Earth and Planetary Science Letters 453 (2016) 108–118

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Constraints on the uplift mechanism of northern Tibet

Haijian Lu[a,*], Bihong Fu[b], Pilong Shi[b], Yuanxu Ma[b], Haibing Li[a]

[a] Institute of Geology, Chinese Academy of Geological Sciences, Baiwanzhuang Road #26, Beijing 100037, China
[b] Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Dengzhuang South Road #9, Beijing 100094, China

ARTICLE INFO

Article history:
Received 9 March 2016
Received in revised form 4 August 2016
Accepted 8 August 2016
Available online 26 August 2016
Editor: M. Bickle

Keywords:
magnetostratigraphy
tectonic rotation
uplift mechanism
tectonic regime
Altyn Tagh fault
northern Tibet

ABSTRACT

Enhanced latest Oligocene to present uplift of northern Tibet is manifest in a variety of geological records. However, the main controversy is how the crust came to be thickened. Theories seeking to explain the growth of northern Tibet include removal of the mantle lithosphere beneath Tibet and the cessation of fast motion on major strike-slip faults. To address this issue, we conducted a detailed paleomagnetic study in the central Kumkol basin, south of the Altyn Tagh fault (ATF). Combined with our previous study from the Janggalsay area, north of the ATF, magnetic declination data suggest fast strike-slip motion for the left-lateral ATF between 22 and 15 Ma. However, the fast motion along the ATF terminated between 15 and <6.3 Ma. This change was accompanied by widespread and simultaneous uplift of northern Tibet at ∼15 Ma. Our results argue in support of a Mid-Miocene transition in tectonic regime from extrusion to distributed shortening in northern Tibet and emphasize the role of the ATF in governing widespread and simultaneous uplift of northern Tibet.

1. Introduction

It is increasingly being recognized that the strain associated with the Cenozoic convergence of India and Asia was transferred to northern Tibet shortly after the collision. However, records of tectonic deformation are only preserved in local regions, such as the western Qaidam basin, the Xining basin and the western Qinling (Yin et al., 2008; Horton et al., 2004; Duvall et al., 2011). Recent mapping of syn-tectonic sedimentary units and low-temperature thermochronology from northern Tibet and its margins suggest that northern Tibet has experienced widespread and episodic shortening deformation and hence mountain building since the latest Oligocene (Wang et al., 2012; Duvall et al., 2013; Yuan et al., 2013; Jiang and Li, 2014). Two hypotheses have been proposed to account for the synchronous contractile deformation and rise of northern Tibet since most scientists do not support the existence of widespread lower crustal flow in northern Tibet (Lease et al., 2012; Tian and Zhang, 2013; Zhao et al., 2013). One school of thought proposes that convective removal of the lower lithosphere beneath Tibet suddenly exerted an increased outward force on Tibet's margins, which subsequently caused an abrupt upward growth of the plateau margins (England and Houseman, 1989; Molnar et al., 1993). Alternatively, the other school of thought argues that the development of distributed shortening deformation should be attributed to the motion of major strike-slip faults. The 25–20 Ma onset of rapid cooling of the Tian Shan may have been linked to a switch from extrusion-dominated to crustal-thickening dominated tectonics as a result of the termination of the major left-lateral movement on the Red-river fault system at ∼23 Ma (Hendrix et al., 1994; Sobel and Dumitru, 1997). Some tectono-sedimentary analyses along the ATF also indicate a re-organization in tectonic style with Oligocene to Mid-Miocene substantial strike-slip motion along the ATF being replaced by distributed crustal thickening and plateau uplift in northern Tibet since 16–13 Ma (Yue and Liou, 1999; Ritts et al., 2004, 2008).

Herein, we try to reveal vertical-axis rotation deformation of the strata south and north of the ATF to test these two models. A growing body of evidence from studies on the tectonics of Tibet has demonstrated a strong partitioning of oblique motion into boundary-parallel strike-slip motion, orthogonal thrusting and large vertical-axis rotation deformation (Avouac and Tapponnier, 1993). Paleomagnetic, geodetic, and seismic studies have also provided compelling evidence that rotation of crustal fragments about vertical axes is a common feature of active continental deformation, in particular of areas in which the deformation is distributed over a wide zone (e.g., McKenzie and Jackson, 1983; Yin et al., 2000; Chen et al., 2002; Zhang et al., 2004). The most direct and independent method to determine block rotations is from paleomagnetic data describing places where the rotation of strike-slip faults results in changes in magnetic declination. We carried out a detailed paleomagnetic study in the Kumkol basin, south of the AFT. Rotation of blocks limited by strike-slip faults seems

---

[*] Corresponding author.
E-mail address: haijianlu2007@126.com (H. Lu).

http://dx.doi.org/10.1016/j.epsl.2016.08.010

to be confined to the upper crust (upper 15–20 km) (Schreurs, 1994). Compared to the quasi-rigid Qaidam block (Braitenberg et al., 2003; Yin et al., 2008), the Kumkol basin and surroundings more readily induce a horizontal decoupling surface at depth in distributed shear deformation. Combined with our existing study from the Janggalsay area north of the ATF (Lu et al., 2014), the geomagnetic declination data suggests a mutually consistent rotational deformation history for the two sites. The results emphasize the role of the ATF in regulating the Oligocene to present tectonic evolution of northern Tibet and indicate that the middle Miocene tectonics of northern Tibet is dominated by distributed shortening.

2. Geological setting

The ENE–WSW trending Altyn Tagh fault (ATF) is approximately 1600-km long and separates the low-lying Tarim Basin to the north from Tibet to the south (Fig. 1A, B). More than 400 km of left-lateral offset on the ATF (Yue and Liou, 1999; Chen et al., 2002), has accommodated the eastward tectonic extrusion of northern Tibet. However, geodetic slip-rates measured from InSAR and GPS cluster around 5–15 mm/a, with a decrease toward the east (Jolivet et al., 2008). The relatively low rates are considered to be too small to support large-scale continental extrusion. The E–W to WNW–ESE striking left-lateral Kunlun fault marks the northern boundary of the high-elevation, low-relief main part of Tibetan Plateau for ∼1500 km (Fig. 1). Recent studies suggest a 10 ± 2 Ma initiation of motion for the central Kunlun strike-slip fault (Fu and Awata, 2007; Duvall et al., 2013).

A broad triangular area consisting of the Kumkol basin, the Qiman Tagh range, and the Qaidam basin are immediately bounded by the Altyn Tagh and Kunlun faults to the NW and to the south, respectively (Fig. 1A). The Qaidam basin, with an average elevation of ∼3000 m, is the largest intermontane basin covering an area of ∼120,000 km^2 in northern Tibet. The dominant structures in the Qaidam basin are a series of NW-trending fold-thrust belts (Yin et al., 2008). Located at the western end of the East Kunlun range, the Qiman Tagh range is considered to accommodate significant NE–SW transpressional deformation related to the sinistral Kunlun fault (Cheng et al., 2014). With an average elevation of ∼4200 m and an area of ∼17,500 km^2, the Kumkol basin is rhomb-shaped in map view (Xiao et al., 2005) (Fig. 1A). Several thrust faults develop along the southern and northern margins, as well as in the center of the basin and are genetically thought as a compressive horse tail structure related to the Kunlun fault (Jolivet et al., 2003). Cenozoic sedimentary rocks crop out mostly along the central axis of the basin (Fig. 1C).

The most continuous and longest sedimentary sequence is exposed along the Baiquanhe section of the central Kumkol basin, where the north-flowing Baiquan River cuts a major anticline in the north and a minor syncline in the south (Fig. 2A, B). The northern Baiquanhe section dips to the NE at angles of 5–45° (Fig. 2A). A steep north-dipping thrust fault breaks through the south limb of the anticline (Fig. 2A).

Previous studies subdivided the Kumkol strata into the Oligocene Shimagou Formation (Fm), the Miocene Shibiliang Fm, and the Pliocene Hongshiliang Fm (Xiao et al., 2005; ShaanXi Geological Survey, 2002). The Shimagou Fm in the northern Baiquanhe section is ∼1277 m-thick and consists dominantly of interbeds of gray conglomerates or sandstones with yellow–brown or yellowish massive, or tabular mudstones (Fig. 2C). The conglomerate deposits exhibit occasional cross-stratification and normal grading. The Shimagou Fm shows a generally fining-upward sequence. The Shibiliang Fm is ∼1367 m-thick and is composed mostly of interbeds of gray–green massive siltstones or muddy siltstones with brown or yellow massive or tabular mudstones (Fig. 2D). The lithology of the Hongshiliang Fm is essentially similar to that of the Shibiliang Fm, except that the color of the mudstone deposits in the Hongshiliang Fm is red-brown (Fig. 2E). The thickness of the Hongshiliang Fm is far more than 225 m as observed in the northern Baiquanhe section.

3. Methods

Sampling was conducted during three consecutive field seasons. A magnetostratigraphic study was carried out on an almost continuous sedimentary section along the northern Baiquanhe in an effort to obtain a chronostratigraphy. We drilled 751 cores spanning ∼2869 m with an average interval of 3.8 m/sample. In addition, N1–N10 and S1–S3, comprising 10–15 drill-core samples per site, were sampled from the northern and southern limbs of the anticline in order to permit a fold test and to test for potential vertical-axis rotations within the Baiquanhe section (Fig. 2). All 2.5-cm-diameter core specimens were obtained in situ using a gas-powered drill. Paleomagnetic samples were oriented with a magnetic compass after correcting for the local magnetic field. We collected samples in fine-grained mudstones, siltstones and sandstones.

The samples were analyzed at the paleomagnetic laboratory of Lanzhou University, China. All samples were subjected to stepwise thermal demagnetization in 19 steps using a TD-48 thermal demagnetizer. Specimens were progressively heated to 690 °C typically in (1) 100–150 °C steps up to 450 °C, and (2) 10–50 °C steps up to 690 °C. Natural remanent magnetization (NRM) and demagnetization measurements were conducted on a 2G-755R cryogenic magnetometer housed in a shielded room with an internal residual field lower than 150 nT.

Isothermal remanent magnetization (IRM) acquisition experiments were performed using an AGICO JR-6A Dual Speed Spinner Magnetometer at the Paleomagnetic Laboratory of the Institute of Geomechanics, CAGS in Beijing. The hard, medium, and soft components were treated in DC fields of 2.2 T, 0.4 T, and 0.15 T along three mutually orthogonal axes (Lowrie, 1990). The specimens were then subjected to progressive thermal demagnetization to 690 °C at 20–80 °C intervals using a thermal demagnetizer (ASC TD-48).

4. Paleomagnetic results

The intensity of natural remanent magnetization (NRM) for the northern Baiquanhe specimens is typically 10^{-2} A/m, with a range of 10^{-1}–10^{-3} A/m. A low-temperature component is typically removed by 150 °C, but sometimes not until 450 °C (Fig. 3). It does not usually decay toward the origin, and thus likely represents a secondary overprint. A higher temperature component (HTC) was separated between 300 °C and 580 °C, or 690 °C for most samples (Fig. 3). The high-temperature component decays toward the origin, typically exhibits stable behavior until 650–690 °C, and is interpreted to reflect the characteristic remnant magnetization (ChRM). Progressive unblocking of the high-temperature component between 300 °C and 580 °C indicates a magnetite carrier. Complete unblocking of the high-temperature component by 690 °C, however, suggests that a hematite carrier is also present. The predominant remanence carriers (magnetite and hematite) of the Baiquanhe section are confirmed further by thermal demagnetization of three-axis composite IRMs (Fig. 4). The high- and medium-coercivity components for all the three components show an unblocking temperature of ∼580 °C (Fig. 4A, C), or ∼690 °C (Fig. 4A–D), indicating the dominant presence of hematite and magnetite.

The characteristic remnant magnetic (ChRM) directions were determined with principal component analysis (Kirschvink, 1980) using at least three consecutive temperature steps to determine