SICHUAN-YUNNAN SEISMIC ACTIVITY, UPLIFT OF TIBET PLATEAU AND RECORD IN LOESS PALEOSOL SEQUENCES

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ABSTRACT

The Sichuan and Yunnan region is located on the south-east edge of the Qinghai-Tibet Plateau, where the Indian and Eurasian plates have continuously collided since about 50 Ma ago. The strain over rocks causes earthquakes to occur regularly, such as the 2008 Sichuan earthquake. These frequent earthquakes are manifestations of the Tibetan Plateau uplift in modern times. Continued uplift of the Qinghai-Tibet Plateau gradually causes the height difference between the land and ocean. This led to increased differences in temperature and more intense summer and winter monsoons. Such intense monsoons thus left a record in loess paleosol sequences: a long-term trend of magnetic susceptibility and particle size. These records show that magnetic susceptibility and particle size increased over the same period. This may imply that there are non orbital elements also affecting the aeolian records. Whilst the Qinghai-Tibet Plateau uplift might be a multi-factor, multi-stage and multi-level non-uniform process, from a macro point of view, the entire plateau uplift may have been basically at a constant speed up the process according to the trend analysis of aeolian grain size.

Key Words: Uplift of tibetan plateau, Earthquakes, Sichuan & Yunan region, Loess deposits

INTRODUCTION

Seismic activity is a consequence of the earth's evolution. This evolutionary process can take on two different forms. First, rapid mutation through strong seismic activity, volcanic eruptions and so on, such as the 2008 Wenchuan earthquake. Secondly, a gradual, mostly unnoticed crustal movement, such as the collision of the Indian plate and Eurasian plate at a few millimeters or centimeters per year (Ding and Lu, 1986; Yang *et al.*, 2005; Zhang *et al.*, 2004; Wang *et al.*, 2001). Such two plates collided and overlapped each other showing stronger movements in the south and west across the Qinhai-Tibetan Plateau (Ding and Lu, 1986; Yang *et al.*, 2005). Whilst undetectable by humans, this slow movement was detected and measured by Global Positioning System (GPS). Such GPS data indicate that the Plateau is contracting horizontally, but expanding vertically. This accumulation of millimeter movements since the Cenozoic over several thousands of years has shaped today's unique third pole - the Tibetan Plateau.

Earth scientists have proposed many alternate theories around the models, time, mechanisms and heights of the Tibetan Plateau uplift; summarized in this discussion. There is general agreement however, that the Indian and Eurasian plate collision began about 50 Ma ago, and

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that the uplift of the Qinghai-Tibet Plateau is the result of plate collision (Teng *et al.*, 1997; Li *et al.*, 1998; Liu *et al.*, 2001; Zhang *et al.*, 2004; Wang *et al.*, 2001). The Qinghai-Tibet Plateau is an enormous geographical unit, its great height and vast plains make it one of the Earth's great cold sources in winter and heat sources in the summer. The Plateau uplift has resulted in increased temperature contrasts between the continent and oceans, intensifying the high and low pressure systems and thus intensifying the South and East Asian monsoons (Qian *et al.*, 1996). This has been recorded in great detail by aeolian strata in the Loess Plateau. The summer monsoon affects the strength of water vapor transmission and the role of pedogenic development in the Loess Plateau; such strength of pedogenesis has also been recorded in the aeolian strata. This implies that the particle size and intensity of soil development on loess sections has a close relationship with the formation of the Qinghai-Tibet Plateau. The uplift of the Qinghai-Tibet Plateau is a very complicated geological process; in this paper we have tried to link the modern seismic activities with the uplift of the Qinghai-Tibet Plateau, and discuss a theory of the Qinghai-Tibet Plateau uplift based on analyzing the trend of aeolian records since 22 Ma.

SEISMIC ACTIVITY AND QINGHAI-TIBET PLATEAU UPLIFT

The tectonic fracture zone of the Sichuan-Yunnan region is located on the south-eastern edge of the Qinghai-Tibet Plateau. The region has mainly developed to the north-west of the Xianshuihe River - Anning River - Xiaojiang fault, the Jinsha River - Red River fault, Nujiang - Lancang fault and north-east of the Longmen Mountains - Jinpingshan - Yulong Snowy Mountain fault and other large faults. The intense tectonic activity, seismic activity and active faults in the area are closely related to each other, mainly due to tectonic earthquakes. In this area, seismic activity occurs with high frequency and high strength. This is the manifestation of Qinghai-Tibet Plateau uplift in modern times: May 12, 2008 Wenchuan (8.0 on the Richter scale); July 1, 2009 Deyuan Mianzhu, Sichuan (5.6); July 9, 2009 Yao'an County, Chuxiong Yunnan Province, (6.0); November 14, 2001, Kunlun Mt., Qinghai (8.1). These earthquakes all occurred in recent years around the Qinghai-Tibet Plateau, indicating that the uplift of the Qinghai-Tibet Plateau is continuing. According to the State Seismological Bureau, from May 12, 2008 (Wenchuan earthquake) to June 30, 2009, more than 57,000 aftershocks took place within the aftershock zone. Among those were 254 shocks between 4.0-4.9, 36 shocks between 5.0-5.9, and 8 shocks between 6.0-6.4. On May 24, 2008, the 6.4 magnitude earthquake in the Qingchuan area was the most intense aftershock. These records indicate that our planet is alive and moving.

The Sichuan and Yunnan region is an active seismic area; recorded seismic data can be traced back to the early 20th century. According to data collected by the China Seismological Bureau, since the 20th century, there have been 37 earthquakes of a magnitude greater than 6.7; of which 21 were of magnitudes greater than 7.0, which is about 57% of the total. Long *et al.* (2006) predicted that an earthquake of a magnitude greater than 6.7 was likely to occur in 2008, based on analysis of these historical seismic records. Unfortunately, they were right. Although accurate prediction of earthquake time and location remains an important question of international scientific research, that paper could be an important contributor to this prediction. This paper reveals that, whilst seismic predictions at a specific location are difficult to achieve with great accuracy, predictions could be made with less accuracy over a larger region as Long *et al.* (2006) have done.

QINGHAI-TIBET PLATEAU UPLIFT AND AEOLIAN DEPOSITS

On the northeastern margin of the Qinghai-Tibet Plateau is a vast area known as the Loess Plateau. Unique aeolian strata in the Plateau provide an excellent record for research on the earth's evolution. The Chinese loess paleoclimate research has made remarkable achievements, under the joint efforts of several generations of scientists. Chinese loess accumulation was first recorded in 2.6 Ma (Heller and Liu, 1982; Liu *et al.*, 1988a), but began at around 1.6 Ma in the Lanzhou area, the western part of the Loess Plateau (Burbank and Li, 1985). The underlying Tertiary Red Clay (2.6 ~ 7.6 Ma) formation is also an aeolian production (Liu *et al.*, 1988b; Ding et. al., 1998; Yang *et al.*, 2000), and a recent study (Guo *et al.* 2002; Qiao *et al.*, 2006) reported an even earlier 22-6 Ma aeolian strata in Gansu province. Therefore, aeolian deposits in China have a complete record throughout the last 22 Ma. Two important parameters, particle size and magnetic susceptibility, have been widely used as proxy indicators for winter and summer monsoon behavior (Heller and Liu, 1984; Liu *et al.*, 1992; Ding *et al.*, 1998; 2002; Guo *et al.*, 2002; Liu and Deng, 2009) and play an important role in studying global change. During the glacial period, winter monsoon strengthened while summer monsoon weakened, loess deposits increased but pedogenesis weakened. During the interglacial period, however, the opposite occurred: the summer monsoon strengthened, bringing more humidity for soil development, but winter monsoon weakened and reduced loess accumulation. In the Loess Plateau, the ancient soil (paleosol) was of a reddish brown color. With the strengthening of soil development (increase in temperature and humidity), the paleosol color darkened and became known as the terrestrial aeolian loess paleosol sequence - one of the most direct records of climatic history. Additionally, the color change from light to dark reddish brown of paleosols is correlated with the concentration of magnetic minerals such as magnetite, maghemite and hematite, as well as the grain size. The reason for higher susceptibility in soils is found to be mainly due to the formation of a number of extra fine grains high-susceptibility minerals (maghemite and magnetite) during pedogenesis (Heller and Liu, 1984; Liu X.M. *et al.*, 1992, 1999; 2008; Liu and Deng, 2009). In this way, the study of paleo-climate from the qualitative research of soil observation in the past has evolved into quantitative and semi-quantitative studies of environmental magnetism and grain size analysis.

In the Chinese Loess Plateau, both magnetic susceptibility and grain size from typical profiles over the Loess Plateau show an increasing trend (Fig. 1). This trend is even more evident towards the west, closer to the Qinghai-Tibet Plateau. Liu *et al.* (2009) tried to explain that this is due to the uplift of the Qinghai-Tibet Plateau. The unique uplift of the Plateau enables simultaneous strengthening of the winter and summer monsoons. Many studies have shown that the geological process of climate change is mainly influenced by the astronomical orbital cycle (Berger and Loutre, 1991; Ruddiman, 2001; Ding *et al.*, 2002). According to this cyclical theory, its long-term trend is a straight line – averaged across time (a straight line superpose/or parallel to time scale). However, the observed long-term climatic trends from Quaternary loess (Fig. 1 and Fig. 2) and the Tertiary Red Clay (Fig. 2) are not a straight line across time. Instead, there is an upward inclining trend, indicating that there is a non-cyclical (tectonic) factor (Ruddiman, 2001) present. Liu *et al.* (2009) attribute this non-linear cycle factors to the uniform tectonic uplift of the Qinghai-Tibet Plateau.

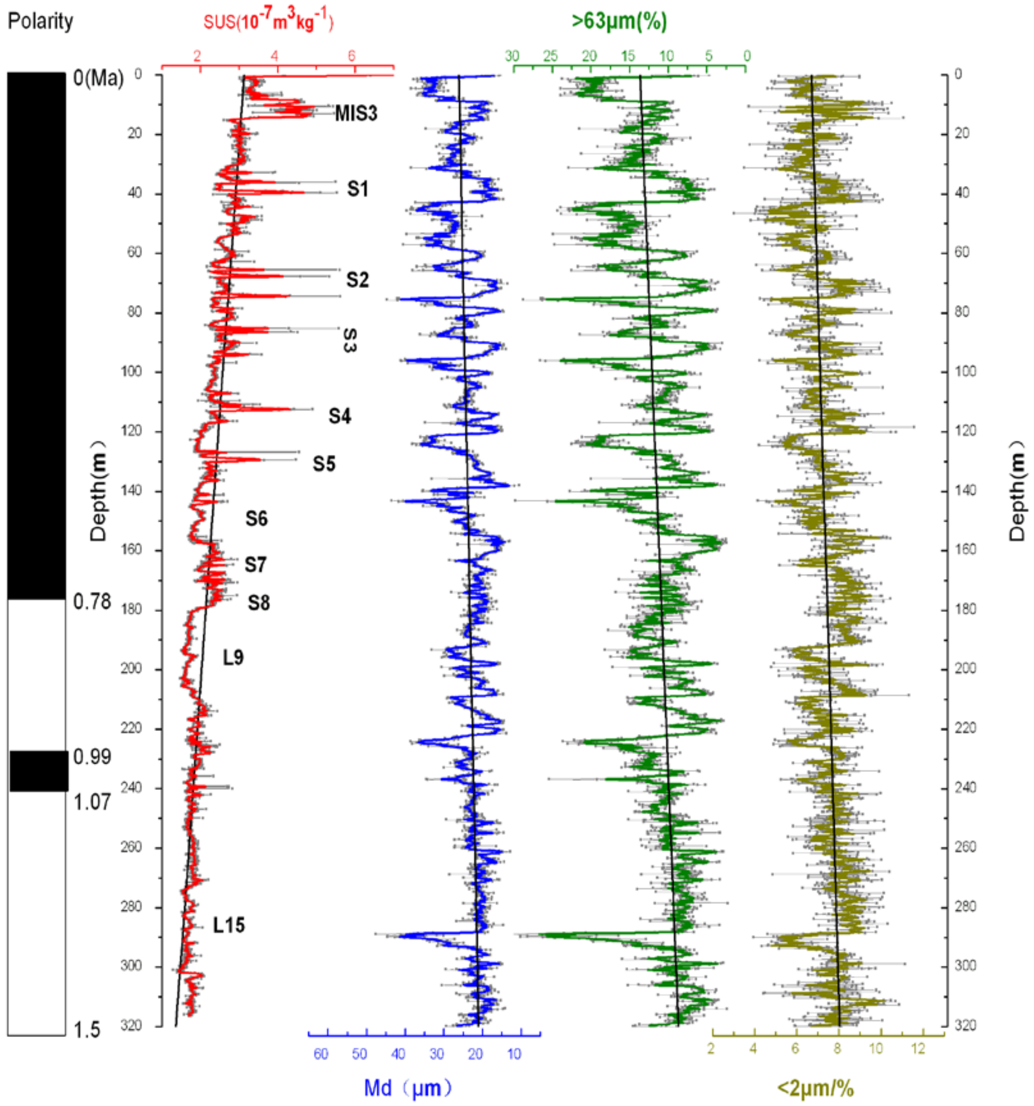

Fig. 1 The magnetic susceptibility (left) and 3 groups of grain-size (right) curves of Jiuzhoutai loess section in Lanzhou showing gradual increase from bottom to top (from Liu *et al.*, 2009; paleomagnetic age from Burbank and Li, 1985)

We can use the trend from the loess record for the last 22 Ma to analyze whether the uplift of the Qinghai-Tibet Plateau has accelerated, decelerated, or remained constant. Figure 1 shows the general trend of grain size and magnetic susceptibility from Lanzhou section in Gansu province. We can see that the trends of both the particle size and magnetic susceptibility are steadily increasing straight lines, with no turning points. This trend indicates that the uplift of the Qinghai-Tibet Plateau, from a macro point of view, was a slow and gradual process, even though from another point of view, this process can appear multi-stage, non-isokinetic and non-uniform (Fig. 3) (Zhong and Ding, 1996; Li and Fang, 1998).

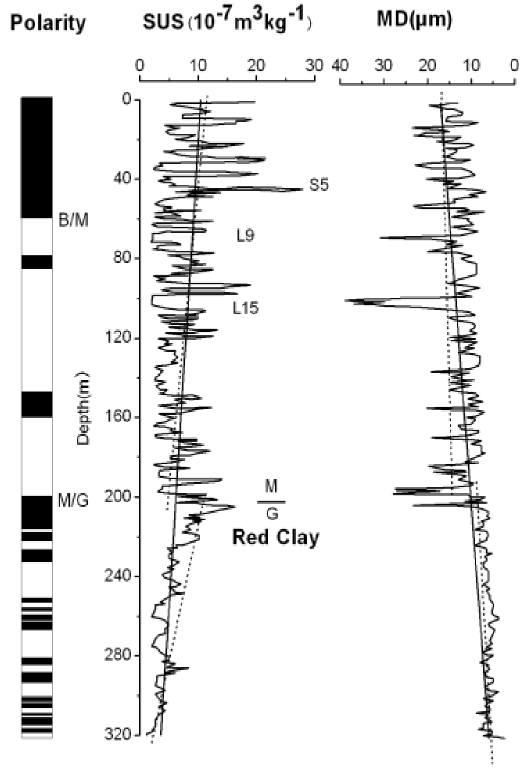

Fig. 2 The variation trend of the magnetic susceptibility (10^{-7} m^3kg^{-1}) and grain size (medium grain size Md: μm), age covers 0-7.8 Ma (from Yang *et al.*, 2000).

DISCUSSIONS AND CONCLUSIONS

The Characteristics of Plateau Uplift

Scholars agree that the seismic activity of the Sichuan-Yunnan region and the uplift of the Qinghai-Tibet Plateau are due to the collision of the Indian and Eurasian plates during the last 50 Ma (Coleman and Hodges, 1992; Harrison *et al.*, 1992; Spicer *et al.*, 2003; Rowley and Currie, 2006; Teng *et al.*, 1997; Li and Fang, 1998). The collision of the plates is the source of tectonic movement for both seismic activity and the uplift of the Plateau. From a geological point of view, the expansion and compression of the plates is a relatively slow and uniform long-term process, compared with volcanic eruptions and tectonic earthquakes. Its dynamics characterizes compression and expansion at a constant rate. Modern GPS measurements indicate that the Qinghai-Tibet Plateau is currently contracting at a rate of a few centimeters per year (Ding and Lu, 1986; Yang *et al.*, 2005; Zhang *et al.*, 2004; Wang *et al.*, 2001). The rate of contraction differs throughout the Plateau: greater in the south (southern Tibet, 26 mm/a) and lesser in the north (Junggar) (14 mm/a; Ding and Lu, 1986; Yang *et al.*, 2005). Similarly, the contraction is greater in the west (Kashi) and lesser in the east (Hami) (Zhang *et al.*, 2003). This reflects that the stress field of plate collision varies from region to region. However, at any given location, observed contraction rates have been close to constant for many years (Ding and Lu, 1986; Zhang *et al.*, 2003), this implies that plate collision has occurred with uniform force over a long period of time. This is consistent with the long-term trend in the Chinese loess record reflecting a uniform trend in the uplift of the Qinghai-Tibet plateau.

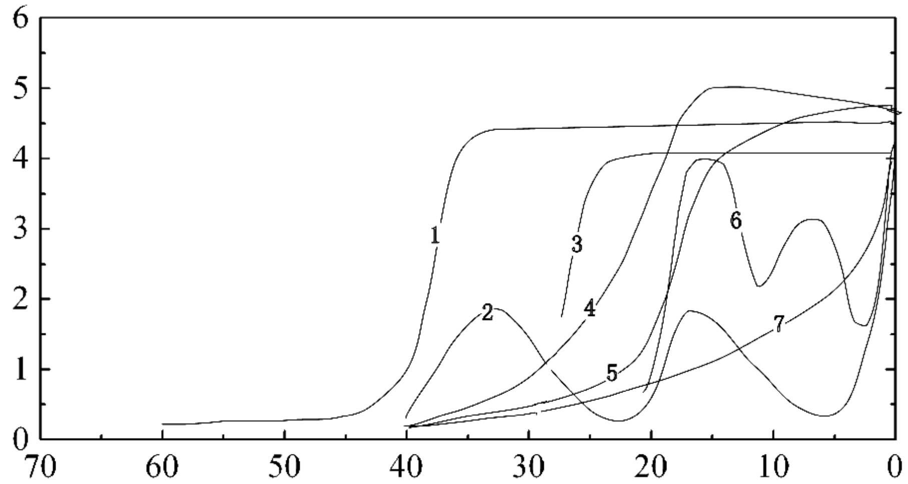

Fig. 3 Scheme of different standpoints on Tibet Plateau uplift (modified from Li *et al.*, 1998). X-axis: age (Ma) and Y-axis: altitude (km).
1: Rowley and Currie (2006); 2: Li *et al.* (1998); 3: Wu *et al.* (2007); 4: Coleman and Hodges (1995); 5: Harrison *et al.* (1992); 6: Rea (1992) + Zhong and Ding (1996); 7: Xu *et al.* (1973) +Li (1995)

The Process and models of Plateau Uplift

The uplift of the Qinghai-Tibet Plateau is undoubtedly a complex process. As discussed above, GPS measurements show variation in the speed of contraction between the north and south and between the east and west regions of the Plateau. Fig. 3 summarizes a few major hypothesises regarding the process and models of Plateau Uplift. Whilst on a regional level, Plateau contraction is multi-stage and non-uniform, on a macro level, based on the long term trend of wind sediment grain size, Plateau uplift over time has been a gradual and uniform process.

While scholars agree on the source of the frequent seismic activity and uplift of the Qinghai-Tibet Plateau, there is much debate about the process and manner of the uplift (Fig.3). There are 3 main divergent points of view: (1) The Qinghai-Tibet Plateau rose to its current height between 8 and 40 Ma ago, after which there has been no further elevation change. Coleman and Hodges (1995) believe the Plateau uplift began around 40 Ma ago, reaching its highest elevation of more than 5000 meters 14 Ma ago, then declining to its present elevation. Harrison *et al.* (1992) postulated that the Plateau reached its present elevation 8 Ma ago, after which there has been no significant uplift. Based on studies of leaf fossils Spicer *et al.* (2003) hypothesized that there is no overall Plateau uplift and that the Plateau was at an elevation of 4600 meters 15 Ma ago. Using oxygen isotope data from the central basin, Rowley and Currie (2006) proposed that the central Plateau reached more than 4,000 meters at least 35 Ma ago, with no further uplift since then; Wu *et al.* (2007) also proposed a similar theory in Fig. 3. (2) The Plateau has continued to rise since 40 Ma ago, but the uplift has accelerated since 8 Ma go: Mericier (1987), Xu *et al.*, (1973) and Li (1995); (3) The uplift is multistaged, non-isokinetic, non-uniform and waving uplift: Li and Fang (1998), Sun and Zheng (1998), Rea (1992), Zhong and Ding (1996); Zheng and Yao (2004). Some of these hypotheses have been shown in Figure 3.

In contrast to the aforementioned studies, this paper attempts to analyze the long term macro trend (but not regional trend) of the Qinghai-Tibet Plateau uplift based on grain size trends (Fig. 1 and Fig. 2). Based on this analysis, we have made two key observations about the

Plateau uplift process. (1) Between 22-8 Ma ago, there was either no uplift or the Plateau was at a height below 2,000 meters above sea level. This is based on no observable change in grain size between 22-8 Ma ago (grain size trend is parallel to the time scale) (Qiao *et al.*, 2006), implying either that the altitude was constant, or that it was below 2,000 meters – altitudes lower than 2,000 meters can not noticeably impact monsoon activity (Ruddiman and Kutzbach, 1989; Tang, 1993; Liu, 1999) . Indeed, only seasonal variations are recorded between 22-8 Ma ago. (2) From 8 Ma ago, the Plateau has begun continuously gradual uplift. This shown through the clear positive correlation between the grain size and time i.e. grain size has increased gradually over the last 8 Ma. Furthermore, the gradient becomes steeper at 2.6 Ma and 8 Ma ago, possibly indicating the rate of Plateau uplift increased at 2.6 Ma and 8 Ma ago respectively (Fig. 1 and Fig. 2). In summary, while the Plateau uplift is a complex and intricate process, from a macro point of view, the long term aeolian trend suggests a gradual and constant uplift from 8 Ma ago.

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