Magnetostratigraphy and AMS study of a late Cretaceous-Paleogene succession in the eastern Xining basin: constraint on K-Pg boundary tectonic event in NE Tibet Plateau

Chicheng He1,2,5, Zhonghang Wang1,2, Yanguo Fang1,2, Maohua Li1,2, Shaokai Li3 and Yueqiao Zhang4

1Three Gorges Geotechnical Consultants Co., Ltd, Wuhan, 430074; 2Changjiang Design Group Co., Ltd, Wuhan, 430010; 3School of Earth and Space Science, Peking University, Beijing, 100871; 4School of Earth Sciences and Engineering, Nanjing University, Nanjing, 210023

5Corresponding author’s e-mail: hcc@pku.edu.cn

Abstract. Cretaceous-Cenozoic basins developed in the NE Tibetan Plateau contain key archives to unravel the growth history of the plateau in response to the India-Eurasia collision. Here we present magnetostratigraphic results of a Late Cretaceous to Paleogene succession of the Zhongba section outcropping at the southern margin of the eastern Xining basin. This succession consists of three lithological units punctuated by two stratigraphic unconformities, which best recorded the deformation history of this foreland basin. Detailed magnetostratigraphic investigation show that the lower terrestrial sedimentary rock unit, the Minhe Group, was deposited in latest Cretaceous in the time span of ~74.5-69.2Ma; the middle unit was deposited in Paleogene in the time span of ~49.3-22Ma; and the upper conglomeratic unit, not dated, possibly was deposited in early Miocene. Accordingly, the K-Pg unconformity, widely observed in the foreland basins of NE Tibet, represents a sedimentary hiatus of ~19.9Ma duration from ~69.2 Ma to ~49.3 Ma, which possibly recorded the far-field response to the tectonic transition from Neo-Tethys oceanic plate subduction to the India-Eurasia collision in southern Tibet. AMS results show a clockwise rotation of the shortening direction from NNE-SWS in Latest-Cretaceous to NE-SW in Paleogene, which support the view that the compressional environment may dominate the NE Tibet in Early-Cenozoic period.

1. Introduction

The northeastern margin of this plateau, bounded to the south by the eastern Kunlun-West Qinling fault zone and to the north by the Altyn Tagh-Qilian Shan-Haiyuan fault zone (Figure 1), has been earlier viewed as the on-going frontier of the outward growth plateau, where the most tectonically vigorous deformation was attributed to a Pliocene-Quaternary plateau-building epoch [1]. In recent two decades, increasing evidences were accumulated in NE Tibet about range exhumation or cooling history, basin formation, and initial ages of fault activities around Paleocene to early-Eocene period, and has revealed a syn-collision tectonism, supporting the view that the plateau margins deformed simultaneously with the initial India-Eurasia collision [2-13].

As a response, many basins in northern Tibet recorded a sedimentary hiatus across the Cretaceous and Paleogene (K-Pg) boundary and revealed a consistent early Eocene age of the initial deposition through magnetostratigraphy studies (Figure 2) [7-13]. This K-Pg unconformity, widely presented in...
most of the basins in NE Tibet, may represent an important epoch of the tectonic transition from the Neo-Tethys subduction in Late Cretaceous to the India-Eurasia collision in Paleogene [14-15]. However, previous work has mostly focused on the age of Cenozoic sedimentary succession in NE Tibet but ignored the timing of this significant stratigraphic unconformity, and its duration was assigned vaguely between Early Cretaceous and Paleogene. Therefore, the question when did the India-Eurasia collision propagate northward to the region of the NE Tibetan margin, still remains elusive.

Another question concerns “How” the Early Cenozoic deformation generated the basin-and-range morphology in the NE Tibet Plateau. One opinion holds that compressional foreland environment prevailed in the NE Tibet in Paleogene [2, 11]. Another one based on extensional normal faults observed in the Paleogene strata of the Xining and other basins in the NE Tibetan Plateau [16-17], envisaged a transtensional setting possibly attributed to the far-field effect of westward subduction of the Pacific Plate.

To solve the above “When” and “How” questions, it needs a more complete stratigraphic chronology of Cretaceous-Paleogene succession in the NE Tibetan Plateau, which is vital for ascertaining the timing and possible northward propagation of deformation before and during the India-Eurasia collision. In this paper, we present the magnetostratigraphy and anisotropy of magnetic susceptibility (AMS) study of a Late Cretaceous to Paleogene succession of the Zhongba section outcropping in the southern margin of the eastern Xining basin, in an attempt to determine the age of the K-Pg unconformity and to explore its tectonic significance.

Figure 1. (A) DEM topography of the Tibetan Plateau and the location of Xining basin; (B) Simplified geological map of the Xining basin and its surrounding regions, showing locations of the previously studied magnetostratigraphic sections and our Zhongba section.
2. Geological setting

As Figure 1 shows, the Xining basin was part of the unified Cretaceous-Cenozoic Longzhong Basin in NE Tibet (Figure 1B) [18-19]. It is separated to south from the Xunhua basin by Riyue Shan-Laji Shan and connects to the east with the Lanzhou-Linxia basin. Laji Shan, and its southward bending Jishi Shan, a branch of central Qilian Shan, has been considered as a young morphotectonic range being emerged in late Cenozoic. The Mesozoic-Cenozoic successions in the Xining basin were deformed in Late Cenozoic [8], forming a set of NNE-SSW striking faults and associated folds developed in the central and southeastern basin.

Cenozoic stratigraphy of the Xining basin consists of a thick and continuous succession, characterized by reddish and dominantly fine-grained lacustrine-fluvial to saline-playa deposits, which unconformably overlies the Cretaceous red beds of the Hekou and Minhe Groups or older basement rocks. The Early-Cretaceous Hekou Group had been partly dated, as ~133-120Ma [19], and the Cenozoic succession has been well established based on magnetostratigraphy studies and mammal fossils, as ~54-4.8Ma [8].

Our section lies at the north foothills of Laji Shan in the south of Xining basin. Figure 2 presents three lithological units separated by two distinct unconformities which are exposed in Zhongba section, and it can well be correlated to other sections in the inner Xining basin. The lower unconformity separates the Cretaceous red beds and Cenozoic strata, and the upper one was overlain by a distinct thick conglomeratic succession never seen before in the inner Xining basin, named Zhongba formation by us. This section was discovered earlier by Ye [20], and the bio-fossils found in the middle lithological unit can generally refer to a time span of Eocene to Oligocene period.

3. Magnetostratigraphy results and AMS analyses

Figure 3 show the magnetostratigraphy results of the Zhongba section. Based on the bio-fossils and magnetozones correlation, the Late Cretaceous Minhe Group was deduced to span the period of ~74.5-
69.2 Ma. The basal age of the Paleogene succession is assigned to ~49.3 Ma, which suggests a hiatus of about 19.9 Ma duration for K-Pg unconformity.

Figure 3. Lithostratigraphy and magnetostratigraphy results of the Zhongba section, and correlations of the observed polarity zones with the geomagnetic polarity timescale (GPTS).
Figure 4 presents the AMS results measured from the 536 specimens of Zhongba section. The Cretaceous AMS fabrics is featured by a cluster of $k_1$ axe perpendicular to shortening direction and $k_3$ axe normal to bedding, while the Paleogene AMS fabrics display a weakly-clustered girdle of $k_3$ axe and show typical “pencil structure”, which indicates more intense deformation [21-22]. The mean pitch directions of $k_1$ calculated for each of the four lithological units by using Fisher statistical method, display a rotational pattern from WNW-ESE (112°) to NW-SE (129.3°) across the K-Pg boundary, and ~10° clockwise rotation at ~32Ma (Figure 4b1, c1).

Unlike the embryonic AMS fabrics which are mainly controlled by the stable hydrodynamic environment and paleocurrent, the AMS results of Unit 1 present that $k_1$ directions concentrated and parallel to the bedding, and it was probably related to the initial deformation [22]. Because weak strains commonly cause $k_1$ directions to be perpendicular to the maximum stress ($\sigma_1$) [21], we infer that the regional compressional direction recorded in the Upper Cretaceous succession (~74.5-69.2Ma) was in NEN-SWS (in the present coordinates without block rotation) and rotated to the NE-SW direction in the Paleogene. This result supports the view the Xining basin was continuously under the compressional stress environment spanning the period from Late Cretaceous to Early Cenozoic.

![Figure 4](image-url)
4. Discussion: Implication of the K-Pg boundary unconformity in NE Tibet

Stratigraphically, the timing of this unconformity (~69.2-49.3Ma) constrained by the Zhongba magnetostratigraphic section provides the enveloping time-span for the real initial age of this K-Pg tectonic event in northern Tibet. This time interval corresponds to the late Cretaceous to Paleocene regional compressional event documented in central-southern Tibet, with the development of the Gangdese proto-Plateau, significant Late Cretaceous to Paleocene magmatic “flare-up” [23-24], major crustal shortening and various basins infilling [25-28], formation of a flexural foreland basin system along the Bangong-Nujiang suture (BNS) and Tanggula Shan orogen [29-31] (Figure 5A), all of these indicating that the Tibetan crust had been thickened substantially prior to the India-Eurasian collision.

Kapp et al. [32] proposed that northward underthrusting of the Lhasa block beneath the Qiangtang terrane in the latest Cretaceous to earliest Paleogene. This Andean-type retro-arc thrusting system may result from low-angle subduction of the Tethyan oceanic lithosphere beneath the Eurasian continent in late Cretaceous [33]. This process may trigger the basal tractions from mantle flow in a complicated mantle environment, as through “slab suction” of old slab remnants beneath Tibet [34], and then influence the vast areas across the NE Tibet Plateau. In short, the overlapping of the time span across the K-Pg unconformity boundary in NE Tibet must record the tectonic transition from the Neo-Tethys subduction to the India-Eurasian collision.

As to the Early-Cenozoic period, some authors hold the view that extensional regime may dominated the NE Tibet, as evidenced by the extensional normal faults observed in the Paleogene strata of the Xining and other basins in the NE-margin of the Tibetan Plateau [17, 35]. This NW-SE extensional regime seems consistent with that prevailed in the Weihe graben and in the southern North China basins in late Paleogene [36]. This finding led to an interpretation that the NE margin of the Tibetan Plateau may have also affected by far-field effect produced by the Pacific plate subduction [17]. In fact, these two plate tectonic processes, the India-Eurasia collision in southern Tibet and westward subduction of the Pacific Plate along the eastern margin of the Asian continent, have operated synchronously in Cenozoic and may have been interacted with each other, which exerted significant effects in the region of east and west Qinling. The NE-SW compression in Paleogene, as revealed by AMS results of the Zhongba section, may favour an eastward escape of the crustal fragments in NE Tibet, accommodated by sinistral strike-slip motion along major boundary fault zones,

![Figure 5.](image-url)

Figure 5. Sketch showing deformation model of the Tibetan Plateau during late Cretaceous 70-60Ma (A) and Paleogene 55-22Ma (B).
as documented in East Qinling [36] (Figure 5B). We suggest that normal faults may form locally in the foreland basin.

5. Conclusion

Magnetostratigraphy of a Late Cretaceous to Early Cenozoic succession across the Zhongba section in the eastern Xining basin yielded the spanning period of ~74.5-69.2 Ma for the Upper Cretaceous unit, of ~49.3-22.0 Ma for the overlying Paleogene unit. This sedimentary succession was punctuated by two distinct unconformities. The lower K-Pg unconformity represents a depositional hiatus of ~19.9 Ma duration, possibly registered the period of the tectonic transition from the Neo-Tethys oceanic plate subduction to the India-Eurasia collision in southern Tibet. The NE-SW compression in Paleogene, as revealed by AMS results of the Zhongba section, may favour an eastward escape of the crustal fragments in NE Tibet, accommodated by sinistral strike-slip motion along major boundary fault zones, arousing several local transtensional faults in the foreland basin.

References

[1] Tapponnier P, Xu Z Q and Roger F 2001 Science 294 5547
[2] Clark M K, Farley K A and Zheng D W 2010 Earth. and Plan. Sci. L. 296 1-2
[3] Dai S, Fang X M and Dupont-Nivet G 2006 JGR: Solid Earth. 111 B11102
[4] Duvall A R, Clark M K and van der Pluijm B A 2011 E. Plan. Sci. L. 304 3-4
[5] Yin A, Dang Y Q and Wang L 2008 Geol. Soc. of A. Bull. 120 7-8
[6] Li W, Dong Y P and Guo A L 2013 J. of A. Ear. Sci. 73
[7] Fang X M, Garzione C and Van der Voo R 2003 Ear. Plan. Sci. L. 210 3-4
[8] Fang X M, Fang Y H and Zan J B 2019 Earth-Science Reviews 190
[9] Dai S, Fang X M and Song C H 2005 Chinese Science Bulletin 50 15
[10] Ji J L, Zhang K X and Clift PD 2017 Gondwana Research 46
[11] Liu S F, Zhang G W and Pan F 2013 Basin Research 25 1
[12] Wang W T, Zhang P Z and Kirby E 2011 Tectonophysics 505 1-4
[13] Wang W T, Zhang P Z and Liu C C 2016 JGR: Solid Earth 121 11
[14] Metcalfe I 2013 J. of A. Ear. Sci. 66
[15] Yuan J, Yang Z Y and Deng C L 2020 National Science Review nwaa173
[16] Wang W T, Kirby E and Zhang P Z 2013 Geol Soc of A Bull 125 3-4
[17] Fan L G, Meng Q and Wu G L 2019 Ear. Plan. Sci. L. 514
[18] Zhai Y P and Cai T L 1984 Gansu Geology 1
[19] Horton B K, Dupont-Nivet G and Zhou J 2004 JGR: Solid Earth 109 B04402
[20] Ye L S 1976 Qinghai Geology 3
[21] Paré J M 2004 Geological Society, London, Special Publications 238 1
[22] Jia D, Chen Z X and Luo L 2007 Progress in Natural Science 17 5
[23] Zhang K J, Zhang Y X and Tang X C 2012 Earth-Science Reviews 114 3-4
[24] Ma L, Wang Q and Li Z X 2013 Lithos 172
[25] Leier A L, DeCelles P G and Kapp P 2007 Geol. Soc. of A. Bull. 119 1-2
[26] Kapp P, DeCelles P G and Leier A L 2007 GSA Today 17 7
[27] Jin C S, Liu Q S and Liang W T 2018 Ear. Plan. Sci. L. 486
[28] Xu Z Q, Zhao Z B and Ma X X 2019 Acta Geologica Sinica 93 1
[29] Kapp P, DeCelles P G and Gehrels G E 2007 Geol. Soc. of A. Bull. 119 7-8
[30] Li Y L, Wang C S and Dai J G 2015 Earth-Science Reviews 143
[31] Wu Z H, Barosh P J and Ye P S 2015 J. of A. Ear. Sci. 114
[32] Kapp P, Yin A and Harrison T M 2005 Geol. Soc. of A. Bull. 117 7/8
[33] Ding L and Lai Q Z 2003 Chinese Science Bulletin 48
[34] Conrad C P and Lithgow B C 2004 JGR: Solid Earth 109 B10407
[35] Zhang J, Wang Y N and Zhang B H 2016 Basin Research 28 2
[36] Zhang Y Q, Dong S W and Li J H 2019 Tectonophysics 769