Climate cyclicity, tectonic pulses and autocyclicity in alluvial fan sediments in the Weihe Basin


Abstract

Core LYH-1 was drilled near the northern margin of the Weihe Basin, in Central China. Previous work showed that the uppermost 221 m of the core (representing the last ~1 Ma) contains sediments formed in a distal alluvial fan environment. Here we analyze the influence of tectonic and climatic forcing on the sedimentary sequence, in addition to autocyclic fan evolution. First, a refined age model is established, based on a correlation of the core’s lithofacies and magnetic susceptibility distribution to the loess-paleosol sequence of the nearby Chinese Loess Plateau (CLP). Subsequently, spectral analyses are performed on carbonate content, the relative grain size of bedload in the alluvial deposits and the relative contribution of fine suspension grained influx.

All proxies show Milankovitch/orbital cyclicities, consisting of eccentricity, obliquity and precession frequencies. Lower frequencies are likely caused by changes in long-term tectonic subsidence, higher frequencies by internal fan dynamics. The presence of orbital cycles provides evidence for climatic influence on sedimentation in the northern Weihe Basin. The strong precession frequency in grain size proxies is likely related to variations in the strength
Climate cyclicity, tectonic pulses and autocyclicity in alluvial fan sediments in the Weihe Basin of the East Asian Summer Monsoon, which varies in pace with solar insolation. Stronger monsoonal rainfall causes increased sediment transport on the alluvial fan system. Variations between detrital influx and carbonate content reflect the erodibility of the source area (CLP) and mean annual temperatures, which vary on a glacial-interglacial timescale. This explains the eccentricity and obliquity bands in magnetic susceptibility, carbonate content and grain size. For example, during interglacial times (eccentricity maxima), the warmer and wetter climate results in expansion of vegetation, reducing the erodibility of the catchment loess and therefore limiting the sediment supply to the alluvial fan system. Simultaneously, authigenic carbonates are formed due to higher temperatures and an increased contrast between the wet and dry seasons. During glacial times, the vegetation cover is reduced, resulting in increased erosion and sediment supply to the alluvial fans in the northern Weihe Basin.

Wavelet power spectra indicate that (climate) cycles are not continuously registered over the past 1 Ma. This is probably caused by autogenic variations of the sedimentary system and by changes in the preservation potential at the depositional site. The latter is best demonstrated by the influx of fine grained sediments, which contains a clear precession cycle from 1.0-0.65 Ma and from 0.25-0 Ma, while this cycle is less pronounced from 0.6-0.25 Ma. This can be explained by diminished tectonic subsidence over the latter period, which results in progradation and bypassing of the core site by the fan, leading to incomplete or even lost climate signals. Increased tectonic activity after 0.25 Ma is deduced from increasing amounts of alluvial deposits. At the onset of the last glacial, a sudden increase of sedimentation rate indicates tectonic displacement along the detachment fault in the northern Weihe Basin.

**6.1 Introduction**

The Weihe Basin in Central China (Fig. 6.1a; b) forms an ideal setting to investigate the combined effects of tectonics and climate change on sedimentary evolution. The basin is an intra-continental rift basin which experienced subsidence since approximately the Eocene (Zhang et al., 2003). As a result of complex tectonic motions along the northern part of the basin, sediments are routed and trapped in elongated intrabasinal depressions. An assemblage of active WSW-ENE orientated listric normal faults created a waveform morphology, consisting of fault-forced folds separated by depocenters (Lin et al., 2015; Fig. 6.1c). Core LYH-1 is drilled in the Luyang Wetland site, which is located in one of the depressions (Fig. 6.1).

Previous analyses on the core showed that the sediment infill represents a distal alluvial fan setting, characterized by sedimentary lithofacies alternations, representing variations in the progradation of the alluvial fan (chapters 3, 4). In addition to fan deposits, shallow ponds and playa lakes developed repeatedly when the fan retreated to a more distal position.

Adjustments in spatial extents of alluvial fans are driven by changes in the ‘sediment supply-to-discharge ratio’, which in turn are forced by climate change and tectonics (Blair and McPherson, 2009). For example, increased or even steady sediment supply results in fan aggradation, whereas a reduction in sediment supply may lead to fan retrogradation (Weissmann et al., 2002; Clarke, 2015). Tectonics generates accommodation space and the potential energy needed to allow sediment transfer (Frostick and Reid, 1987; Blair
Climate and tectonic influence on alluvial dynamics in the Weihe Basin, Central China and Bilodeau, 1988; Gawthorpe and Leeder, 2000; Withjack et al., 2002), whereas climate determines the hydrodynamic conditions and controls the spatial and temporal distribution of depositional agents. In addition, climatically induced variations in vegetation cover, weathering rate and sediment generation in the catchment exerts an important influence on the sediment supply (Quigley et al., 2007; Shellberg et al., 2016).

Thus far, knowledge regarding paleoclimate variation in the region of the Weihe Basin is primarily derived from the analysis of the loess-paleosol sequences in the Central Loess
The thick packages of windblown dust on the plateau shows a distinct variation between yellowish loess layers and darker paleosol layers, which in turn is linked to EAM variation in the region. The loess layers represent glacial climates when the East Asian Winter Monsoon (EAWM) is most powerful, and the soils represent interglacials and interstadials, when the East Asian Summer Monsoon (EASM) gains in strength. The EASM brings moisture to the area, which in combination with increased temperatures, promotes the widespread growth of vegetation and induces pedogenic alteration of the loess.

Like every other monsoonal system on earth, the East Asian Monsoon (EAM) is forced by fluctuations in solar insolation, which in turn are driven by cyclic variations in the Earth’s orbital parameters (Milankovitch cycles) (e.g. Sun et al., 2015). Precession controls to a large extent the seasonal cycle of incoming solar radiation and its spatial distribution. It is therefore considered to play a major role in monsoonal intensity (Ziegler et al., 2010; Peterse et al., 2014; Mohtadi et al., 2016). This is well demonstrated by precipitation reconstructions of the EASM, derived from high resolution speleothem δ¹⁸O records (Wang et al. 2001; 2008; Cheng et al. 2016). Cyclicity in this record shows an almost exclusive forcing by 19-23 kyr cycles, belonging to precession.

In addition to precession forcing, the dynamics of the EAM are also linked to forcing from eccentricity (dominantly 100 kyr) and obliquity (41 kyr) (Ding et al., 1995). These are often associated to effects of glacial-interglacial forcing, such as variations in ice volume or CO₂ concentrations (Mohtadi et al., 2016). Eccentricity and obliquity induced changes in cryosphere extent can alter oceanic and atmospheric circulation systems on glacial-interglacial time scales (Eagle et al., 2013). Growing ice-sheets in the northern hemisphere (including the ice-sheets on the Tibetan Plateau) will affect the position of the Siberian High and the trajectory of the Westerlies, which suppresses the influence of the EASM in the region of the Weihe Basin. In addition, growing ice sheets during glacial times will cause a sea level drop and eventually reduce moisture supply to the EASM (Griffiths et al., 2009).

In this chapter, data from the uppermost 221 m of core LYH-1 will be studied to evaluate the roles of tectonic forcing factors and Quaternary climate change in the development of the distal alluvial sequence in the northern Weihe Basin. The aim of this chapter is (1) to gain an understanding of how the sediment routing system responded to perturbations in their tectonic and climatic driving forces, (2) to analyze the alluvial fan sequence in the context of monsoonal variation, providing a dynamic explanation for the evolution of alluvial fan aggradation during the last 1 million years.

### 6.2 Setting and sediment infill of the northern Weihe Basin

#### 6.2.1 Setting

The Weihe Basin is part of a large and active rift system, which developed around the stable Ordos Block. Formation of this rift system is related to the uplift of the Qinling Mountains.
and the Tibetan Plateau to the South (Peltzer and Tapponnier, 1988; Zhang et al., 1995; 1998). The Weihe Basin received approximately 7000 m of terrestrial sediments since subsidence was initiated in Eocene time (Zhang et al., 2003). Due to the faster slip rates in the southern margin, the basin is slightly tilted (Rao et al., 2014).

Climate in the Weihe Basin is semi-arid (averaged precipitation is 573 mma.-1) and strongly influenced by variations in the EAM (Fig. 6.1a; Sun and Wang, 2005). The effect of the two monsoons can be observed on a seasonal basis with hot, humid summers and cold, dry winters. The summer monsoon creates a gradual decreasing precipitation trend from the south-east to the north-west, with highest precipitation in July. A dry continental northwesterly EAWM is dominant in glacial times, while a wet southeasterly EASM strengthened in interglacial times.

Core LYH-1 is drilled in a structurally controlled intrabasinal depression close to the northern margin of the Weihe Basin (Fig. 6.1). The basin is surrounded by the CLP in the north, the Qinling Mountains in the South, the northeastern part of the Tibetan Plateau in the west and the Tai Hang Mountains in the East (Fig. 6.1b). The exact drill site comprises a wetland complex of approximately 10 x 20 km, characterized by a wide variety of small ponds and alkaline soils. The Wei- and Yellow River originate from the northeastern Tibetan Plateau and merge in the southeastern part of the Weihe Basin to leave through the Sanmen Gorge. The Wei River flows parallel to the orientation of the basin, while the Yellow River flows in the eastern part (Fig. 6.1b). The most proximal rivers are the Luo River and the Sichuan River, which together with the more distant Jing River drain the CLP from the north. The Luo and Jing Rivers merge with the Wei River close to the southern margin of the Weihe Basin, while the Sichuan River is currently dry. In addition to these relatively large rivers, there are several gullies originating from the Beishan Mountains that cut through proximal alluvial fans and flow towards the drill site (Fig. 6.1c).

6.2.2 Sediment infill

The uppermost 221 m of core LYH-1 contains sediments with grain sizes in the range of clay to fine sand. The most outstanding characteristic of the sedimentary sequence as recorded by the core is the alternation between periods of enhanced detrital influx and periods with extensive evaporative concentration of mainly authigenic carbonates (chapters 3, 4). The sedimentary sequence in the core can be subdivided into five main lithofacies (Fig. 6.2), consisting of 1) eolian sediments, 2) fluvial deposits (thick banded relative coarse sediment), 3) lacustrine suspension deposits (thin banded and fine sediment) and rich in flora and fauna, 4) carbonate-rich playa deposits with abundant brine shrimp droppings (high salinity) and 5) soils (lack of sedimentary structures and irregular structures, e.g. gypsum growth). The lithofacies assemblage, in combination with the geographical location, is typical for a distal alluvial fan environment (chapter 3).
6.3 Material and methods

Core LYH is located at 34°480 43.4900 N, 109°310 53.9500 E (Fig. 6.1) and was drilled to a depth of ~1097 m. Previous research used a variety of analyses (e.g. micropaleontology, color reflectance, grain size distribution, magnetic susceptibility (MS), carbonate content, loss-on-ignition (LOI), XRF scanning, XRD and C:N analyses) to study the uppermost 221 m of the core (chapters 3, 4) magnetic susceptibility, color and grain size data will be addressed in this chapter.

Magnetic susceptibility (MS) is a dimensionless measure of the degree to which sediments can be magnetised during exposure to a magnetic field, which in turn depends on the amount of ferromagnetic minerals. These are derived from eroded soils. The MS signal in the core sediment thus represents allogenic influx (Ellwood et al., 2000) and will be used to fine-tune the age model (see below). MS measurements with a 10 cm resolution were carried out at the Nanjing Normal University by using a Bartington 779-ring set-up, while the core tube was still intact.

The color spectrum of the core was measured in a line scan on an Avaatech XRF core scanner in the Nanjing University, Nanjing (0.5 cm resolution). The lightness index (L*) correlates extremely well with carbonate content and is therefore used as its proxy.

Grain size analyses were performed on 2127 samples (10 cm resolution) following the method described in Konert and Vandenberghe (1997). Subsequently, the dataset was decomposed into 6 grain size end-members by the end-member modeling algorithm (EMMA) developed by Weltje (1997). The six end-members (EM1-6) have modes of 150 µm, 75 µm, 50 µm, 25 µm, 15 µm and 4-6 µm respectively. A detailed interpretation of the end-members is given in chapter 3. Here we use two indices based on the grain size end-member results. The ‘relative bedload grain size index’ (BGi) is defined:

\[
BGi = \frac{\sum_{i=1}^{2} pEM(i)}{\sum_{i=1}^{3} pEM(i)}
\]  

(6.1)

where pEM stands for the proportion of grain size end-members. EM1-3 are the coarsest grain size end-members. The ratio is used to study the occurrence of alluvial flooding and is a measure for the relative contribution of bedload grain size in alluvial deposits. The ratio makes the index independent from overall alluvial fluxes. The ‘relative contribution of fine grained index’ (FGi) is defined as the sum of the two finest grain size end-members:

\[
FGi = \sum_{i=5}^{6} pEM(i)
\]  

(6.2)

This index is used to analyze fine grained sediment flux (cf. chapter 3). Statistical data analyses were performed by using the ‘PAST’ software package (Hammer et al., 2001). We applied two types of time series analysis, available in the package. In order to identify
periodic components, we applied a Fast Fourier Transform (FFT) function using the REDFIT program (Schulz and Mudelsee, 2002). Continuous wavelet power spectra are calculated to visualize localized variations of power within the temporal record (Torrence and Compo, 1998). A Morlet basis function was used for these calculations. In order to conduct both time series analysis, the data was evenly spaced by using a constrained cubic spline function.

6.4 Results and interpretation

6.4.1 Refined age model

A preliminary age model of the uppermost 220 m of core LYH-1 was established by using paleomagnetic measurements (chapter 3). Our inclination record clearly shows that the ‘Blake-event’ and the B/M-boundary, both occurring in warm interglacial periods, are recorded in playa facies (chapter 3; Facies 4). These carbonate layers represent interglacial times when a stronger temperature contrast over different seasons promote evaporative concentration (chapter 4). To establish a refined age model, we therefore correlate the thick playa deposits to the well-dated paleosol layers in loess sequences on the CLP (Fig. 6.2).

Figure 6.2 - Comparison of the lithofacies model of core LYH-1 with the loess-paleosol stratigraphy of the CLP. Thick evaporite layers were deposited in interglacial times (chapter 4), and therefore correlated to the paleosol layers on the CLP.
The MS record of core LYH-1 is used to further fine-tune the age model. In the loess sequences on the CLP, MS is generally higher in interglacial periods, because the warm and wet climate conditions promote pedogenic alteration of the loess, which induces higher MS values due to increased amounts of low-coercivity ferromagnetic minerals like magnetite and maghemite (Song et al., 2014). However, in deltaic settings this proxy is positively related to detrital influx (Ellwood et al., 2000). A similar relationship is assumed for the sedimentation at the core site, because the magnetic minerals are dominantly composed of magnetite and hematite, whereas the carbonate-rich autogenic layers (Facies 4; chapter 3) are characterized by low concentrations of magnetic minerals. The MS record in the core is therefore opposite to those from loess sequences on the CLP, because allogenic influx carries magnetic susceptible minerals whereas the authigenic carbonates do not.

The MS of the top 220 m of core LYH-1 shows a strong resemblance with the benthic oxygen isotope record of Lisiecki and Raymo (2005) (Fig. 6.3a), suggesting that indeed increased influx correlates with glacial stages. We fine-tuned the age model by lining up the maxima and minima of the MS signal with the stacked oxygen isotope record, within the limits of the assigned paleomagnetic datum levels. A total of 27 tie points were used to construct the age model. The refined age model is presented in Fig. 6.3b and is used as input for times series analysis. Table 6.1 shows the mean accumulation rates, based on the refined age model.

Figure 6.3 - (a) Comparison of the MS of core LYH-1 (blue line) and the LR04 stacked benthic δ¹⁸O record of Lisiecki and Raymo (2005) after fine-tuning of the age model. (b) Refined age model for the uppermost 280 m of core LYH-1, based on the tuning in Figure 3a and the paleomagnetic stratigraphy of the core (red dots).
6.4.2 Temporal variation

Figure 6.4 shows the temporal record of the grain size end-member contributions (chapter 3). Although the highest contributions of coarse grained sediments (EM1, EM2 and EM3) occur in glacial times, there are also clear peaks in interglacial times. The highest contributions of the coarse fraction in the alluvial deposits is present from 1.0-0.65 Ma, whereas these are almost absent from 0.65-0.25 Ma, as reflected by a decreased contribution of the coarsest end-members. They reoccur over the interval from 0.25-0.0 Ma, in both glacial and interglacial times.

![Graph showing cumulative grain size end-member contributions](image)

**Figure 6.4 -** Cumulative grain size end-member model. EM1-6 have modes of: 150 µm, 75 µm, 50 µm, 25 µm, 15 µm, 4-6 µm respectively. See chapter 3 for genetic interpretation. The red dashed lines indicate the middle interval with decreased tectonic subsidence.
Figure 6.5a-d shows the MS, L*, BGi, and FGi records against age. The red shaded bands in this figure indicate warmer interglacial periods that correspond to paleosol layers on the CLP. Since MS represents for detrital influx and L* carbonate content, the two proxies are inversely proportional over many intervals. As expected because of the tuning, MS shows most of the elevated values in glacial periods (Fig. 6.5a). However, there also exist considerable fluctuations during interglacial periods, which indicate that influx is not exclusively taking place during full glacial periods but also during stadials. In the same way,
carbonate sedimentation occurs mostly during interglacials, but evaporative concentration can also occur in glacial periods, during warmer episodes (interstadials) (Fig. 6.5b).

The BGi varies between 0-1 and has oscillations with large amplitude (Fig. 6.5c). The relative high frequency changes of this proxy, suggests that pulses of alluvial floods (regardless of the total alluvial flux to the core site) occurs at a regular pace through both glacial and interglacial periods. There is no trend visible over the last 1 Ma, suggesting that the relative grain size of bedload in an alluvial flood does not change much over separate flood deposits. The relative composition of the sediment packages in floods is similar, despite differences in flood intensity (Fig. 6.4). Peaks and lows in the curve can be recognized in both glacial and interglacial periods. However, there is a slightly lowered contribution of coarse sediments in floods during the last two interglacials (MIS5 and 7) (Fig. 6.5d).

The influx of fine sediments (FGi) fluctuates regularly over the interval from 1-0.65 Ma (Fig. 6.5d). This is the result of the high frequency at which alluvial deposition occurs (Fig. 6.4). From 0.65-0.25 Ma, the relative contribution of fine influx is generally higher, but the amplitude decreased. From MIS 8 onwards, this changes again, probably due to increased alluvial deposition.

### 6.4.3 Time series analyses

The power spectra of MS, L*, BGi and FGi show a hierarchy of temporal cycles (Fig. 6.6). The three Milankovitch cycles (eccentricity (~100 kyr), obliquity (~41 kyr) and precession (~23-19 kyr) are highlighted with grey bands in Figure 6.6. MS has cycles with a wavelength of ~ 260, 93, 50, 41, 33, 26 and 15 kyr. L* contains cycles with a length of ~ 260, 93, 41, 15 and 11 kyr. The BGi has cycles with lengths of ~84, 38 and 25 kyr, similar to the three orbital cycles. Interestingly, this proxy lacks the long wavelength which is present in the other proxies. The FGi has cycles with lengths of ~325, 163, 109-93, 59, 25 and 10.5 kyr. The four analyzed proxies all display dominant frequencies in or around the assigned orbital Milankovitch bands, with additionally multiple high frequency cycles such as indicated on the right side of Figure 6.6.

Figure 6.7 shows the wavelet power spectra of the four proxies. Although the dominant Milankovitch frequencies are clearly visible, they are not continuously present throughout the studied record and display different occurrence intervals for the different proxies. For example, the power spectra of the MS record shows a notable gap in the eccentricity signal from approximately 0.70-0.55 Ma (Fig. 6.7a), while the lightness record appears to be forced by eccentricity over the entire investigated interval (although it is relatively stronger over the interval from 1.0-0.35 Ma) (Fig. 6.7b). The figure also shows that, although precession and obliquity forcing is present in MS (Fig. 6.6a), it is limited to intervals in the middle part of the core (Fig. 6.7a).

The pace at which alluvial flooding occurs (BGi) appears to be strongly forced by all three orbital parameters and has, in contrast to the other proxies, a relatively continuous signal (Fig. 6.7c). The FGi is also forced by eccentricity, obliquity and precession, but for the latter two frequency bands, it is focused in certain intervals (Fig. 6.7d). Both grain size end-member indices show a considerably patched signal in the high frequency domain (Fig. 6.7c; d).
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Figure 6.6 - Fast Fourier power spectra of (a) MS, (b) L*, (c) BGi, (d) FGi. The left and right figures contain the low and high frequencies respectively. Note the different y-axis scale. The grey dashed lines from light to dark indicate confidence levels of 80%, 90% and 95% respectively. The grey bars indicate the frequencies of the eccentricity, obliquity and precession bands. An eccentricity frequency is present in all proxies, while precession is only dominantly present in proxies related to grain size sorting.
6.5 Discussion

6.5.1 Tectonic influence on sedimentation rate

The spectral analysis results show that all proxies, with the exception of BGi (see 4.3), have a distinct periodicity with a frequency that lies in between the long and short eccentricity cycles (400 resp. 100 kyr) (Fig. 6.6) and can therefore not readily be explained by Earth’s orbital parameters. We propose that these low frequencies are related to tectonism in the basin. Previous research already indicated that there exists a tripartition in the core, separating a middle interval with decreased tectonic subsidence from intervals with increased subsidence (chapter 3). During the period of decreased subsidence the alluvial fan system responds by progradation (e.g. Gawthorpe and Leeder, 2000; Hardy and Gawthorpe, 2002; Densmore et al., 2007), which lead to overfilling and bypassing of the core site. The flattened topography did not allow for coarse material to be deposited in large quantities, hence there was dominant deposition of relatively fine sediments (Fig. 6.5). The duration of this middle interval coincides roughly with the low frequency wavelength occurrence in the measured parameters, suggesting a change in average tectonic subsidence.

The sedimentation rate of core LYH-1 over the last glacial period (especially MIS 4) is more than 5 times higher compared to older intervals (Table 6.1). Climate change and anthropogenic influences could not account for such a high increase of sedimentation rate, because the last glacial period is not substantially different from the penultimate glacial period and humans only began to seriously alter the landscape during the Holocene. Also compaction cannot
Climate cyclicity, tectonic pulses and autocyclicity in alluvial fan sediments in the Weihe Basin explain the dramatic change in sedimentation rate, because porosity is not expected to decrease significantly over the 220 m length of the core (Das, 2008). Therefore, the most plausible explanation for the dramatic change in sedimentation in the study area is a sediment pulse resulting indirectly from normal fault motions. This generates accommodation space and increased sediment input, due to footwall incision (Hardy and Gawthorpe, 2002; Allen, 2008). The normal fault motions must be related to movement of the Beishan Piedmont detachment Fault (BPF) at the northern margin of the Weihe Basin at the start of the last glacial period. If faults, more proximal to the core, would have moved, it would certainly have impacted the Luo River terraces located along strike of these faults. However, there is no tectonic displacement visible in these terraces, which are younger than 240 ka (chapter 5).

In chapter 3, we already indicated that the increased influx of coarser sediments from ~240 ka onwards, is closely related to tectonic activity in the basin. Detailed sedimentological and morphological analysis on the proximal Luo River indicated that the river contributed sediments to the Luyang Wetland area through its alluvial fans prior to ~240 ka (chapter 5) and thus before the proposed increase in tectonic displacement along the northern Weihe Basin. However, the river was forced to incise due to the activation of a fault that also defines the southern margin of the Luyang Wetland (Fig. 6.1). The timing of this event also coincides with increased incision of the Yellow River in the eastern Weihe Basin (Hu et al., 2012) and indicates a broad scale tectonic event in this part of the basin. Figure 6.1c show morphological proof for substantial erosion and sediment fluxes close to the BPF. Several gullies can be recognized on the pediment surface that runs from the basin margin towards the Luyang Wetland core site (Fig. 6.1c). These gullies clearly demonstrate that sediment flux from a northern direction is important for the sedimentation in this area.

6.5.2 Climate forcing of sedimentation in the northern Weihe Basin

The complex sediment cycles of alluvial fan progradation and retreat are largely controlled by the erodibility of the loess on the CLP (chapters 3, 5) and therefore susceptible to monsoonal dynamics. The temporal variation of MS is a good indication of detrital influx (Ellwood et al., 2000). As expected because of the tuning, most peaks of MS occur in glacial periods (Fig. 6.5a), indicating that sediment supply is higher in colder periods. During glacial periods, the source area of the sediments in the core site (the CLP) is more vulnerable to erosion due to lowered vegetation cover (Liu et al., 2011). The relative high sedimentation rates in MIS 4 and 2 highlight the importance of fluvial activity in glacial periods. Nevertheless, detrital influx also takes place during interglacial times. For example, during MIS 7 there is an increased detrital influx, given the peaks in both the MS and the coarser grain size fraction (Figs. 6.4; 6.5a). This particular event is related to a colder phase (stadial) within the overall interglacial period (Fig. 6.5i).

Orbital cycles

The spectral analysis of the investigated records shows the existence of the eccentricity (100 kyr), obliquity and precession cycles in the core sediments. This indicates that climatic forcing exerts an important influence on the alluvial dynamics in the northern Weihe Basin. Similar frequencies observed in loess-based proxies, have been attributed to the combined influence
of mean summer insolation (precession) and glacial boundary conditions (eccentricity and obliquity) (Sun et al., 2010; 2015; Peterse et al., 2014).

Figure 6.6 shows that our record contains a strong precession cycle in indices that are related to sediment flux (MS) and grain size (BGi and FGi). Importantly, the grain size indices were not used for the age tuning. Precession determines to a large extent the amount of rainfall associated to the EASM, as demonstrated by analysis in speleothem δ¹⁸O records (Wang et al., 2001; 2008; Cheng et al., 2016) (Fig. 6.5e; f). Our results therefore suggest a significant influence of the intensity of monsoonal rains on the sedimentation at the studied site. Monsoonal rains create high intensity floods, which could have triggered enhanced sediment transport and deposition on the alluvial fan system (Harvey et al., 1999; Jain and Tandon, 2003; Arzani, 2005; Fuchs et al., 2015). Periods of maximum coarse influx coincide with periods of maximum monsoonal rainfall as deduced from the stacked speleothem record of Cheng et al. (2016) (Figs. 6.4; 6.5). However, especially the FGi appears to be strongly controlled by precession induced variation in monsoonal rainfall (Fig. 6.6d), suggesting that the broad dispersal of fine sediments over the distal fan system is very sensitive to seasonal variations. Unlike the allogenic proxies, lightness (L*) (an autogenic proxy related to carbonate deposition) lacks the precession signal. Apparently, the formation of evaporites is not directly controlled by precession induced variations in rainfall, but responds to glacial-interglacial variability and mean annual temperatures (Cleaveland et al., 2002; Dupont-Nivet et al., 2007).

In contrast to the speleothem δ¹⁸O records, our record also contains a significant eccentricity signal in all proxies as well as an obliquity signal in the MS, L* and BGi. Most studies on nearby loess sequences also found a distinct glacial-interglacial variability with a dominant eccentricity cycle (Peterse et al., 2014; Sun et al., 2015). Expansion of ice sheets during eccentricity minima affects the EAM by enhancing the strength of the EAWM and reducing the strength of the EASM. This results in the large-scale accumulation of loess and minimal vegetation growth. As described above, this makes the CLP more vulnerable to fluvial erosion, which results in increased sediment supply to the alluvial fans of the northern Weihe Basin.

The wavelet spectra indicate that the eccentricity, obliquity and precession frequencies in the sediments of core LYH-1 are not continuously present (Fig. 6.7). For example, the strong precession cycles in FGi are present in discrete intervals (Fig. 6.7d), resembling the distinct depositional packages of about 1-3 m thickness from the Late-Pleistocene alluvial sediments on the southern tip of the Baja California peninsula, described by Antinao et al. (2016). They attributed these layers to precessionally forced tropical precipitation events. Core LYH-1 precession cycles in FGi are most dominant over intervals where an increased tectonic subsidence occurs, which results in increased sedimentation rates and a better preservation of the sediments. This reflects the importance of tectonically induced accommodation space in recording climate signals. The physical processes that are involved in sediment transport change in intensity as relief declines. When there is insufficient accommodation space, the fan by-passes the core site, resulting in incomplete climate signals and a loss of information. This seems to have occurred during the middle interval in the studied core.

Nevertheless, the BGi contains the most continuous signals of orbital forcing (Fig. 6.7c). This proxy reveals changes in the relative composition of individual flood deposits, which is less dependent on total alluvial influx. The lack of a trend in this composition implies that high and low energetic floods have roughly similar relative proportions of coarse grained
end-members. Therefore, the BGi precession cycle persists over the middle interval when tectonics are less intense and the energy of alluvial flooding is lowered. This would also explain why this proxy does not contain the low frequency wavelength, as it is argued that this is related to average tectonic motions in this part of the Weihe Basin. Another implication of these results is that climatic forcing of sedimentation occurs continuously, but factors as tectonics and associated accommodation space affect climate signal preservation.

6.5.3 Autocyclicity

In addition to the Milankovitch cycles and tectonic pulses, there are also many high frequency cycles (Figs. 6.6; 6.7). The multitude of sub-Milankovitch cycles (Fig. 6.6) cannot all be related to direct climate or tectonic forcing. They are likely reflecting the internal dynamics (autocyclicity) of the alluvial system in the northern Weihe Basin with thicknesses of individual cycles ranging from approximately 0.5 to 1.5 m.

In general an alluvial fan system comprises a complex sedimentary environment with active and inactive sediment lobes, which migrate laterally depending on the size of the entire system and external perturbations (Nichols and Fisher, 2007). Allen (2008) proved that these alluvial sequences are organized into cycles of various scales and cannot always be attributed to primary extrinsic controls. Similar conclusions were drawn from analogue and numerical modeling studies, which showed that migration of the active sediment lobes occur in a cyclic manner and is caused by self-induced perturbations of topographic relief (Whipple et al., 1998; Kim and Paola, 2007; Nicholas and Quine, 2007; Van Dijk et al., 2009). Variations in external controls (e.g. tectonics and climate change) produces new perturbations to which the autocyclic behavior of the sedimentary environment will respond (Peper and Cloetingh, 1995). This explains why the sediments in core LYH-1 contain a multitude of frequencies in the high frequency domain.

In the case of our study area, the situation is even more complex, because it receives sediment from multiple directions. Over the recent past, sediment input predominantly came from northerly sources, but in addition to these northerly source, the Luo River must have contributed to the sedimentation in the core site prior to 240 ka (chapter 5). This might not be the only large river that delivered sediments, because the Sichuan River (currently dry) has its valley proximal to the wetland on the west side.

6.6 Conclusions

This study shows that core LYH-1, drilled in a distal alluvial fan setting, provides a record of tectonically and climate modulated sedimentation as evidenced by rigorous spectral analysis. Predominant occurrence of orbital variations in the Milankovitch bands, indicates climatic control on the sedimentation in the core. The presence of eccentricity (~100 kyr) and obliquity (~41 kyr) bands demonstrates a glacial-interglacial forcing on the sedimentation. In glacial times, reduction in vegetation cover on the CLP causes increased sediment supply. The warmer and wetter climate during interglacial periods promote vegetation growth in the catchment, which eventually hampers sediment supply to the alluvial fan and results in the
formation of playa lakes. Precessionally forced intensity of the monsoonal rains are reflected in proxies related to detrital influx. However, this signal is not continuously present and depends on tectonically induced accommodation space and internal dynamics -autocyclicity- of the fan system. This results in a stronger precession signal for fine grained influx in the oldest and youngest core intervals, when tectonic subsidence increased accommodation space. The flood deposits with a relatively continuous precessional component, however, is independent from large-scale tectonic motions. The presence of a low frequency band (>>100 kyr), in three out of the four analyzed proxies, is attributed to changes in tectonic motions. Decreased tectonic activity occurred from approximately 0.65-0.25 Ma, whereas a dramatic increase in sedimentation rate at the transition from MIS 5 to 4 indicates a recent tectonic activity, probably related to offset along the detachment fault in the northern Weihe Basin (BPF). Autocyclicity is mainly expressed by a chaotic frequency distribution in the studied proxy records, especially in the high frequency domain. This might overprint climate signals and therefore, care should be taken into account when interpreting these records in terms of climate change.

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