

SHI Xuhua, Eric KIRBY, Kevin P. FURLONG, MENG Kai, Erchie WANG, Ruth ROBINSON and LU Haijian, 2013. Determining Crustal Strength from Shoreline Deformation, Central Tibet. *Acta Geologica Sinica* (English Edition), 87(supp.): 151-152.

Determining Crustal Strength from Shoreline Deformation, Central Tibet

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Whether the deep crust beneath the central Tibetan Plateau is weak enough to flow on geologic timescales remains one of the first-order questions in the tectonic evolution of this archetypal orogeny (Engleng and Houseman, 1986; Royden et al., 1997; Tapponnier et al., 2001; Beaumont et al., 2001). Geophysical observations of the present physical state of Tibetan crust are consistent with relatively hot, fluid-rich middle crust (e.g., Brown et al., 1996; Nelson et al., 1996; Wei et al., 2001; Unsworth et al., 2005; and see reviews in Klemperer, 2006), conditions favorable for low viscosity (Beaumont et al., 2004). However, the distribution of regions of low seismic velocity (e.g., Yao et al., 2010; Hetényi et al., 2011; Yang et al., 2012) and high electrical conductivity (e.g., Bai et al., 2010) appears to be quite heterogeneous, and bulk rheologic properties determined at post-seismic timescales do not require low viscosity (e.g., Hilley et al., 2005; Ryder et al., 2010; 2011; Wen et al., 2012). Yet, the geologic history of the growth of portions of the eastern Tibetan Plateau appears to require some version of lower crustal flow on a regional scale (e.g., Clark and Royden, 2000; Burchfiel and Royden, 2008). Discrimination of these models thus requires constraints on the rheology of Tibetan crust at longer timescales. Here we constrain the effective elastic thickness (T_e) and viscosity of Tibetan crust by exploiting flexural deformation of highstand Holocene shorelines around Siling Co, in central Tibet, in response to climatically induced lake recession.

Extensive flights of spectacular paleo-shorelines are well-preserved around the lake, extending up to ~100 m above modern lake level. In this study we targeted the most recent highstand shoreline (~4594 m a.s.l.) to examine its deflection. This shoreline is characterized by prominent constructional features (beach ridges, benches, spits, bars and cusps) that continuously connect to

wave-cut scarps. Collectively, these define a clear geomorphic boundary between an older landscape characterized by dissected alluvial channels/gullies and a lower one characterized by younger, recessional shorelines. The age of beach ridges along the highstand shoreline complex range from ~ 8 ka to ~ 4 ka dated by OSL (optically stimulated luminescence), which suggests a relatively stable lake level during this time.

By comparing observed shoreline deflections with results from forward elastic models of flexural response to removal of a 3D water load, the elastic thickness of central Tibetan crust is determined to be relatively thin ($T_e = 13 \pm 2$ km), suggesting that most of the mechanical strength of the crust resides in the upper crust. Moreover, the timescale of lake recession (< 10 ka) implies strain rates on the order of $\sim 10^{-16}$ s⁻¹. These results, when combined with existing constraints on the thermal and seismic velocity structure of the crust in central Tibet, allow us to place bounds on the range of probable viscosity beneath central Tibet. Assuming a simple, two-layer model with a viscous layer beneath the elastic upper crust implies viscosity on the order of $\sim 10^{19}$ Pa s. A more comprehensive consideration of possible strength profiles consistent with available seismic and thermal data is consistent with a significant reduction in effective viscosity below depths of ~ 20 – 40 km. This analysis shows that viscosities above this level range from 10^{20} – 10^{22} Pa s, while viscosities at depth range from 10^{18} – 10^{20} Pa s. Collectively, our findings of thin elastic upper crust and a reduction in viscosity at depth suggests that the middle and lower crust beneath central Tibet is likely relatively weak at timescales of 10^4 – 10^5 yr. But, our results do not require extremely low viscosities ($\sim 10^{16}$ Pa s) required by some of the end-member models for flow in a mid-crustal channel (e.g., Clark and Royden, 2000). Current efforts to better understand the time-dependent lake loads will allow a refined determination of crustal

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Key words: rheology, elastic thickness, viscosity, shoreline deformation, Siling Co

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