Earth and Planetary Science Letters ••• (••••) •••–•••

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Spatio-temporal trends in normal-fault segmentation recorded by low-temperature thermochronology: Livingstone fault scarp, Malawi Rift, East African Rift System

Estelle Mortimer[a,b,*], Linda A. Kirstein[c], Finlay M. Stuart[d], Manfred R. Strecker[a]

[a] Institut für Erd- und Umweltwissenschaften Universität Potsdam, Potsdam, Germany
[b] School of Earth and Environment, University of Leeds, Woodhouse Lane, Leeds, UK[1]
[c] School of Geosciences, University of Edinburgh, West Mains Road, Edinburgh, EH9 3FE, UK
[d] Isotope Geosciences Unit, Scottish Universities Environmental Research Centre, East Kilbride, Scotland, UK

ARTICLE INFO

Article history:
Received 22 March 2016
Received in revised form 12 August 2016
Accepted 29 August 2016
Available online xxxx
Editor: A. Yin

Keywords:
apatite helium thermochronology
normal-fault evolution
fault linkage
East African Rift System

ABSTRACT

The evolution of through-going normal-fault arrays from initial nucleation to growth and subsequent interaction and mechanical linkage is well documented in many extensional provinces. Over time, these processes lead to predictable spatial and temporal variations in the amount and rate of displacement accumulated along strike of individual fault segments, which should be manifested in the patterns of footwall exhumation.

Here, we investigate the along-strike and vertical distribution of low-temperature apatite (U–Th)/He (AHe) cooling ages along the bounding fault system, the Livingstone fault, of the Karonga Basin of the northern Malawi Rift. The fault evolution and linkage from rift initiation to the present day has been previously constrained through investigations of the hanging wall basin fill. The new cooling ages from the footwall of the Livingstone fault can be related to the adjacent depocentre evolution and across a relay zone between two palaeo-fault segments. Our data are complimented by published apatite fission-track (AFT) data and reveal significant variation in rock cooling history along-strike: the centre of the footwall yields younger cooling ages than the former tips of earlier fault segments that are now linked. This suggests that low-temperature thermochronology can detect fault interactions along strike. That these former segment boundaries are preserved within exhumed footwall rocks is a function of the relatively recent linkage of the system.

Our study highlights that changes in AHe (and potentially AFT) ages associated with the along-strike displacement profile can occur over relatively short horizontal distances (of a few kilometres). This is fundamentally important in the assessment of the vertical cooling history of footwalls in extensional systems: temporal differences in the rate of tectonically driven exhumation at a given location along fault strike may be of greater importance in controlling changes in rates of vertical exhumation than commonly invoked climatic fluctuations.

1. Introduction

The displacement across a crustal-scale normal-fault is accommodated by a combination of hanging wall subsidence and, as a consequence of isostatic adjustments, to a lesser extent corresponding footwall uplift (e.g., Jackson and McKenzie, 1983; Walsh and Watterson, 1987; Stein and Barrientos, 1985). This process leads to the vertical exhumation of rock through the footwall over time, and should be a function of the amount and rate of displacement both across and along strike of the fault at a first order, modified by any climatically driven variation in exhumation. The amount and rate of displacement along individual normal-faults within developing fault arrays evolves in a predictable manner (e.g., Walsh and Watterson, 1987, 1991; Gupta et al., 1998; Cowie et al., 2000; Trudgill and Cartwright, 1994). Due to the increase in relief and surface-process gradients this spatial distribution of displacement accumulation along an evolving fault array should be manifested in the patterns of footwall exhumation. While many studies have utilized low-temperature thermochronology to determine changes in vertical rates of exhuma-

* Corresponding author at: School of Earth and Environment, University of Leeds, Woodhouse Lane, Leeds, UK.
E-mail address: e.j.mortimer@leeds.ac.uk (E. Mortimer).
[1] Present address.

http://dx.doi.org/10.1016/j.epsl.2016.08.040

tion, specifically to constrain the onset of rifting (Fitzgerald, 1992; Bauer et al., 2010; Woodruff et al., 2013) or to elucidate changes in climatically driven exhumation (e.g., Ehlers et al., 2006; Spiegel et al., 2007), few studies have utilized the technique to determine along-strike fault displacement variations through time. Armstrong et al. (2004) demonstrated a lack of along-strike variation in apatite (U–Th)/He ages (AHe) for the Wasatch fault, USA, such that mechanical segmentation of the fault is not preserved despite its segmented footwall topography. Conversely, Krugh (2008) demonstrated different cooling ages in relay zones that correspond to different timing of mechanical linkage between fault segments along the Wassuk Range in the Basin and Range province, USA.

The lack of thermochronology case studies is surprising as the manner by which extensional fault systems grow is well documented from natural examples and numerical modelling. Normal-faults typically grow through a combination of fault-tip propagation and displacement accumulation, and through fault linkage to produce arrays comprising a series of kinematically linked segments (e.g., Dawers et al., 1993; Gupta et al., 1998; Cowie et al., 2000). Isolated faults propagate in length as stress builds up at the fault tip; when this overcomes the yield strength of the surrounding rock, it ruptures (e.g., Cowie and Scholz, 1992). As isolated faults propagate toward each other their stress fields interact to produce a feedback effect, whereby the displacement on one structure causes slip on another (Cowie, 1998; Gupta and Scholz, 2000). The anticipated maximum displacement on a single fault is scaled to its overall length (Schlische et al., 1996; Dawers and Anders, 1995). Additionally, the spatial distribution of displacement along strike of individual faults occurs in a relatively predictable pattern due to the mechanisms of fault growth and linkage (Fig. 1). Fault-displacement profiles, that is the amount of displacement accumulated across the fault versus distance along strike, of isolated faults have a bell-shaped (often flat topped) profile with the greatest amount of displacement occurring toward the centre of a fault and displacement minima at the fault tip Walsh and Watterson, 1991; Dawers et al., 1993; Cartwright et al., 1995). This idealised displacement profile demonstrated for isolated faults is also documented for evolving fault arrays. Interacting faults achieve a combined displacement for the entire length of the linked array, with maximum displacement in the centre and minimum at the tip (e.g., Gupta et al., 1998; Cowie et al., 2000; McLeod et al., 2000). Not all faults achieve this displacement profile through a constant interplay of propagating length and then acquiring displacement. Some isolated segments achieve their length early and then accrue displacement. In this case, fault length is often determined by the interaction with other propagating faults, and structures are initially under-displaced until the bell-shaped profile is achieved (Walsh et al., 2002).

The ideal model of fault interaction (Fig. 1) commences with nucleating isolated normal-faults (Cowie and Scholz, 1992). As these isolated faults propagate they interact with neighbouring structures along strike (Cowie et al., 2000). Their fault tips may propagate past one another, and stress builds up within the region of overlapping fault tips; while they are inhibited in lengthening further as the fault tip propagates into the region of reduced stress on the neighbouring fault (Gupta and Scholz, 2000). This leads to a steeper displacement gradient close to the overlapping fault tips, and the displacement profile of the individual fault segments becomes asymmetrically skewed toward one another as they interact (Peacock and Sanderson, 1991; Nicol et al., 1996).

Instead of continuing to propagate as an isolated fault, the fault segments become mechanically linked across the region of overlap, or "relay" zone to form a single through-going fault, often abandoning the fault tips as the relay is breached (e.g., Walsh and Watterson, 1991; Peacock and Sanderson, 1991; Trudgill and Cartwright, 1994).

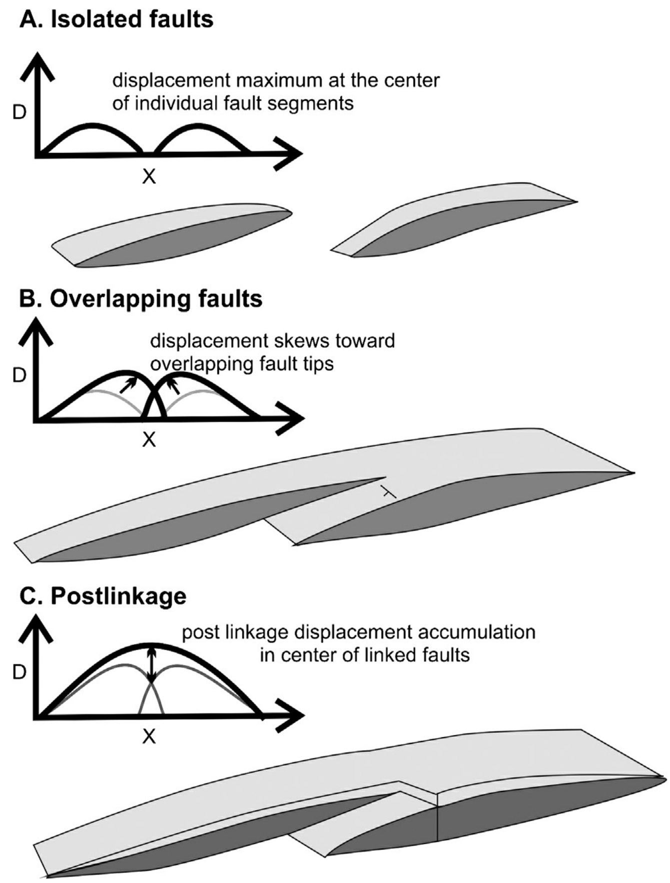

Fig. 1. Growth and linkage of normal-faults and the predicted corresponding along strike displacement accumulation. The displacement profile is the amount of displacement, D, measured along fault strike, X. The idealised displacement profile for a normal-fault is a bell shaped curve with maximum displacement in the centre and zero at the fault tip, such as in A. As two faults propagate toward each other, their tips can overlap (overlapping faults, B), forming a relay ramp. Their stress fields interact and displacement on each fault segment is skewed toward the centre of the overlap. Finally, the faults become linked as the relay ramp is breached (C) and the fault is initially under-displaced in the centre (compared to an idealised profile). Post linkage displacement is, therefore, greatest in the centre of the linked fault, where previously the tips overlapped (B and C are modified from Trudgill and Cartwright, 1994).

During this interaction, therefore, the overall length of the fault becomes the combined length of the overlapping fault segments. Where previously there was minimal displacement at the former fault tips, this region is now the centre of the through-going fault after linkage. Thus the displacement amount and rate within the relay zone increases as the fault moves towards a bell-shaped displacement profile, with maximum displacement in the centre, and minimum at the tip (Gupta et al., 1998). This process can lead to faults appearing to be "under-displaced" in the region of a former relay zone as the amount of displacement in the centre adjusts to the new fault length (Gupta et al., 1998). Not all faults will follow this idealised pattern. In the same manner as some fault segments can propagate their length first and later accrue displacement; fault arrays can rapidly acquire their length and subsequently accrue displacement (Morley, 1999).

These patterns of fault growth and linkage should be manifested in AHe dating, as the cooling history along fault strike should vary, reflecting the different rates of displacement accumulation on a propagating normal-fault array.

Here, we apply apatite (U–Th)/He dating to the segmented border fault system of the Karonga Basin of the Malawi Rift, East African Rift System (EARS; Fig. 2). The structural evolution of the Karonga Basin is well constrained from previous studies that uti-

Please cite this article in press as: Mortimer, E., et al. Spatio-temporal trends in normal-fault segmentation recorded by low-temperature thermochronology: Livingstone fault scarp, Malawi Rift, East African Rift System. Earth Planet. Sci. Lett. (2016), http://dx.doi.org/10.1016/j.epsl.2016.08.040