Tectonic vs. Climatic Records on Tibetan Plateau Stratigraphy, Cretaceous to Early Tertiary basin formation on the Eastern Tibetan Plateau region

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ABSTRACT

The Himalayan-Tibetan orogen was created by the Indo-Asian collision and is the youngest and most spectacular active continent collision belt on Earth. The formation of Tibetan plateau is thought to have significantly altered the earth’s climate. The aim of this research is to understand the timing of the Tibetan plateau and its relation to global and regional climate change. High-resolution age control is done by magnetostratigraphy of sediments from the Longzhong basin at two locations which is used to unravel early uplift of the Tibetan plateau and Paleogene climatic events. The obtained magnetostratigraphic record of the Dahonggou section indicates nine normal and eight reversed polarity zones in an interval of 700 meter, resulting in two correlation options which are the most likely. However, for the, in this research obtained, magnetostratigraphic record of the Dahonggou section it is hard to make a clear correlation to the GPTS. Therefore, it is impossible to constrain a clear timing of the uplift of the Tibetan Plateau. Further research is needed to be able to assess the effects of the major change in the heart of the Asian continent and to decipher between early uplift of the Tibetan plateau and Paleogene climatic events.
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1. Introduction

The Himalayan-Tibetan orogen was created by the Indo-Asian collision and is the youngest and most spectacular active continent collision belt on Earth. The formation of Tibetan plateau (Figure 1) is thought to have significantly altered the earth’s climate. Regionally, Tibetan uplift has lead to enhanced contrast of sea-continent temperatures resulting in intensification of the Asian monsoon (i.e. during summer heating, a low pressure cell formed over the land surface triggering inland Indian airflow). On a global scale, Tibetan uplift caused massive rock weathering that consumed atmospheric CO$_2$ possibly responsible for the earth cooling from greenhouse to icehouse conditions since $\sim$60 Ma (Ruddiman, 1997; Raymo & Ruddiman, 1992). The age of the Tibetan uplift is however controversial. There is a debate whether the plateau raised continuously since Indo-Asia collision ca. 55 Ma or that the uplift occurred mainly in several recent steps (Tapponnier, 2001; Ruddiman, 1998; Molnar et al., 1993).

![Figure 1. General map of Tibetan Plateau and adjacent regions, including principal active faults, sedimentary basins and rivers (Horton, 2004)](image-url)
The aim of this research is to understand the timing of the Tibetan plateau and its relation to global and regional climate change. To achieve this goal key sedimentary successions recording the early history (ca. 50 to 30 Ma) of the Tibetan Plateau were studied (Dai et al., 2006). Accurate dating using high-resolution chronostratigraphy (magnetostratigraphy and cyclostratigraphy) in concert with the analysis of depositional environment has proven efficient to study the tectonic and climatic signal recorded in the sediments (Dupont-Nivet et al., 2007). This previous work indicates that the successions may record tectonic events and initiation of basin formation related to early Tibetan uplift. In addition, accurate dating reveals that the strata also include a major global climate change at the Eocene-Oligocene boundary 34 Ma. This shift in climate conditions is well-documented in the marine realm and on other continents but not in Asia. New results are provided in this research to further assess the effects of this major change in the heart of the Asian continent. High-resolution age control is done by magnetostratigraphy of sediments from the Longzhong basin at two locations which is used to unravel early uplift of the Tibetan plateau and Paleogene climatic events.
1.2 Geological background

Tibet is the largest, highest and flattest plateau in Earth with an average elevation exceeding 5000 meters and covers an area of more than a million square kilometers (Ruddiman, 1998). The formation of the Tibetan Plateau is the result of the collision of India into Asia 65-55 Ma (Molnar and Tapponnier, 1975; Yin and Harrison, 2000). However, the exact age of the Tibetan uplift is controversial. There is an ongoing debate whether the plateau rose continuously since Indo-Asia collision or that the uplift occurred in several recent steps (Molnar et al., 1993; Tapponnier, 2001). The Tibetan Plateau is bounded by the Kunlun Range in the northwest and in the northeast by the Qilian Range, in the south the plateau is delineated by the Himalaya-Karakoram complex. The field research areas are both located in the Longzhong Basin (Figure 2).

The Longzhong Basin is one of the largest Tertiary basins in China, located in central Gansu Province and eastern Qinghai Province. The Longzhong Basin covers over 100,000 km² delimited by the Tibetan Plateau to the southwest, by the Qinling Mountains to the south and by the lower-elevation ranges of the Laohu Shan and Liupan Shan to the north and east. The large Longzhong Basin is divided into four Cenozoic sub-basins, the Xining Basin to the west, the Lanzhou and Longxi-Jingning sub basins to the east and the Linxia sub basin to the southwest. The boundaries separating the different subbasins are defined by WNW-ESE trending structures (Dai et al., 2006; Yan et al., 2006; Zhou et al., 2006). These sub basins contain several hundred up to 2000 meters of Tertiary red beds.

Figure 2. Detailed map of the Longzhong Basin with indicated the sampled area.
The many strike-slip and thrust faults may have played a role in different times and in different ways.

For this research the Lanzhou and Xining basins are of special interest. The Lanzhou Basin is located at the northeast rim of the Tibetan Plateau near the city of Lanzhou (Gansu province, China). The Lanzhou Basin covers an area around the 300 km² and is, tectonically, the easternmost part of the long sedimentary belt stretching all along the northern foredeep of the Qilian Mountains (Qiu et al., 2001; Zha and Cai 1984). The Xining Basin is located west of the Lanzhou basin, on the northeastern Qinghai-Xizang Plateau and is bounded by the N-S tending Haiyan fault. The nearby Qaidam Basin and Gobi-desert cause well developed thick, integrated deposits of loess or paleosol sequence. It is unclear when the deformation in Xining Basin occurred, but according to Dai et al., 2006 the stratigraphy was undisturbed until 17 Ma, giving a maximum age for the deformation affecting this area.

It is thought that accumulation of sediments in this foreland basin (Lanzhou basin) started in the beginning of the Cretaceous (~100 Ma) before the Indo-Asian collision ca 55 Ma. The second and most important phase of sedimentation, possibly associated to Tibetan uplift, started during the Early Tertiary (~50 Ma) based on preliminary magnetostratigraphic dating of the Lanzhou basin stratigraphy (Qiu et al., 2001). Associated to this event are the Tertiary continental deposits forming a thick 1500 meter sedimentary pile composed by the Xiliugou, Yehucheng and Xianshuihe Formations bearing a rich and well-studied fossil record including important mammal faunas (Yu et al., 2003; Qiu & Qiu, 1995). The Cenozoic stratigraphy is very well developed in the Longzhong Basin and is divided into the Paleogene Xining group and the Neogene Guide Group (Zhai and Cai, 1984). The contact between these two groups (the Eocene-Oligocene boundary) is disconformable in the Lanzhou Basin, but found conformable in the Xining Basin (Dai et al., 2006).

For the purpose of this research on Paleogene events, the lower 700-meter thick part including the Xiliugou and Yehucheng Formations were sampled and analyzed for magnetostratigraphic dating. Disconformally overlying the Yehucheng Formation is the lower member of the Xianshuihe Formation starting with a laterally extensive basal layer of dusky yellow conglomeratic sandstone including well-dated fossil assemblages (late early Oligocene) which are used as an upper reference frame for
dating the Yehucheng Formation (Qiu et al., 2001; Yue et al, 2001). The targeted sampling location (the Dahonggou section, 36.37°N, 103.49°E) is ideally exposed within a broad N-S trending synclinal fold in the eastern part of the basin (Figure 2). The Dahonggou section is a perfect section for magnetostratigraphic analysis because of its length and its completeness.

The studied sediments of the Dahonggou section include fluvial massive, middle to coarse grained sandstones characteristic of tectonic activity and lacustrine thin- and medium-layered mudstones with cyclic intercalated gypsum possibly recording paleoclimatic variations. The available samples of the Xining Basin are from the Pingan section (36.26°N, 102.01°E). These sediments include mostly mudstones interchanged by medium sand layers and some gypsum beds.
2. Method

2.1 Principle of Magnetostratigraphy

The earth magnetic field reverses polarity during intervals of known age (Butler, 1992). The principle of the magnetostratigraphic dating method is to recognize these reversals in the paleomagnetic field recorded throughout a stratigraphical column and divided into a number of polarity zones. If a characteristic pattern of polarity zones can be linked to patterns of the Geomagnetic Polarity Time Scale (GPTS), an age constraint can be made. The GPTS itself is based on marine magnetic anomalies dated by radiometric methods on seafloor samples and assuming constant seafloor spreading between these dates. More recently, the age of the paleomagnetic reversals has been improved by astronomical tuning of these reversals in sedimentary record resulting in the construction of the astronomically tuned Polarity Time Scale (APTS, Lourens, 2004). Magnetostratigraphy is a powerful dating tool, especially when content in fossils or ash layers is poor. A well calibrated magnetostratigraphy provides high resolution age control enabling direct correlation between marine and continental sequences and between sequences at the northern and southern hemisphere.

2.2 Magnetostratigraphic analysis

2.2.1 Paleomagnetic sampling

Paleomagnetic sampling was done using a water cooled portable electrical drill. The samples were taken on a one-meter interval basis and resulted in a total of 573 samples collected over 704 meters of section. The bedding attitudes of sedimentary layers (~30° southern dip throughout the section) were measured at regular intervals. Samples were cut into standard size (2.5 cm high cylinders of 1 cm diameter) and weighted before paleomagnetic analysis.
2.2.2 Demagnetization procedures

To isolate the primary direction of the magnetic field recorded in the sediments during or soon after deposition, stepwise demagnetization methods are used to clean eventual secondary components (Butler, 1992). There are several laboratory techniques available to separate the various magnetization components. In this research most of the samples are demagnetized by using thermal demagnetization, but parts of them were demagnetized using the alternating field demagnetizer (time saving method).

The thermal demagnetization method is based on the relationship between relaxation time and temperature, e.g. magnetic carriers (grains) which have a low relaxation time also have a low blocking temperature. The samples are heated to a specific temperature and then cooled down to room temperature in a zero magnetic field. This causes demagnetization of all the grains with a blocking temperature lower than the specific temperature to which the samples were heated, thereby deleting the natural remanent magnetization (NRM) carried by these grains. Stepwise demagnetization at subsequently higher temperatures will therefore result in the progressive demagnetization of grains with increasing blocking temperatures. Primary magnetizations with high unblocking temperatures are thus isolated from secondary overprints with low unblocking temperatures.

The basis for alternating field demagnetization is that components with short relaxation times also have low coercivities (resistance to an applied field). The samples are exposed to an alternating magnetic field. This alternating field is generated at specific peak intensity and decays away, randomizing all magnetic moments that are softer than the peak field that have a component parallel to the applied field direction. To erase the soft component from the sample, the procedure is repeated along all three axes. Increasingly high pick fields are applied in stepwise fashion to progressively isolate the primary component from lower coercivity secondary components.

Figure 4. The 2G cryogenic magnetometer of the Paleomagnetism Laboratory of the Utrecht University, the Netherlands
The samples DH1-272, DH274-572 (even numbers) and every fifth sample were thermally demagnetized in 21 steps at 5-50°C intervals between 20 and 680°C. The samples DH273-573 (odd numbers) were demagnetized by using an alternating field method. The specimens were measured on the 2G cryogenic magnetometer in the Paleomagnetism Laboratory of the Utrecht University, The Netherlands (Figure 4). The magnetometer uses superconducting quantum interference devices (SQUIDs). In a SQUID, the flux of an inserted sample is contrasted by a current in a loop of superconducting wire. The superconducting loop is constructed with a weak link which will stop conducting when the current density is very low, corresponding to very small quantum of flux. The flux within the loop can be changed by discrete quanta. Each incremental change is counted and the total flux is proportional to the magnetization along the axis of the SQUID.

2.2.3 Reversal Test

The property of the geomagnetic field that the time-averaged geomagnetic field directions during a normal-polarity interval and during a reversed-polarity interval differ by 180° is the basis for the reversals test of paleomagnetic stability. The ChRM directions “pass the reversals test” if the mean direction computed from the normal-polarity sites is anti parallel to the mean direction for the reversed-polarity sites. The reversals test is used to be sure that the obtained ChRM directions are free of secondary NRM components. Furthermore, if the sets of normal- and reversed-polarity sites are conform the stratigraphic layering, the ChRM is probably a primary NRM. If the data set “fails the reversals test,” the average directions for the normal and reversed polarity sites differ by an angle that is significantly less than 180°. Failure of the reversals test can indicate either (a) presence of an unremoved secondary NRM component or (b) inadequate sampling of geomagnetic secular variation during either (or both) of the polarity intervals (Tauxe, 1998).

2.3 Susceptibility and rock magnetic analysis

Before the samples were demagnetized, the susceptibility was measured on the AGICO KLY-2 susceptibility bridge. The susceptibility describes the degree of magnetization of the sample in response to an applied magnetic field.
3. Results

3.1 Field Results

The sampling of the Pingan section was started 1 meter above the top of the basal sand. This 9-10 meter thick yellow to gray gypsiferous, cross-bedded, multilayered sand with lenses of dark gray shaley mudstone is probably of fluvial origin. The base of the sands is characterized by a discomformity on Cretaceous red sandstone of the Minhe Formation. The sampling is assumed to go through the Qijiachuan Formation and the base of the Honggou Formation (Eh1). The sampling stops at a 10 meter thick yellow sand layer that is the middle member of the Honggou Formation (Eh2).

The Dahonggou section consists of the Xiliugou Formation and the Yehucheng Formation, where the Xiliugou Formation unconformably overlies the Hekou Group. Horton et al. (2004) showed that the Minhe Group can be confidently correlated to the Hekou Group. Using this information a correlation can be made between the Dahonggou and the Pingan sections. In this research is assumed that the base of the formation at the base of the Dahonggou section (basal layer with white pebbles) can be correlated to the yellow to grey sand at the base of the Qijiachuan Formation in the Pingan section.

Figure 5 a) Thin blue sand layers; b) Thin gypsiferous bands in sandstone; c) Thick (>1m) gypsum layer (Alabastine)
Figure 6 shows the stratigraphical column of the Dahonggou section, which is 700 m thick. In general a fining upward trend can be seen in the section. At the base blue-green sand layers with cross beddings can be found on top of which an alternation of red siltstone with a lot of small blue-green sand layers (Figure 5a) were deposited. Later thick medium-coarse red-orange laminated gypsiferous sand bodies were deposited (Figure 5c), indicating an energetic increase in depositional environment. On top of the sands the depositional environment returned back to the earlier setting of red laminated siltstones and evaporites. The latest gypsum layer is found at 378 meter (Figure 5b). On top of the last gypsum there is again an alternation of red sands and small blue-grey cross bedded sands with a gradual fining upward towards red mudstones.

The Pingan section (Figure 7) with a thickness of 80 meters shows overall a subtle coarsening upward trend. On top of the basal conglomeratic sand layer is an alternation deposited consisting muddy gypsum and calcareous mudstones. Overlying this sequence are red and grey gypsiferous mudstones interbedded with green gypsum layers and blue sand layers.
Figure 6 Observed stratigraphy and paleomagnetic polarity zones (black for normal and white for reversed) indicated by calculated latitude of virtual geomagnetic pole (VGP latitude) at the Dahonggou section. Paleomagnetic samples of quality 2 (white dots) have been discarded to determine the polarity zones. Polarity zones which are only defined by quality 2 samples are indicated as grey zones.
Figure 7 Observed stratigraphy and paleomagnetic polarity zones (whole section shows reversed signal) indicated by calculated latitude of virtual geomagnetic pole (VGP latitude) at the Pingan section. Paleomagnetic samples of quality 2 (white dots) have been discarded to determine the polarity zones.
3.2 Paleomagnetic results

In the fieldwork a total number of 573 samples were taken from the Dahonggou section. Back in the laboratory 18 samples could not be used for further research, because they were crushed, broken or lost their orientation mark during transport.

3.2.1 NRM components

After the initial measurement of the natural remnant magnetization (NRM), the samples were thermally demagnetized in 21 temperature steps up to 680°C. All the samples show their own characteristic demagnetization pattern.

Based on the demagnetization behaviour of the samples, they were subdivided into three components. Different components of NRM can be distinguished based on their difference in direction and intensity. The low temperature component (LTC) is characterized by a normal polarity and will generally be removed between 50-350°C. The LTC can be interpreted as the removal of a secondary remnant magnetization, caused by the present day magnetic field. The LTC is normally only apparent in the samples which have a low magnetic intensity of the HTC. All the samples are fresh rock samples, so it is unlikely that the low temperature present day field component was caused by weathering. An intermediate temperature component (ITC) shows vector components which can be both normal and reverse direction in a temperature interval roughly from 350-620°C. The third component is the high temperature component (HTC) which ranges from 620 up to 680°C; indicating a hematite component.

The demagnetization pattern can be described by vector components. The best linefit through the demagnetization temperatures are calculated by using the computer programs Paldir and Palmid based on the method of Kirschvink 1980. For the use of polarity, samples which had a maximum angular deviation (MAD) exceeding the 30° were rejected from further analysis (quality 3), samples with a MAD < 15° were labelled as quality 1, MAD ranging between 15°-30° were labelled as quality 2 samples (Figure 8).
Figure 8 Demagnetization patterns of the different type of quality samples of the Dahonggou section. The numbers adjacent to each data point indicate the associated temperatures (in °C). Open circles indicate vector end points projected onto the vertical plane; the black circles indicate vector end points projected onto the horizontal plane.
For a number of samples the demagnetization behaviour shows a low initial remanance with unstable directions, which do not project towards the origin. From this kind of samples no characteristic remnant magnetization (ChRM) can be obtained. To remove possible transitional directions, we applied the recursive cut-off method developed by Vandamme et al. (1994) on separated sets of reverse and normal polarity directions.

Also reversal tests (Tauxe, 1998) were performed on the data set, which gave a negative result. The data set in this research fails the reversal test; the average directions for the normal and reversed polarity sites differ by an angel less than 180° (Figure 9 and 10). The failure to the reversal test can be the result of the presence of a secondary magnetization component which is not separated or insufficient sampling of geomagnetic secular variation (Butler, 1992).

There is no visible relation between the grainsize or lithology and the polarity of the samples; they are randomly distributed (Figure 6).

**Figure 9** Great circle analysis for the Pingan section. Equal-area projections of characteristic remanent magnetization (ChRM) directions in stratigraphic (after tilt correction) coordinates for Pingan section. Downward (upward) directions are shown as solid (open) circles. ChRM directions have negative fold test and reversal tests (Tauxe, 1998). Demagnetization pattern of a samples of the Pingan section. The numbers adjacent to each data point indicate the associated temperatures (in °C). Open circles indicate vector end points projected onto the vertical plane; the black circles indicate vector end points projected onto the horizontal plane.
Figure 10 Equal-area projections of characteristic remanent magnetization (ChRM) directions in geographic (before tilt correction) and stratigraphic (after tilt correction) coordinates for the Dahonggou section. Downward (upward) directions are shown as solid (open) circles. ChRM directions have negative fold test and reversal tests (Tauxe, 1998)
3.2.2 Polarity zones

The obtained magnetostratigraphic record shows nine normal polarity zones and eight reversed zones in the Dahonggou section (Figure 5). Beside these clear zones, there are three questionable polarity zones mostly defined by quality 2 samples (indicated in grey). These debatable polarity zones may be the result of an unidentified secondary magnetization component (Dai et al., 2006). But, some of these dubious samples may also represent a primary record of the paleomagnetic field and thus have to be taken into account. (Figure 5)

3.2.3 Pingan section

The sampled Pingan section belongs to the Qijiachuan Formation. The Qijachuan Formation lies on top of the Cretaceous Minhe Group and contains large quantities of ostracods. The occurrence of fossils makes it possible to create a time constraint of this formation. The magnetostratigraphic record of the Pingan section shows one large reversed zone (Figure 7).

3.2.4 Susceptibility and rock magnetic analysis

The lower part of the stratigraphic column of the Dahonggou section shows a clear correlation between the grain size and the susceptibility. The large grain sizes coincide with low susceptibilities. This trend can also be found higher up in the section, but it is less distinctive in that part. This indicates that susceptibility measurements of samples can be used as a proxy for grainsize and, hence, as a proxy for (cyclic) changes in the depositional regime.
4. Discussion

4.1 Correlation to the GPTS

4.1.1 Correlation of the Dahonggou section to the GPTS

The obtained magnetostratigraphic record of the Dahonggou section (Figure 6) indicates nine normal and eight reversed polarity zones in an interval of 700 meter. In addition there are three questionable polarity zones of mostly quality 2 samples (indicated in grey). In order to correlate the section to the GPTS, the four long reversed zones were used as a primary indicator. According to this method there are two correlation options which are the most likely (correlation A and correlation B, Figure 10).

As a starting point for the correlation the estimated age of the same area determined by Qiu et al. (2001) is used. Qiu et al. (2001) estimated the age of the section to be Eocene – Late Early Oligocene, based on the fossil content (Table 1). By using this information plus the magnetostratigraphic record obtained in their research correlation A is made (Figure 11). The nine normal zones are correlated to 17n-9n. It shows that there are some problems when making this correlation. In the GPTS 16n consists of two separated normal zone, while the corresponded zone in our section only consists of one zone. The same feature is seen for 11n. A possible explanation is that the reversed zone in between is very small and therefore may be missed with the sampling, which is not likely because of the 1 meter interval sampling. Another problem with this correlation to the GPTS are large differences in the relative length of the different zones. It is not likely that changes in the accumulation rate of sediments could have caused these large differences, because the section consists mainly of mudstone and gypsum layers.
Figure 11 The central column shows the polarity zones associated with the Dahonggou section. The left and right columns are the GPTS, which are linked to the Dahonggou section by two different correlations. The GPTS on the left indicates the chron of the various polarity zones and the GPTS on the right in shows the associated ages.
For correlation B only the observed polarity is used and the estimated age for the section by Qiu et al. (2001) is discarded. In this case the magnetostratigraphy of the Dahonggou section is linked to 21n-9n of the GPTS (Figure 11) and covers a larger time span. With this correlation the relative lengths of the different zones match more consistently to the GPTS. However, a few zones are completely missing: zone 10n, 15n, 17n and 19n. It is not assumable that all these zones are missing by erosional events in the section, because they were not recognised in the field and could not be missed because of sampling every 1 meter. Therefore, this correlation is also not very likely.

A part of this research was done in order to understand the timing of the Tibetan Plateau and its relation to global and regional climate change. However, for the, in this research obtained, magnetostratigraphic record of the Dahonggou section it is hard to make a clear correlation to the GPTS (see Figure 11). Therefore, it is impossible to constrain a clear timing of the uplift of the Tibetan Plateau. The main reason for this could be the relatively low amount of quality 1 samples; samples of which the result is definitely valid. To make a time constraint on the Dahonggou section, without the use of magnetostratigraphy, additional geological information has to be used. However, the time constraint obtained with this alternative method will not be accurate enough to create a high resolution age control and link the timing of the plateau to climate changes, but may give an idea about the tectonic evolution of the Longzhong basin. This will be discussed in the second part of the discussion.

Further research is needed to be able to assess the effects of the major change in the heart of the Asian continent and to decipher between early uplift of the Tibetan plateau and Paleogene climatic events. This can be done by more detailed sampling of other sections in the area with a similar time span as the Dahonggou section, or by using other dating techniques like pollen analysis.
4.1.2 Correlation of the Pingan section to the GPTS

In order to correlate the Pingan section to the GPTS, at first the results of Horton et al. (2004) for the Pingan and East Xining sections were used. In their research the magnetic signal, from the base of the Honggou Fm. upwards, was analyzed (see Figure 12). For this research the analyses already started at the base of the Qijiachuan Fm and continued till halfway the Honggou Fm. All the samples in this research showed a reversed signal (Figure 7) and can be used as additional information on the paleomagnetic data of Horton et al. (2004) which stops at the base of the Honggou Fm. This indicates that probably the whole Qijiachuan Fm is part of the same chron as the reversed lower part of the Honggou Fm, which would indicate an age of ~62,5 Ma. An updated correlation of the by Horton et al. (2004) studied Pingan section to the GPTS is made by Dai et al. (2006). Adding the obtained reversed signal to their correlation would indicate that the base of the Qijiachuan Fm equals C22r (~51Ma) (Figure 12).
Figure 12: Figure showing the two different correlation options of the Pingan and Dahonggou sections. The figure also indicates the basis of the particularly correlation. Note the significant thickness difference between the two sections. Note the difference in scale.
4.2 Correlating the Dahonggou and Pingan sections

By correlating the Dahonggou and Pingan sections, i.e. the Lanzhou and Xining sub basins, the evolution of Cretaceous to Early Tertiary basin formation on the Eastern Tibetan Plateau region can be reconstructed. Previous work indicates that the successions of both sections may record tectonic events and basin initiation related to early Tibetan uplift (Dupont-Nivet et al., 2007).

The, in this research obtained, lithological sequences and magnetostratigraphy can be very helpful tools for creating a correlation between the two sections. However, it is shown that the correlation of the Dahonggou section to the GPTS is non-unique and not reliable. Moreover, the magnetostratigraphical record shows a pattern which is not consistent with a previous record by Qiu et al. (2001). Therefore, in this discussion the age determined by Qiu (2001) is used for correlation between the two basins (~51-50 Ma for the Xiliugou-Yehuchen boundary). Moreover, for the Pingan section the base of the Qijiachuan Fm is estimated to be around 51 Ma according to Dai et al. (2006).

Using the lithological stratigraphy as a correlation tool also creates some difficulties. Horton et al. (2004) correlated the Pingan and Xining section by along strike correlation in the field. According to the correlation of the two stratigraphical columns of both sections, sand bodies are not continuous between the two sections and are, consequently, useless for correlation in the large Longzhong basin. Therefore, another method has to be used for the correlation of the Pingan and the Dahonggou sections, possibly by correlating the different gypsum layers. In the Dahonggou section there are three clear gypsum events plus one which is debatable (Figure 6). These three gypsum events can be linked to the first three gypsum events in the Pingan section (Figure 7), which would mean that the Dahonggou section did not experience any gypsum event after the third, where the Pingan section did. After the third gypsum the Dahonggou section only shows fining upward mudstones. However, when comparing the gypsum layers of the Xining and the Pingan sections it turns out that the Xining section shows much more gypsum layers than the Pingan section (Figure 7). This implies that also the gypsum layers can not be used directly to correlate the sections.
Moreover, on top of the Honggou Fm is the Mahalagou Fm, which starts with green-white muddy gypsum with red gypsiferous mudstone and changes to red sandy mudstone with gypsiferous sandy mudstone (Dai et al., 2006). This does not correspond to the sediments deposited on top of the last gypsum in the Dahonggou section.

However, when combining the magnetostratigraphy, lithological sequence and also the basin configuration all together a correlation can be made between the Lanzhou and Xining basins (Figure 12). It turns out that there are two possible options to make a correlation, which can be related to different tectonic histories of the region.

**Option 1. Early Tertiary tectonic event**

In the Dahonggou section the first Tertiary deposits are of the Xiliugou Fm. (Qiu et al., 2001). This is based on Tertiary fossils which are found in the overlying Yehuchen Fm (Table 1). Because the Yehuchen Fm. is conformably deposited on top of the Xiliugou Fm, the Xiliugou Fm is assumed to be also of Tertiary age. The absence of a clear hiatus between these two formations also supports the fact that it is not likely to find the KT-boundary between the two formations. Moreover, at the KT-boundary is always found an Ir-rich layer, which is absent at this boundary. In the Pingan section the first Tertiary deposits are of the Qijiachuan Fm. This formation lies concordant on top of the Cretaceous Minhe Group (Horton et al., 2004, Da-Ning et al., 1990).

When discarding the magnetostratigraphic record of the Pingan section obtained in this research and only looking at previous data the Xiliugou-Yehuchen boundary corresponds to the base of the Honggou Fm and has an age of ~51 Ma (Dai et al., 2006). However, when taking the data of this research into account (base of Qijiachuan Fm ~51Ma) the base of the Yehuchen Fm will correspond to the base of the Qijiachuan Fm (Figure 12). In this scenario the Minhe Group is missing in the Dahonggou section. An option is that the Dahonggou section during the Cretaceous was closer to the deformation front, experienced more uplift, and therefore more erosion occurred. After this erosional event the subsidence occurred, which was larger in the east (Dahonggou section). Instead of the missing Cretaceous group the Dahonggou section has one Tertiary group extra (Xiliugou Fm.) compared to the Pingan section.
Moreover, the Dahonggou section is significantly thicker over the same time scale (500m versus 240 meters (Horton et al., 2004)).

This implies that the Dahonggou section is situated in a deeper part of the basin and at a certain moment too deep for the deposition, or even formation, of gypsum. Also the fining upward in the Dahonggou section can be an indicator for a decrease in energetic environment, which indicates a more distal setting. This option supports the presence of one continuous E-W orientated basin (Longzhong) which experienced an deepening towards the east during the Early Tertiary.

**Option 2. Middle Cretaceous tectonic event**

Based on the lithological stratigraphy the base of the Qijiachuan can be linked to the Xiliugou-Yehuchen boundary (Figure 12). At the base of the Pingan section, according to Horton et al. (2004), conglomerates and thick sandstones are deposited. This is similar to the massive sandstones and basal anguclasts, which are deposited in at the base of the Xiliugou Fm (Qiu et al., 2001). At the Pingan section conformably on top of the conglomerate and sand bodies an alternation of thick mudstone layers with thin gypsum and sand layers is deposited, which is similar to the Dahonggou section. However, the massive sandstones of the Xiliugou Fm are of Tertiary age, where the sand bodies in the Pingan section are of Cretaceous age. So these two sections can not be correlated in this way. Zhai and Cai (1984) found Miocene charophytes in the Xianshuihe Fm and therefore the Xiliugou and Yehuchen Fm were reassigned to the Early Tertiary. So, the Xiliugou Fm must be deposited rapidly just after the disconformity on top of the Hekou Group.

<table>
<thead>
<tr>
<th><strong>Xiliugou Fm</strong></th>
<th><strong>Yehucheng Fm</strong></th>
<th><strong>Xianshuihe Fm</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LOWER</strong></td>
<td><strong>MIDDLE</strong></td>
<td><strong>UPPER</strong></td>
</tr>
<tr>
<td>Late Eocene mammals</td>
<td>Early Oligocene pollen</td>
<td>~18 Ma (Qiu &amp; Qiu, 1995)</td>
</tr>
<tr>
<td>(Qiu &amp; Qiu, 1995)</td>
<td>(Geng, 2001)</td>
<td>(Qiu &amp; Qiu, 1995)</td>
</tr>
<tr>
<td>Late Eocene spore - pollen assemblage</td>
<td>Early Oligocene</td>
<td>~18 Ma (Qiu &amp; Qiu, 1995)</td>
</tr>
<tr>
<td>(Yu et al., 2003)</td>
<td>(Qiu &amp; Qiu, 1995)</td>
<td></td>
</tr>
<tr>
<td>Lower Eocene Paleocene (Xie, 2004)</td>
<td>Lower Oligocene - Lower Eocene (Xie, 2004)</td>
<td>Late Early Oligocene - Late Miocene (Xie, 2004)</td>
</tr>
<tr>
<td><strong>Table 1</strong></td>
<td>Table showing the ages determined for the Xiliugou Fm, Yehuchen Fm and Xianshuihe Fm based on their fossils content, by different researches.</td>
<td></td>
</tr>
</tbody>
</table>
Furthermore, the Dahonggou section (Xiluigou and Yehucheng Formations) has a thickness of 704 meters, while the corresponding Pingan section (Qijachuan and part of Honggou formations) is only 240 meters thick (Horton et al., 2004; Dai et al., 2006).

This difference in thickness indicates that the Lanzhou basin experienced a significantly more subsidence, almost three times as much, over a time of ~17 Ma. A thickness difference of this magnitude over relatively small distance between the two sections indicates clear influence of tectonic forces on the two sub basins.

The presence of the disconformity at the base of the Dahonggou section and the absence at the base of the Pingan section indicate a different early tectonic history of the two sub basins. The difference in deformation histories of both basins could be explained by gradual subsidence of the Xining Basin through time, where the Lanzhou Basin first experienced no subsidence (possibly even uplift) before a period of rapid subsidence. The partitioning of the original Mesozoic Xining-Minhe basin by narrow ranges as a result of Cenozoic shortening and strike slip deformation (Horton et al., 2004) could be a reason which caused the difference in tectonic evolution of the two basins. This is consistent with the NW-SE stretching more to the south (Ratschbacher 2003), which occurred at the same time as the Early Cretaceous crustal extension and sinistral transtension in Dabie (a mountain range in central China). This event is followed by dextral wrenching during or after deposition of widespread Late Cretaceous deposition.

The last option is that both sections have nothing to do with each other and are not formed in the same basin environment.

Based on new data gathered in this research and data from previous research (Horton et al., 2004; Dai et al., 2006; Qiu et al., 2001) it is not possible to find a unique timing of the Dahonggou section and the tectonic processes associated with this section. Further research will be required to get a better time estimate on the onset of the uplift of the Tibetan plateau in order to be able to relate it to the known Oligocene-Eocene climate change. Suggestions of further research are more detailed sampling of other sections in the area with a similar time span as the Dahonggou section, or the use of other dating techniques like pollen analysis.
5. Conclusions

- A part of this research was done in order to understand the timing of the Tibetan Plateau and its relation to global and regional climate change. However, for the in this research obtained magnetostratigraphic record of the Dahonggou section it is hard to make an unique correlation to the GPTS.

- Correlation of the Dahonggou and Pingan sections (i.e. the Lanzhou and Xining sub basins) the evolution of Cretaceous to Early Tertiary basin formation on the Eastern Tibetan Plateau region could not be clearly reconstructed. Base on data from this project and previous research it turned out that there were two possible options to make a correlation, which can be related to different tectonic histories of the region: (1) an Early Tertiary tectonic event, (2) Middle Cretaceous tectonic event.

- Further research will be required to get a better time estimate on the onset of the uplift of the Tibetan plateau in order to be able to relate it to the known Oligocene-Eocene climate change.

- Suggestions of further research are more detailed sampling of other sections in the area with a similar time span as the Dahonggou section, or the use of other dating techniques like pollen analysis.
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