. *zandaensis*	tot juv.
Z01	6	4	0	1	0	0	0	0	1
Z02	32	68	1	4	0	0	0	0	59
Z03	16	43	15	4	0	0	0	0	50
Z04	48	6	16	18	0	0	0	0	20
Z05	10	0	0	4	0	0	0	0	2
Z06	2	0	2	0	0	0	0	0	1
Z07	4	2	1	8	0	0	0	0	6
Z08	27	0	0	12	0	0	0	0	3
Z09	14	0	2	2	0	0	2	0	3
Z010	36	33	5	1	0	0	0	0	35
Z010 dirty	40	0	3	0	0	0	8	0	7
Z011	25	7	3	14	0	0	0	1	19
Z012	13	1	0	5	1	0	0	0	3
Z013	20	0	8	12	0	0	0	0	12
Z014	11	0	3	4	0	0	0	0	5
Z015	37	0	0	5	0	0	0	0	3
Z016	7	10	26	4	0	0	0	0	32
Z017	12	1	9	3	0	0	0	0	4
Z018	2	57	44	1	1	0	12	0	70
Z018a	37	29	18	11	2	0	0	0	46
Z019	3	12	16	43	3	0	0	0	45
Z020	5	8	45	11	0	0	1	0	34
Z021	4	0	4	0	12	0	0	0	14
Z022	0	3	26	1	0	0	0	0	21
Z023	0	0	10	0	0	0	0	0	2
Z024	0	33	64	6	0	0	0	0	74
Z025	1	1	0	0	1	0	3	0	4
Z026	0	0	0	0	3	0	0	0	3
Z027	0	8	8	0	0	0	4	0	18
Z027a	0	35	49	5	1	0	0	0	76
Z028dirty	1	33	24	0	5	0	34	0	70
Z029	1	3	11	0	5	0	0	0	19
Z036	22	8	2	2	2	0	0	0	9
Z037	10	18	37	8	0	0	0	0	46
Z039	27	19	46	2	0	0	7	0	69
Z042	0	0	6	0	0	0	0	0	2
Z043	0	5	10	5	7	0	10	0	22
Z044	0	7	7	12	15	0	13	0	45
Z045	5	11	2	1	86	0	0	0	96
Z046	7	10	5	7	64	0	46	0	118
Z047	0	15	3	0	0	0	9	0	19
Z048	3	6	0	1	29	0	0	0	36
Z049	3	27	0	2	70	0	0	0	95

Z050	1	42	1	3	46	0	5	0	79
Z052	10	3	0	2	68	0	6	0	77
Z053	1	93	6	2	52	1	1	2	134
Z054	1	44	9	4	15	0	22	1	55
Z055	6	23	7	1	25	0	30	0	81
Z055 dirty	1	0	0	0	0	0	0	0	0
Z057	0	4	4	0	0	0	0	0	8
Z058	1	22	1	0	1	0	0	0	16
Z059	3	4	0	0	3	0	1	0	7
Z060	0	78	9	0	0	0	0	0	78
Z061	0	5	1	0	0	0	0	0	6
Z062	7	7	1	0	0	2	27	0	23
Z063	71	7	1	3	8	0	0	1	31
Z064	11	50	0	0	16	2	9	0	60
Z065	6	53	4	1	1	0	12	0	53
Z067	0	108	0	0	0	0	18	0	88
Z068	0	172	0	0	0	0	25	0	101
Z069	6	116	0	0	0	0	18	0	99
Z070	2	35	0	1	0	0	45	0	39
Z071	2	53	1	0	0	0	35	0	44
Z072	0	61	0	0	0	0	21	0	47
Z073	0	81	0	0	0	0	18	0	47
Z074	0	64	6	0	0	0	28	0	73
Z077	6	0	6	11	0	0	4	0	14
Z078	0	1	0	0	0	0	0	0	1
Z079	0	0	4	1	0	0	0	0	4
Z080	0	8	5	1	0	0	0	0	6
Z081	0	0	12	0	0	0	0	0	2
Z082	0	0	6	0	0	0	0	0	2
Z083	0	2	4	0	0	0	0	0	6
Z084	0	9	30	0	0	0	0	0	16
Z085	0	5	16	3	0	0	0	0	11
Z086	0	0	12	4	0	0	0	0	5
Z089	0	17	9	0	0	0	0	0	18
Z090	0	82	61	0	0	0	0	0	89
Z091	2	4	23	30	0	0	0	0	39
Z092	29	144	62	19	0	0	0	0	96
Z093	16	25	26	9	0	0	0	0	19
Z094	0	0	22	0	0	0	0	0	22
Z095	0	53	20	5	4	0	0	12	52
Z096	0	64	9	4	10	0	0	11	71
Z097	0	62	1	18	5	0	0	10	78
Z098	0	121	4	4	0	0	0	0	60
Z099	0	98	1	6	0	0	0	0	65
Z0100	0	120	10	2	4	0	0	0	83

Z0101	0	63	12	0	0	0	0	1	34
Z0102	0	51	26	0	0	0	6	0	56
Z0103	0	119	12	4	0	0	6	0	92
Z0104	0	103	10	33	0	0	0	0	96
Z0105	0	11	1	1	0	0	0	0	9
Z0106	0	1	9	0	0	0	0	0	5
Z0107	0	21	12	1	0	0	0	0	11
Z0108	0	67	12	6	3	0	0	0	52
Z0109	0	32	4	18	62	0	0	0	86
Z0110	0	11	12	4	7	0	10	18	22
Z0111	0	82	3	23	21	0	9	2	61
Z0112	0	109	14	13	4	0	0	0	85
Z0113	0	63	8	1	4	0	0	0	40
Z0115	0	2	0	0	1	0	1	0	2
Z0117	0	0	0	0	75	0	0	0	75
Z0118	3	4	0	0	6	0	0	0	8
Z0119	0	0	0	0	3	0	0	0	3
Z0121	0	0	1	0	4	0	0	0	5
Z0122	0	0	0	0	1	0	0	0	1

Tab.1 Counted valves of ostracod species and adult/juvenile ratio in sediment samples taken from the Zhada basin. Samples without ostracod valves are omitted.

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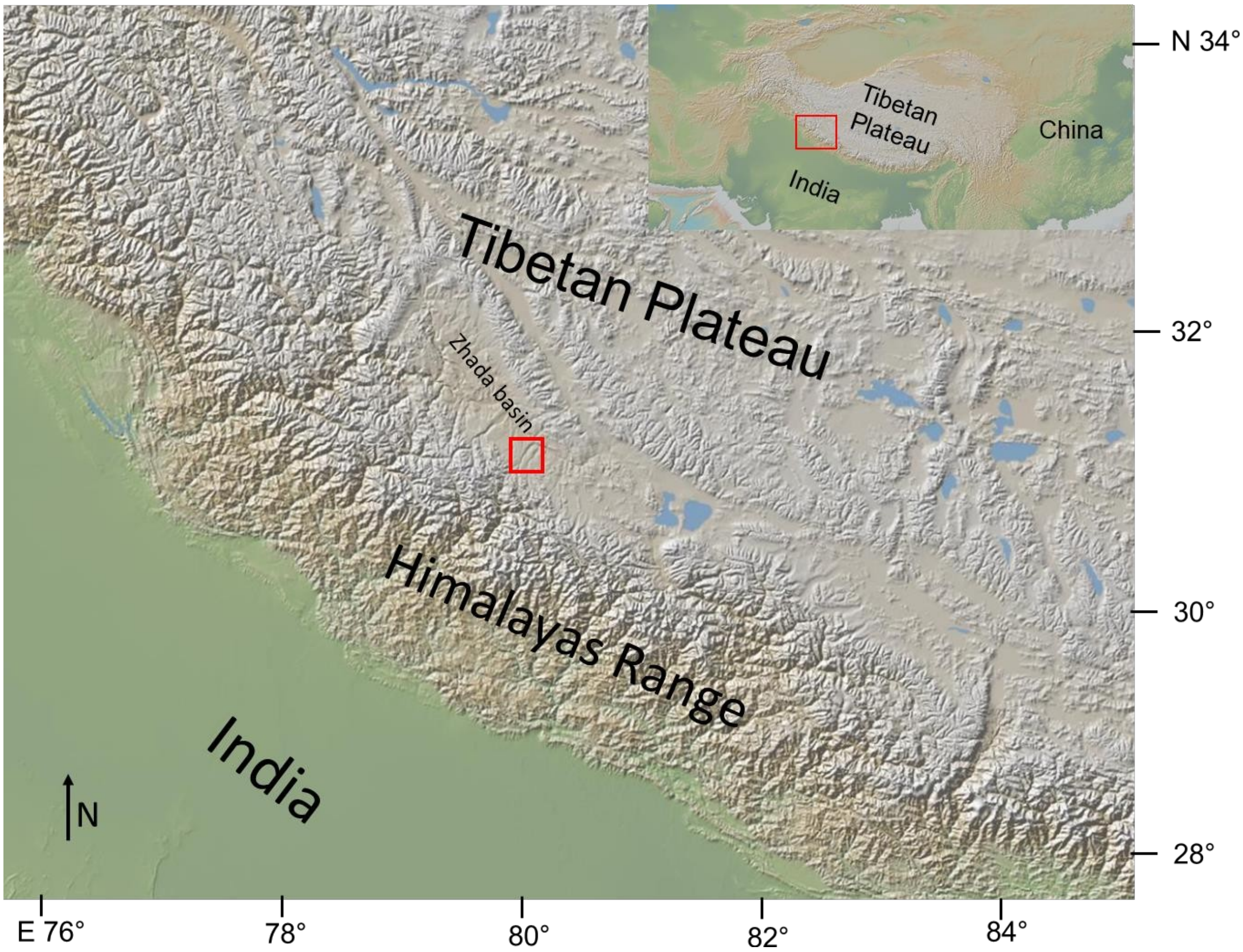

Fig.1 Location of the Zhada basin on the Tibetan Plateau and position of the sampling area (Geomapapp image modified).

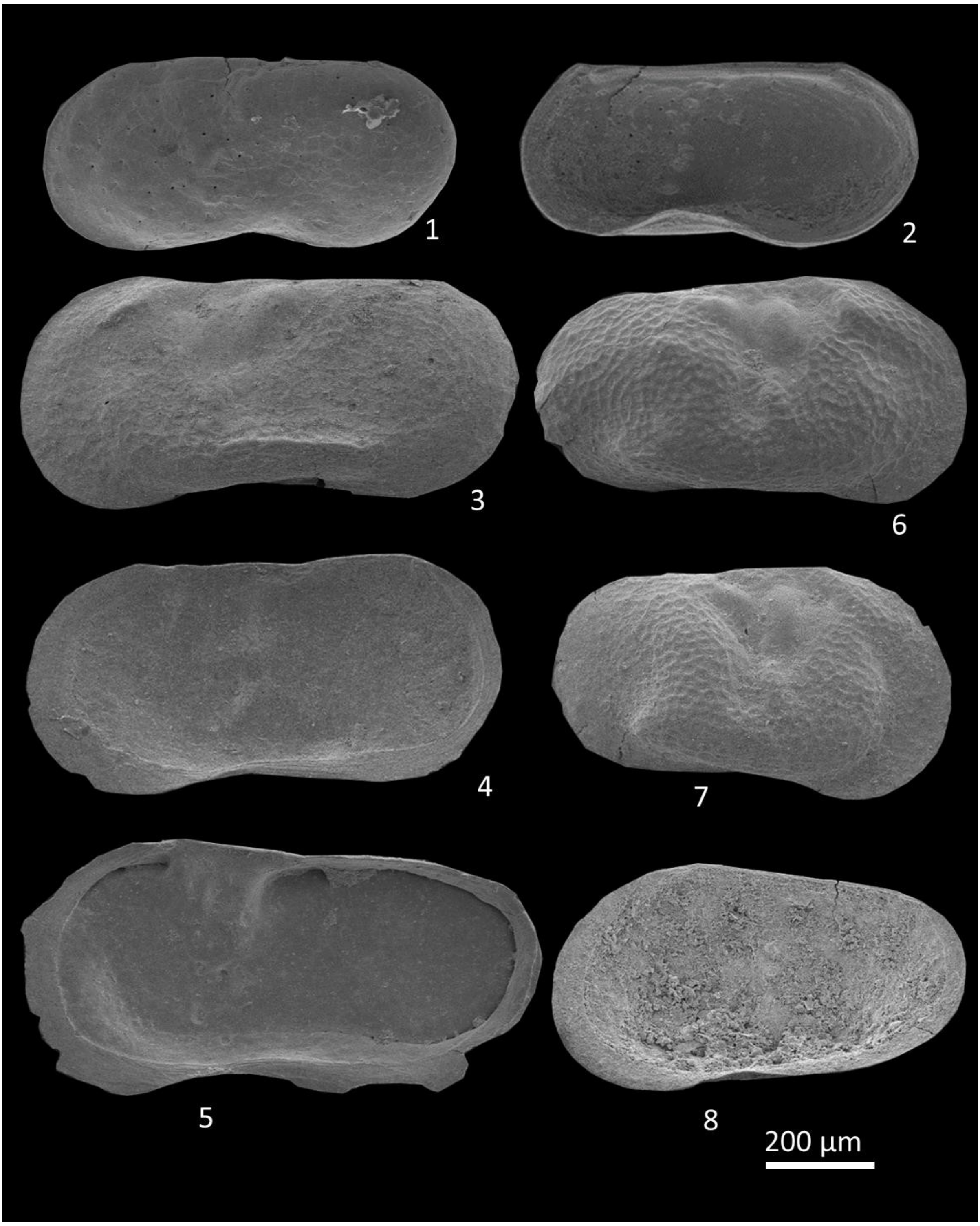

Fig.2: *L.sinensis* (Huang, 1982) (1) a. RV ext., sample Z063, (2) a. LV int., sample Z063); *Leucocythere postilirata* (Pang, 1985) (3) LV ext. sample Z0104, (4) RV int. sample Z037, (5) RV. int sample Z037;? *L.dorsotuberosa* (Huang, 1982) (6) RV ext. sample Z0110, (7) RV ext. sample Z0112, (8) RV ext. Z0112

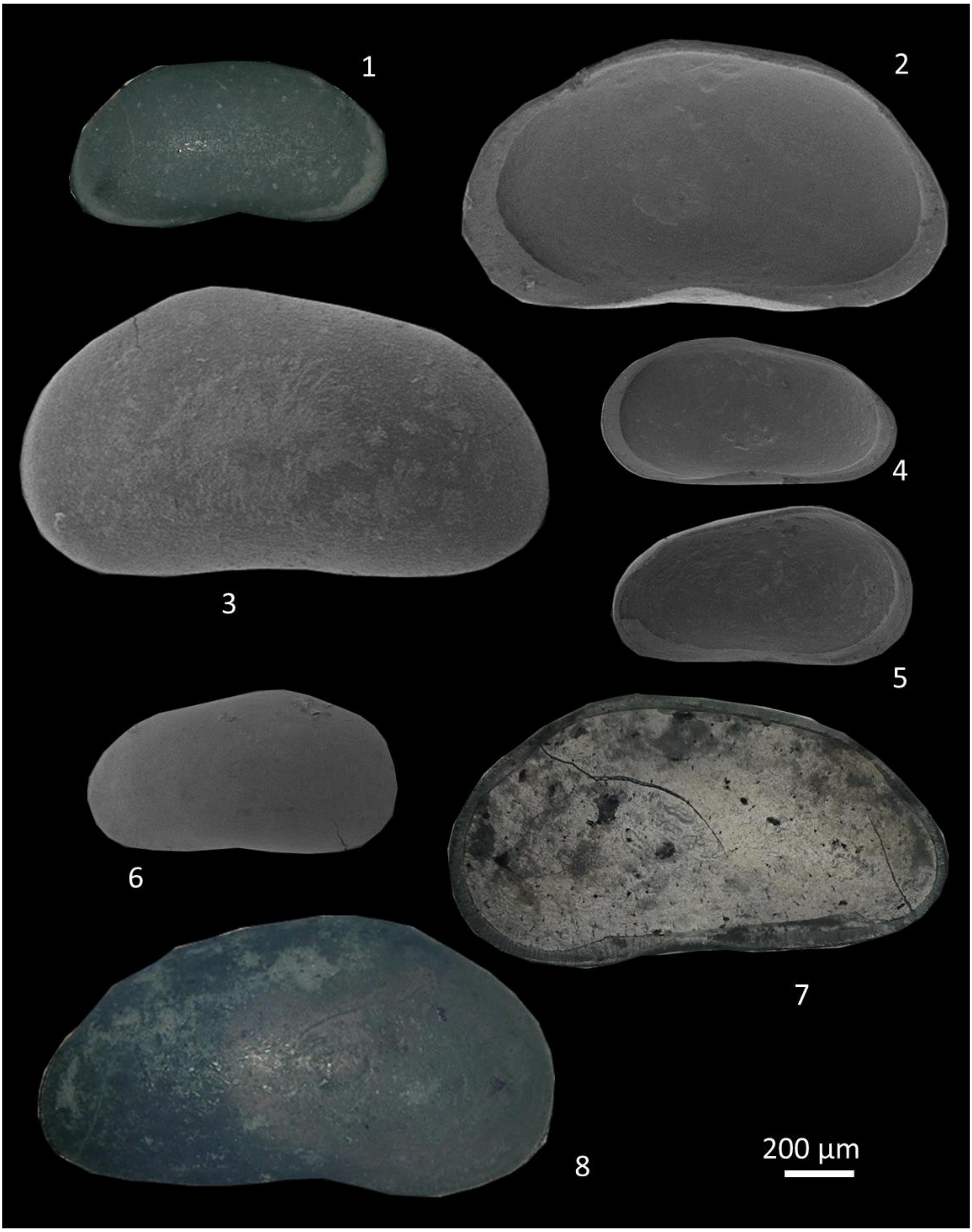

Fig.3: *Eucypris cf. zandaensis* Yang, 1982 (1) LV, ext., sample Z095; (2) a. RV int., sample Z096; *Paraeucypris* sp. (3) RV ext., sample Z053; (4) LV int., sample Z053; (5) RV int., sample Z053; (6) LV int., sample Z053; ?*Trajancypris* sp. (7) RV ext sample Z018; (8) RV int sample Z018

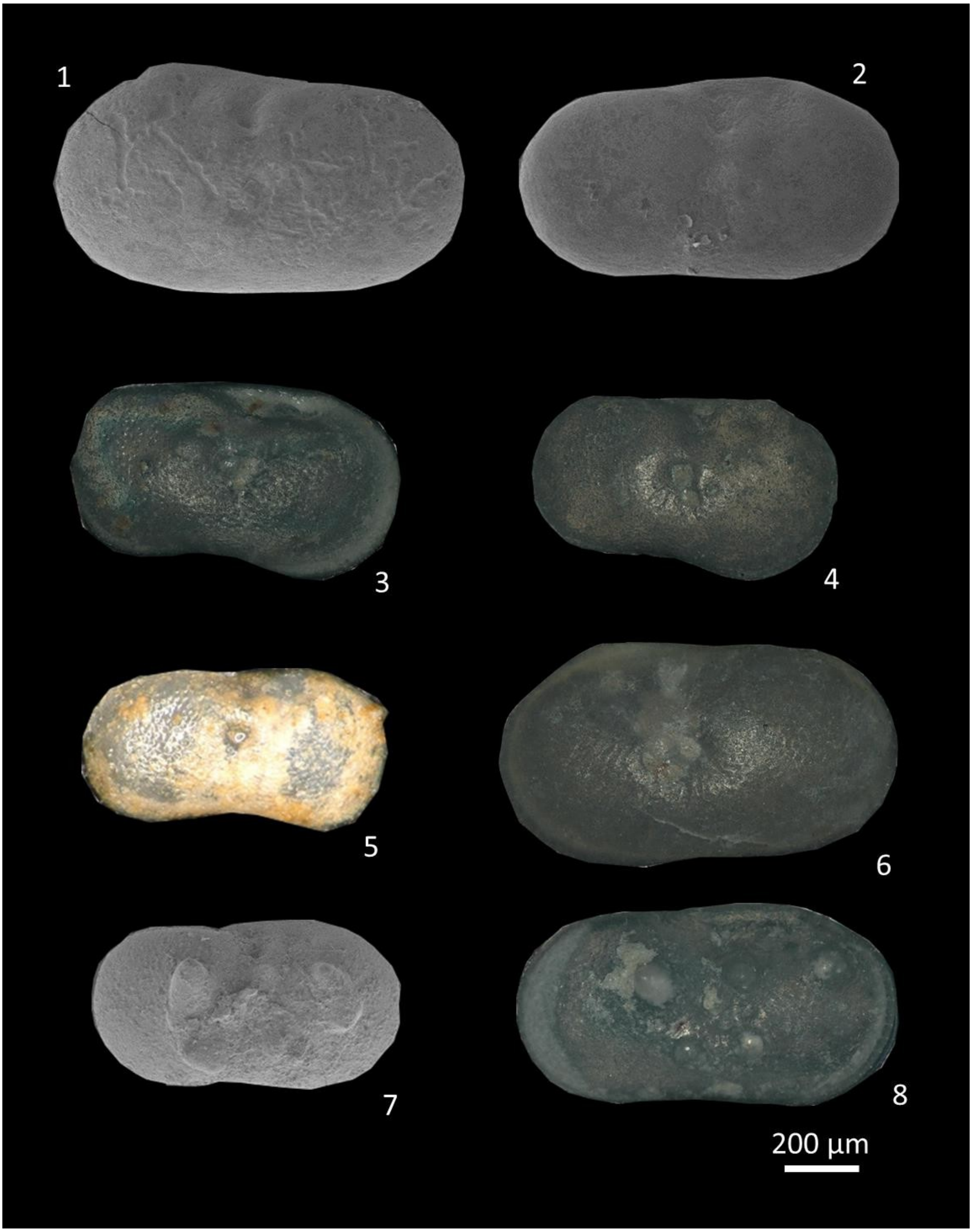

Fig.4: *Ilyocypris* spp. (1) LV, ext., sample Z010; (2) RV, ext sample Z010; (3) RV, ext., sample Z010; (4) RV, ext., sample Z010; (5) RV, ext., sample Z010; (6) LV, ext., sample Z010; (7) RV, ext., Z093; (8) RV, ext., sample Z010

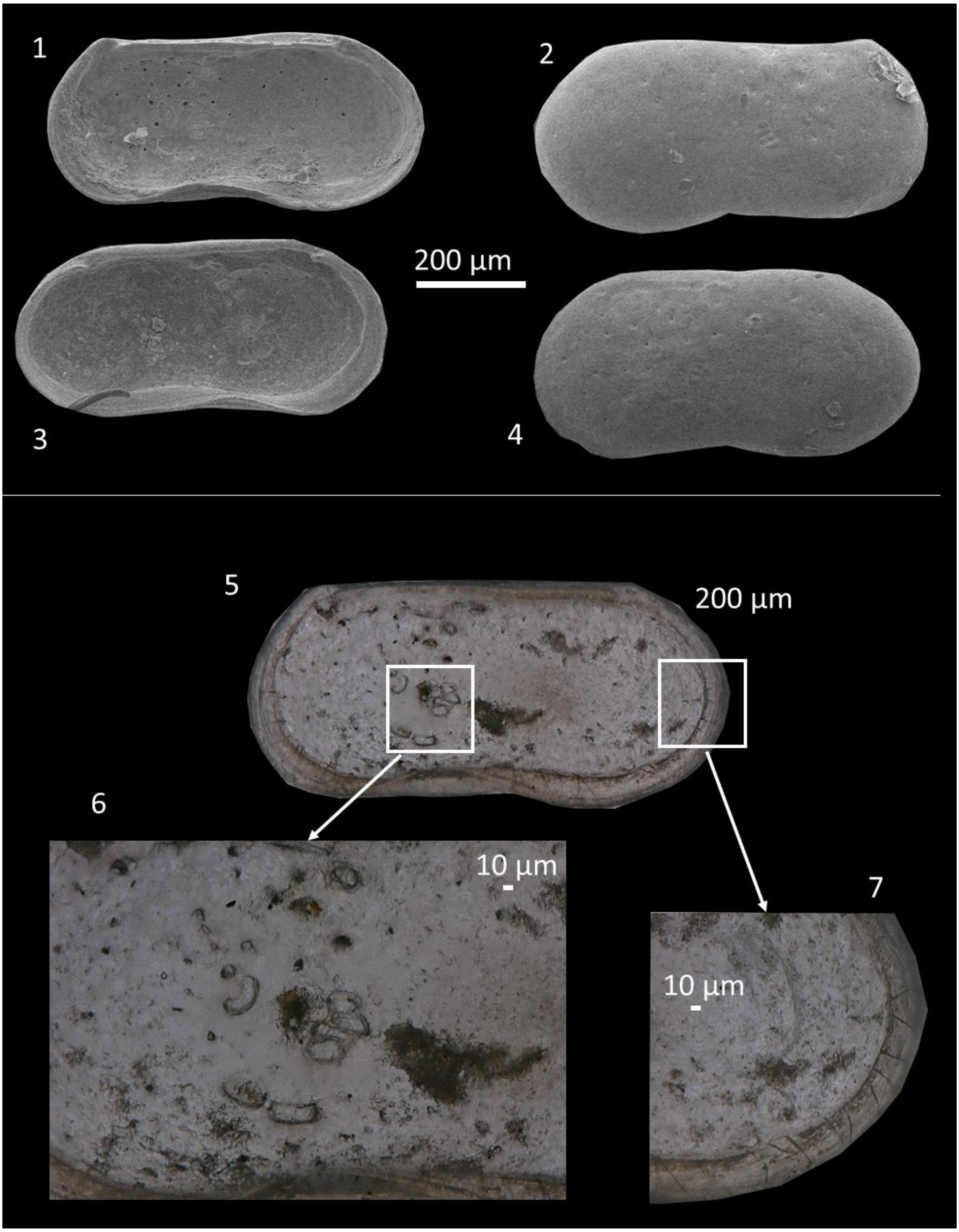

Fig.5: *Leucocytherella dangeloi* Alivernini sp. nov. (1) RV, int., sample Z068; (2) RV ext., sample Z069; (3) LV int., sample Z068; (4) LV ext., sample Z069; (5) RV int., sample Z068; (6) muscle scars; (7) marginal pores

Chapter 5 - *Synthesis*

In the three conducted studies ostracod taxonomy, lake levels variations and related climate changes were discussed. The lake level evolution of the Taro Co system for the last 40 ka and Tangra Yumco system for the last 17 ka were reconstructed using different approaches: The first study was conducted on the Taro Co lake system. Its Late Quaternary history was investigated to reconstruct local hydrological conditions and the regional moisture availability. For this aim, ostracod-based water depth and habitat reconstructions combined with OSL and radiocarbon dating were performed to better understand lake system evolution. The results show a high-stand at 36.1 ka before present which represents the highest lake level since then related to a wet stage and resulting in a merging of Taro Co and its neighbouring lakes Zabuye and Lagkor Co. The lake level then decreased and reached its minimum around 30 ka. After c. 20 ka, the lake rose above the present day level. A minor low-stand, with colder and drier conditions, is documented at 12.5 cal. ka BP. Taro Co, Zabuye and Lagkor Co formed one large lake with a corresponding high-stand during the early Holocene (11.2–9.7 cal. ka BP). After this Holocene lake level maximum, all three lakes shrank, probably related to drier conditions, and the lakes became separated from Taro Co. The accelerating lake-level decrease of Taro Co was interrupted by a short-term lake level rise after 2 ka BP, probably related to minor variations of the monsoonal components. A last minor high-stand occurred at about 0.8 ka before today. The remodelled chronology applied to the previous works of Ma *et al.* (2014) and Guo *et al.* (2016) allowed a direct comparison among the different reconstructions.

The second study concerned the Tangra Yumco lake system, located about 240 km east of Taro Co in the central–southern part of the Tibetan Plateau. The extension and position of this lake system makes it valuable for reconstructing palaeoclimatic variations through the lake history and to compare both with the adjacent lake systems. We reconstructed Late Quaternary lake level changes based on data from two lacustrine sediment cores. A micropalaeontological analysis focusing on Ostracoda was carried out combined with dating ^{14}C, ^{210}Pb, ^{137}Cs), sedimentology and stable isotope data from bulk sediment. An ostracod-based transfer function for specific conductivity was applied to assess and refine the reconstruction of lake level changes and to compare the results with other reconstructions from the Tibetan Plateau for evaluating inter-regional climatic patterns. The synthesis of ostracod-based environmental reconstruction and chronology for samples from Tangra Yumco reveals the evolution of the lake system during the past 17 ka. A low lake level around 17 cal ka BP is followed by a recovering until a high stand around 8–9 cal ka BP. Subsequently, between 7.7 and 2.5 cal ka BP, the lake level remained relatively stable with a subsequent short-living lowstand–highstand cycle at around 2 ka. Thereafter, the ostracod-based conductivity transfer function shows a decrease of conductivity corresponding to a lake level rising phase at around 0.4 ka. The recorded changes are indicators of past climatic conditions and refine the palaeoclimatic models in this area.

Among the two lake systems several synchronous trends were highlighted:

1) A general growth of the water bodies between 14-10 ka with a fluctuation of the lake levels at around 12-11 ka. In this case, the only information available were the ostracod fauna (Taro Co and Tangra Yumco) and stable oxygen isotopes from bulk sediment (Tangra Yumco).

2) An increase of the lake levels during the early Holocene, with a corresponding highstand at around 10-9 ka. For Taro Co no ostracod assemblage was available, and the reconstruction was carried out by sedimentology. Concerning Tangra Yumco, however, the transfer function was able to assess the increasing trend and to evaluate interaction among lakes of this system.

3) In the following, a progressive general lowering of the lakes happened. During the Early and Middle Holocene the quantity of obtained samples was scarce and consequently, information about ostracod fauna is poor.

4) A minor lowstand-highstand sequence occurred between 2 and 0.8 ka. Concerning Tangra Yumco this was assessed already in the previous work of Ahlborn *et al*. (2016) and was confirmed by the ostracod-based transfer function. Taro Co's assemblages were useful to give an evaluation of the highstand at this point.

The third study focuses on ostracod associations of the Zhada Basin located in the western Tibetan Plateau. In this area almost no taxonomical studies were carried out so far, and, aiming to a future use of ostracods as palaeoenvironmental proxy for this sector of the Tibetan Plateau, a documentation of several unknown species was performed. This work increases the taxonomical knowledge and sets up a database for further studies on the poorly studied Pleistocene and Neogene sediments, especially in the western part of the Tibetan Plateau.

Our list of ostracod taxa from the Zhada Basin contains at least eight species, several of them are already described for the Tibetan Plateau. Among them *L. sinensis* is the most abundant species often observed together with ?*L. dorsotuberosa* and ?*L. postilirata* like known for recent faunas (e.g. Wrozyna *et al*., 2009b, Akita *et al*., 2016). Wrozyna (in Kempf *et al*., 2009) lists only five species from the Zhada Basin. One of them, *Candona xizangensis* Huang, 1982, was not found in our study. We assume the harsh environmental conditions of the high elevation to be the cause for the low diversity observed. The taxa from the Zhada Basin and also known from the recent ostracod fauna of the Tibetan Plateau are mainly lacustrine species indicating lake sediments for most samples. The ostracod-based palaeoenvironment of the sediment varies from estuarine-like to moderately deep lacustrine water. The new species *Leucocytherella dangeloi* sp. nov. is very interesting for the evolution of the genus *Leucocytherella* Huang, 1982 endemic to the Tibetan Plateau and points to a lacustrine habitat as well. Species in open nomenclature as *Ilyocypris* spp., *Paraeucypris* sp., *Eucypris* cf. *zandaensis* and ?*Trajancypris* sp. need more material and further studies to be classified on the species level.

Based on the taxonomical analysis and more sample material a quantitative palaeoecological analysis of ostracod faunas from the Plio-Pleistocene Zhada Basin will enable new palaeoenvironmental and palaeoclimatic reconstructions.

Chapter 6 - Discussion

6.1 *Analysis of methods used*

6.1.1 *Ostracoda*

In this thesis the use of ostracods as tools to achieve and refine lake-level curves was discussed in the included articles. One of the most useful points for this group of Crustacea is their sensitivity to the environmental changes and consequently their use for transfer functions. This tool for the Taro Co lake system's case, offered to evaluate a range of previous water depth for the sampling points. This could be particularly valuable in case of difficult facies attribution for the assumed ancient shorelines. However, the difference in RMSEP with the previous article of Guo *et al*. (2016) suggests the necessity of a reliable taxonomical and ecological ostracod dataset because bigger uncertainties would blur the transfer function's potential. Another important issue is a stable lake system for reliable water depth estimates. Greater salinity or productivity changes would distort the results of the water depth estimates increasing the inaccuracies.

Concerning the Tangra Yumco lake system another important point related to the ostracod-based conductivity transfer function is the possibility to reconstruct, in association with the stable oxygen isotopes, the interactions among lakes and their possible conductivity conditions in a specific time frame. Also in this case, the technique has the limitations of the ostracod dataset, as long as if they do not have a narrow range of conductivity tolerance their transfer functions will show a high error. Another problem, like for Tangra Yumco and Tanqung Co interaction around 10 ka, the ostracod assemblage's answers could be affected by the interactions among the water bodies and not only by difference in water level and the assemblages should be always considered within more proxies to achieve a reliable reconstruction.

6.1.2 *Dating*

The dating methods used for this work were OSL and ^{14}C and the combined use of the two methodologies avoided problems often associated with organic material for ^{14}C, difficult to obtain on paleoshorelines or affected by hard water effects (Berger *et al*., 2002, Li *et al*., 2002, Forman *et al.* 2006, Lee *et al*., 2009). Problems related to the particle sizes of the sediment are relevant for OSL dating.

OSL dating is based on time-dependent dosimetric properties of quartz and feldspar (Aitken, 1998) and provides an estimate of the time since mineral grains, like quartz and K-feldspar, were last exposed to sunlight prior to ultimate burial. However, recent work comparing independently dated sediments with luminescence ages based on feldspars has shown that, at least in some circumstances, feldspars underestimate the age (Wallinga *et al*., 2001). Many feldspars suffer from a phenomenon known as 'anomalous fading' whereby charge trapped within the crystal that is predicted to be stable for periods of hundreds of thousands of years, or more, can be observed to decrease during laboratory experiments lasting a few tens of days (Duller, 2004). In this work we used quartz grains, unaffected by anomalous fading (Duller, 2004), and fading test were not necessary.

Other problems affecting the reliability of the OSL dating of Quaternary sediments are (1) the possible exposure of some grains to sufficient daylight to reset pre-existing luminescence signals, and (2) some grains that received little or no exposure to daylight and hence retained a large signal at deposition (Duller, 2004). For the first case, it would be necessary to use methodologies based on the scatter in OSL results, the form of the optical decay curve or the comparison of different luminescence signals (Wallinga *et al*., 2001). If these methods are not applicable, the age obtained should be interpreted as a maximum age for the deposits.

The second point could be related to the presence of turbid water in lacustrine environments, where the intensity of the light is greatly reduced, and the spectrum of the light is restricted (Wallinga *et al*., 2001). As a consequence, some trapped charge might remain at the time of deposition and burial of the grains. As luminescence measurements cannot distinguish between charge trapped before and after burial, such remaining trapped charge may lead to a significant overestimation of the luminescence age. In this case Duller (2004) suggests to check the variations of single aliquots of grains (in extreme cases, among single grains), to check the variability of light exposure and eventually to identify samples with ages that may be suspect.

Radiocarbon dating has been the most commonly applied method to establish chronologies for Quaternary records. Unfortunately, dating sediments on the Tibetan Plateau is a challenge since most of the lacustrine archives are affected by a reservoir effect varying from lake to lake and can be as high as >6000 years (Hou *et al*., 2012). Different approaches have been used to determine the reservoir effect and overcome this hurdle in establishing reliable and robust chronologies in individual lakes. However, a uniform and effective method has not yet been established. To solve this problem, it is common to obtain an age from the sediment–water interface or modern water plant which is subtracted from the other ages using the assumption of a constant reservoir effect over time (Hou *et al*., 2012; Kasper *et al*., 2012; Mischke *et al.,* 2013). Recently, radiocarbon-based chronologies for the late Holocene have been evaluated using palaeomagnetic secular variation data from lake sediments and they proved to be a valuable tool (Kasper *et al*., 2012; Ahlborn *et al*., 2015; Haberzettl *et al*., 2015), in combination with measurements on ^{210}Pb and ^{137}Cs activity on the uppermost part of the cores. Haberzettl *et al*. (2015), through magnetostratigraphy and ^{210}Pb measurements, corrected the previously reported reservoir effect and determined a new one of 120 ± 30 years for the late Holocene sediments from Taro Co. Following Guo *et al.* (2016) and Ma *et al*. (2014), our results would not be chronologically in phase for the Taro Co lake system but, after the dating correction of Haberzettl *et al*. (2015), their results are comparable with those discussed in the present study.

6.1.3 *Ancient shorelines and lake horizon identification*

In general, one of the most difficult problem for the reliability of the lake level reconstruction on the Tibetan Plateau are the sequences were the lake level was lower than present, because their presence could be hidden or eroded by the lake's water. For the Tibetan lakes it could be very relevant during the LGM, where the majority of the water bodies dropped strongly. In this case coring inside the basins are necessary to assess their depth during this lower phases. If shorelines or phases of lake sedimentation of previous higher lake levels are not easily recognisable or sortable, the ostracod association combined with sedimentology could be a further proxy to discern them by evaluating their palaeoenvironments.

6.2 *Palaeoclimate reconstruction*

6.2.1 *Factors influencing the Tibetan Plateau lakes' evolution and their study*

In general differences between the observed lake records may be not only related to climate factors. Other important components could be the tectonic impact on climate and hydrography of lake systems. In a large scale, the uplift of the Tibetan Plateau, which began 50 Ma ago (An *et al*., 2001), is considered the primary cause of monsoon initiation and intensification (Kutzbach *et al*., 1989; Yanai *et al*., 1992; Zhang *et al*., 2015). Concerning the period between the Late Miocene until recent times the NE Tibetan Plateau was best investigated (e.g. An *et al*., 2001 Zhang *et al*., 2007), showing accelerated uplift and differential rotation phases from 8 ka until recent times (Li *et al*., 2014b). The tectonic trend reported in literature is in phase with the one of Tangra Yumco and Taro Co lake system levels, where a general aridification from ca. 8 ka is reported. In this work time-frame, however, if the tectonic could be an important factor to cause the opening or closing of lake systems, it is difficult to assess a direct climate influence for the considered area, mainly because the short period of time considered. In order to evaluate on a smaller time-scale the climate response to the tectonic in the studied area, it is still to assess if the whole Tibetan Plateau has been subjected to a similar or a differential compression among its sub-regions, which has been not investigated so far. Anyhow, concerning the investigated lakes Armijo *et al*. (1986) consider neotectonics probably with only a minor role in the lakes interaction in this region.

The Asian monsoon system interplay with the mid-latitude westerlies over large parts of China (fig. 2) is considered the most important factor which controls the climate on the Tibetan

Plateau (Wang *et al*., 2001; Hu *et al*., 2008; Liu *et al*., 2014). The existing paleoclimate records on the Tibetan Plateau disagree on the timing and nature of climate change and it is unclear whether these differences are due to hydroclimatic spatial heterogeneity or due to differences between proxies. Furthermore, it is difficult to distinguish between the influence of different moisture sources using existing individual proxy reconstructions. In addition, summer monsoon and extratropical circulation are controlled by different forcing mechanisms on millennial and orbital time scales. For this, the relative predominance of monsoons and westerlies are still uncertain, mainly due to the different methodologies used as well as many interpretations lack an in-depth discussion of interacting processes which are fundamental preconditions for the understanding of hydro-climatic variations over longer time scales. However, in the last decades several studies discussed the possibility to bound and reconstruct the single forces driving the moisture availability on the Tibetan Plateau, e.g. Hou *et al*., (2017) reconstruct the Indian summer monsoon influence using leaf wax δD records. The results showed a moderate

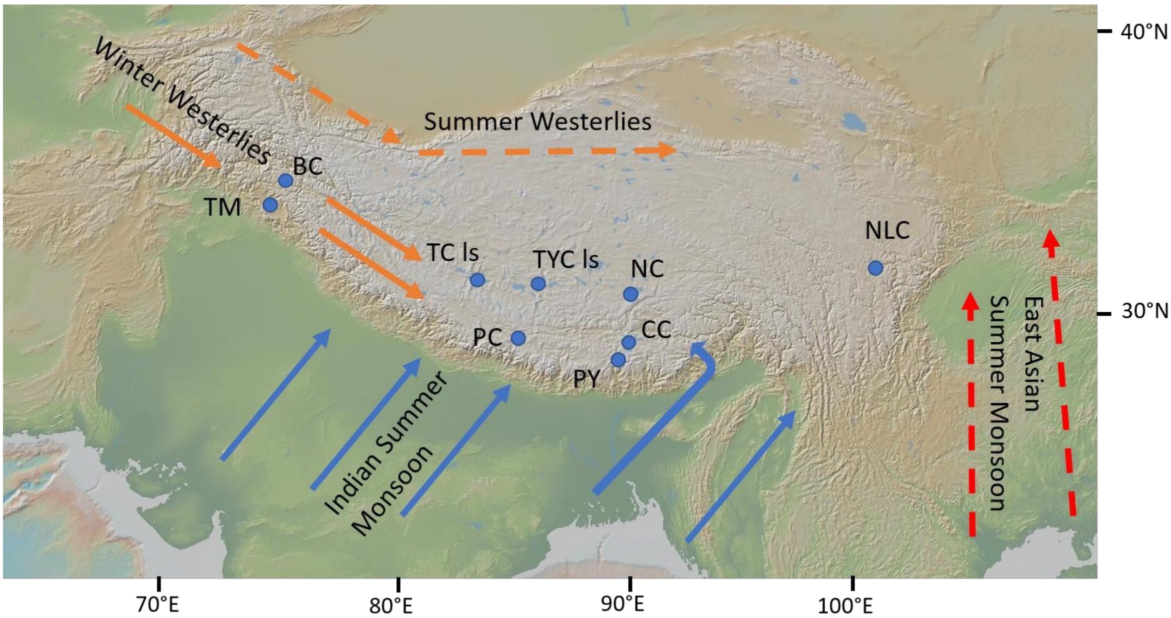

Figure 2: Major atmospheric circulation pattern on the Tibetan Plateau derived after Wünnemann *et al*., 2018. Coloured arrows: Indian summer monsoon (blue), East Asian summer monsoon (dotted red); major position of westerly jet in winter (orange) and summer (dotted orange). The full names for the discussed lakes are given in fig. 1.

influence of this force during the Late Pleistocene and from the Middle to the Late Holocene, suggesting drier periods during these time intervals, which is in general phase with the results of the present study. Concerning the Asian summer monsoon evolution, several studies proposed a migration of the Asian summer monsoon deep into the interior of the plateau during the early and middle Holocene followed by a general decline of summer monsoon strength after about 6 ka (e.g. Gasse *et al*., 1991; Yao *et al*., 1997; Qiang *et al*., 2017). Its boundary detection is limited at the north-eastern part (Wünnemann *et al.,* 2018) of the Tibetan Plateau and so far it was not possible to distinguish clearly its penetration limit in the inner part, increasing the risk of a wrong interpretation if transferred directly to the southern and western area.

Another important factor that could potentially shift the lake level reconstructions is the meltwater influx in the considered lakes, but unfortunately there are no many references about a strong influence of the glaciers water overall the Tibetan Plateau in the literature. It is, however, considered a possible important factor only for the lakes close to the Himalaya chain (e.g. Zhang *et al*., 2012; Wünnemann *et al*., 2015). In Taro Co, Guo *et al*. (2016) consider this input present but not dominant.

Because of all these reasons, a comparison of synchronisms among different lakes on the Tibetan Plateau needs a detailed analysis and interpretation between the individual factors, which is not always available. For the comparison lakes have therefore been considered in which the analyses envisaged research approaches based on palaeobiological, sedimentary and / or geochemical components, although obviously this is not a safety index on their complete reliability. However, a temporal correlation between the different lakes is made difficult by the time intervals considered in the various works, of which most consider phases since 20 ka and rarely before.

6.2.2 *Synchronicity and general trends on the Southern Tibetan Plateau*

This thesis evaluates and compares the results among the investigated lake systems of Tangra Yumco and Taro Co with other lakes on the southern part of the Tibetan Plateau. Concerning this, we considered water bodies already investigated by several authors along a west-east transect, in order to check possible synchronicity with Tangra Yumco and Taro Co evolution (fig. 3):

Considering the first stage (40-30 ka) for the southern Tibetan Plateau we have information only about the already discussed Taro Co lake system and for Paiku Co (Wünnemann *et al*., 2015) with different trends reported. Taro Co shows a high lake level followed by a fast decline between 35 and 30 ka, Paiku Co a generally increasing trend. The only possible confirmation of this different trend is related to works on the northern part of the Plateau, where a large-scale increasing of water bodies is reported by Zheng *et al*. (2005). However, the general lack of information and the different condition of Paiku Co where probably meltwater plays a bigger role than in Taro Co could be also an explanation for the different water bodies evolution, especially in case of warm conditions.

During the time frame 30-25 ka Taro Co shows stable conditions followed by a rising of the lake level. This process is not in phase with the lake reconstructions of Paiku Co and Chen Co, where a stable to decreasing and a falling lake level are reported, respectively. This could be related to a bigger influence of the winter westerlies on the region meeting more the western part and a weaker Indian monsoonal component.

In the third stage (25-22 ka) Chen Co lake level continued to fall, whilst Paiku Co passed from stable to increasing conditions and Taro Co rose. Following the precedent statement, a possible intensification of the winter westerlies with a correspondent decreasing influence from west to east is a potential explanation, although for these firsts three stages, the dataset is still too scarce to elaborate a more detailed climate evolution of the area.

During the fourth stage (22-18 ka) a general increasing trend for almost all the lakes considered is reported, with the only exception of Paiku Co. In this case a possible reinforcing of the Indian Monsoon component could be also taken in consideration following its differential spreading through the Himalayan chain (Wünnemann *et al*., 2018) meeting Chen Co and Nam Co but with negligible or no effect on Paiku Co.

In the following stage (18-14 ka) the general reconstructed climate conditions were splitted in two regions, with the transect from Tso Moriri to Nam Co registering increasing of lake levels, and the eastern and south eastern part with a falling lake level. The only exception is Taro Co, where, however, the lacking of data in the dataset during this period could suggest a slightly different trend, where the lake level is still rising. The general tendency suggests a major role of the Westerlies compared to the Indian Monsoon at this time frame.

The fifth stage (14-10 ka) is characterised by a general increasing trend for all the lakes considered. Almost all records report fluctuations at around 12-11 ka, reflecting variations in the intensity of the circulation factors at the transition to the Holocene, confirming the investigated trend of the ostracod assemblages and $\delta^{18}O$ for Taro Co and Tangra Yumco.

After this interval, between 10-7 ka, lake levels generally fell after a highstand at around 9-8 ka, with the only exception of Chen Co. It is difficult to evaluate the different response of Chen Co, where local factors like meltwater input are predominant (Zhu *et al*., 2003) and dating should be revised following Haberzettl *et al*. (2015).

In the last stage (7-0.4 ka), the lakes follow a discontinuous negative trend. Important fluctuations between 3-0.8 ka is reported for Tso Moriri (1.1-0.4 ka) Taro Co (2-0.8 ka), Tangra Yumco (2.3-1.8 ka), Nam Co (2.4-1.8 ka), Puma Yumco (~2 ka) and Bangong Co (2.2-1.2 ka).

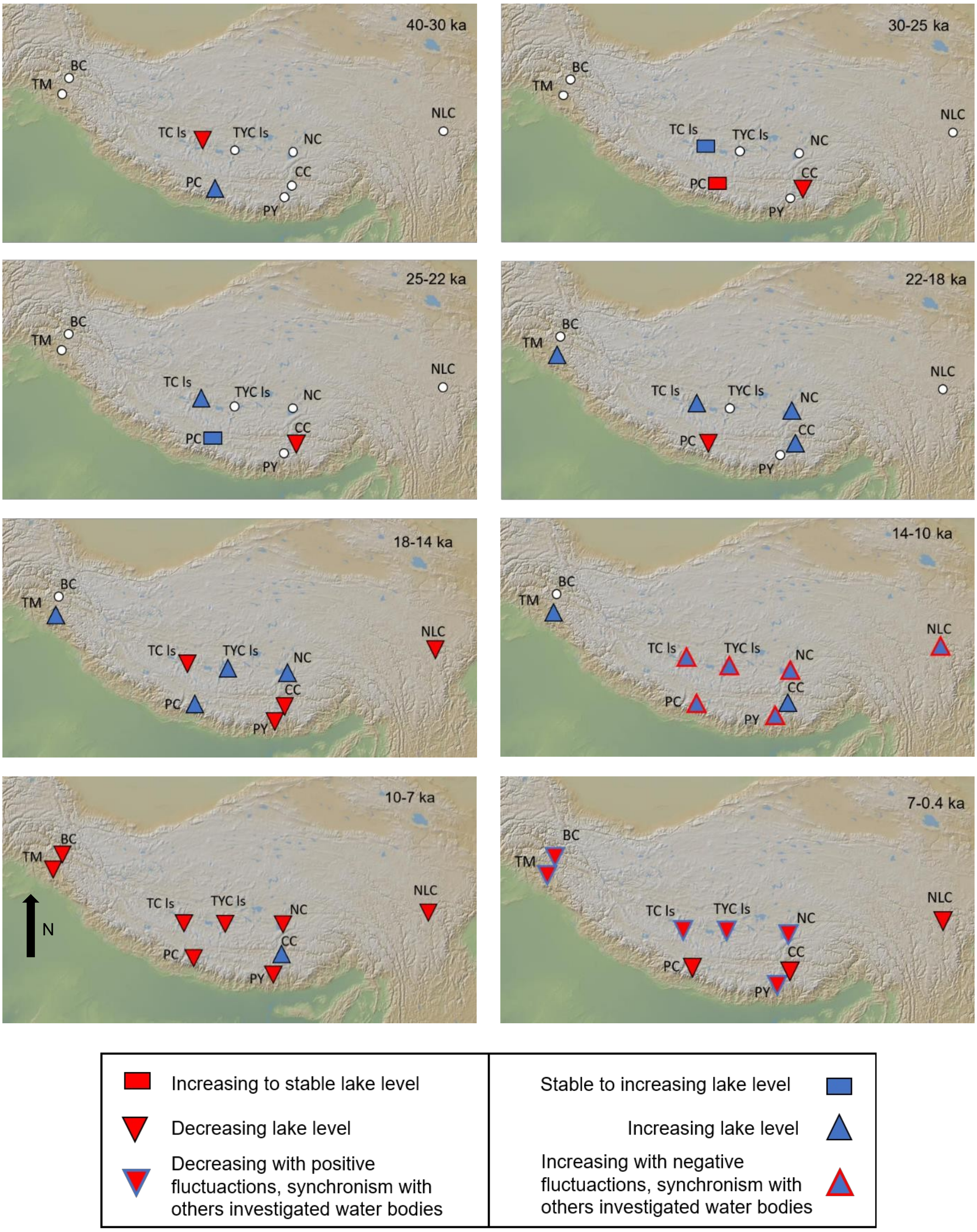

Figure 3: Lake level evolution for the considered water bodies in the period 40-0.4 ka. The white points indicate lacking of information for the correspondent time frame. The better general synchronicity of lake evolution from 14 ka is evident, where more information are available. For the name of the lakes see fig. 1.

Considering the uncertainties of the chronological model for the Tso Moriri core (Peng *et al.,* 2013; Leipe *et al*. 2014) and the time-lag for this event comparing the two records we assume a possible synchronous timing. This last sequence is probably related to minor variations of the monsoonal components in the considered lakes (Kasper *et al*. 2012, Ahlborn *et al*. 2016). As fig. 2 suggests, the lakes present in the northern part of the Tibetan Plateau are not easily comparable to the southern lakes, because of the influence of the East Asian Summer Monsoon and of the Summer Westerlies. However, the climate reconstruction for lake Kuhai (Wünnemann *et al*., 2018) shows the hydro-climatic optimum with the highest lake level during the middle Holocene shifted about 1-2 ka later compared to the southern lakes, probably due to the influence of the East Asian Summer Monsoon, negligible in the considered lakes. Anyhow, a strong decline afterwards due to climate deterioration is also reported, showing the general weakness of influence of the summer monsoonal components.

Chapter 7 - Conclusion and outlook

This thesis is part of the research on the Tibetan Plateau climate evolution, investigating two different lake systems according to ostracod-based approaches. To prove the reliability of the present study's lake level reconstructions, possible synchronisms or asynchronisms with others Tibetan water bodies were checked and evaluated. An additional work to characterize the poorly studied ostracods fauna of Zhada Basin was carried out. Concerning the scientific questions of this study it was possible to give the following answers:

1) The evolution of the lake level of the Taro Co lake system can be divided into five main phases: (1) at about 36 ka BP, the presence of a Late Pleistocene highstand, with the three lakes merged together; (2) since then, a rapid decline in lake level during a dry phase between 35 and 23 ka before the present day; (3) the three lake basins were combined into one large lake during the early and middle Holocene. The lake reached the highest level of the entire Holocene during c. 11.2–9.7 ka cal BP; (4) Lagkor Co was separated from Taro Co at around 7 ka and Zabuye Lake was separated at around 3.5 ka; (5) a least a minor high stand occurred at about 0.8 ka before present.

2) The lake level evolution of the Tangra Yumco lake system as refined with the ostracod-based transfer function and the $\delta^{18}O$ analysis can be divided into six main phases; (1) in the oldest stage (17–10.5 ka) of generally increasing lake levels. (2) At around 10 ka, a decrease of conductivity explained by a switch from an open to a closed lake basin; (3) between 9.8 and 7.5cal ka BP progressive lowering of the lake level. This trend is also confirmed by $\delta^{18}O$ analysis. (4) During the period 7.5–3.7 cal ka BP the general lack of data does not allow a more precise reconstruction, but the moderate trend of increasing $\delta^{18}O$ could be related to a decrease of the lake level; (5) after this, the conductivity is in general in good agreement with Ahlborn *et al.*'s (2016) lake level curve, especially around 2 ka, where the fast switch of decreasing and later increasing lake level is synchronously mirrored by the conductivity curve; (6) thereafter, the conductivity, $\delta^{18}O$ and lake level curve agree until 0.4 ka, where the conductivity starts to decrease earlier than the rise of the lake level and the positive shift of $\delta^{18}O$.

3) The general trends and the synchronicity of the studied lakes compared with other lakes on the Tibetan Plateau were mostly recognisable. Especially in the time frame after 18 ka, where more information are available, our results correspond with only some time-shift, probably due to different dating or different exposure to the Indian Monsoon and the Westerlies.

4) Our taxonomic work highlights the presence of several ostracod taxa in the Zhada Basin, correspondent as well as not correspondent to species already described on the Tibetan

Plateau so far. The new species *Leucocytherella dangeloi* shows a higher rounding in the posterior part and a general weaker ornamentation than in *Leucocytherella sinensis*. It was possible to classify it as distinct species. *Ilyocypris* spp. belong probably to three different species, although for the complexity of the taxonomical classification of this genus, further work is needed as well as for the species in open nomenclature: *Ilyocypris* spp., *Paraeucypris* sp., *Eucypris* cf. *zandaensis* and ?*Trajancypris* sp. The taxa from the Zhada Basin are mainly lacustrine species indicating lake sediments for most samples. Based on the taxonomical analysis and more sample material a quantitative palaeoecological analysis of ostracod faunas from the Plio-Pleistocene Zhada Basin will enable new palaeoenvironmental and palaeoclimatic reconstructions.

The multi-proxy approach including micropalaeontology, sedimentology and dating in both the lakes was proven to be a valuable tool for lake level reconstructing and their refining. However, several time frames for both the lake systems are still with incomplete datasets and further sampling and dating to cover that intervals are needed. Another necessary point should be an additional work to assess the ostracods' (palaeo)ecology in these water bodies, especially based on living individuals. A more complete dataset could reduce the errors intervals for the ostracod-based transfer functions for both depth and conductivity, allowing a better level of detail in reconstructions.

Regarding the investigated lake systems' evolution a very interesting point would be the influence of tectonic, meltwaters or underground springs in these water bodies. The evaluation of their impact would be of great interest to better assess the impact of westerlies and summer monsoons in this area.

The most incomplete lakes dataset for the whole region is the western part mainly due to its difficult accessibility. As already mentioned in the previous paragraphs only a few works were carried out so far and almost nothing concerning ostracods. Because of the relative isolation and the possibility of endemisms additional taxonomical and (palaeo)ecological work on the local faunal assemblages is needed. The present study in the Zhada basin starts with taxonomical work in the area and time frame, but in the future further work is needed.

The comparison among lakes from the southern part of the Tibetan Plateau showed several critical points, due to the fact that lake level records are based mainly on different proxies and it is not easy to resolve the variable influence of the moisture sources. Good opportunities are the stable oxygen isotopes that can shed some more light on this aspect to check the dominant factors (e.g. Yao *et al* 2013; Maussion *et al*., 2014 Li and Garzione, 2017) and are able to distinguish impact of local recycled /convective water resources and/or mixture with westerlies or monsoonal components.

The evaluation of the circulation pattern is another crucial point. Although some boundaries of the monsoonal and westerlies components' influence were detected (e.g. Polanski *et al*., 2013;

Chiang *et al*., 2015; Wünnemann *et al*., 2018) their seasonal interplay in the most internal part of the Tibetan Plateau is still to assess. Reanalysis data show that the moisture transport from the Bay of Bengal is blocked by the Himalayan mountains and redirected north-eastwards and not directly transported to the Tibetan Plateau (Maussion *et al*. 2014). Thus, the sources of monsoonal air masses and the transport route are still unknown and setting up and refining of climate models is needed.

Misinterpretation due to uncertain chronologies and poor understanding of the proxies (Mischke *et al*. 2010b, Opitz *et al*. 2015) are a problem for palaeoclimatic reconstructions. To scope with this problem, the multi-proxies approach of Tangra Yumco and Taro Co proved to be a suitable method. As valid chronologies are a crucial precondition for climate reconstruction (Haberzettl *et al*., 2015) more effort should be spent on this, also re-calibrating previous works in order to compare easier the different lake evolutions.

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I hereby certify that this thesis has been composed by me and is based on my own work, unless stated otherwise. No other person's work has been used without due acknowledgement in this thesis. All references have been quoted and all sources of information have been specifically acknowledged.

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