Quaternary Science Reviews 105 (2014) 66–85

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Quaternary landscape development, alluvial fan chronology and erosion of the Mecca Hills at the southern end of the San Andreas Fault zone

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ARTICLE INFO

Article history:
Received 8 February 2014
Received in revised form
14 August 2014
Accepted 5 September 2014
Available online

Keywords:
Terrestrial cosmogenic nuclides
Beryllium-10
Surface exposure dating
Mecca Hills
San Andreas Fault

ABSTRACT

Quantitative geomorphic analysis combined with cosmogenic nuclide ^{10}Be-based geochronology and denudation rates have been used to further the understanding of the Quaternary landscape development of the Mecca Hills, a zone of transpressional uplift along the southern end of the San Andreas Fault, in southern California. The similar timing of convergent uplifts along the San Andreas Fault with the initiation of the sub-parallel San Jacinto Fault suggest a possible link between the two tectonic events. The ages of alluvial fans and the rates of catchment-wide denudation have been integrated to assess the relative influence of climate and tectonic uplift on the development of catchments within the Mecca Hills. Ages for major geomorphic surfaces based on ^{10}Be surface exposure dating of boulders and ^{10}Be depth profiles define the timing of surface stabilization to 2.6 +5.6/−1.3 ka (Qyf1 surface), 67.2 ± 5.3 ka (Qvof2 surface), and 280 ± 24 ka (Qvof1 surface). Comparison of ^{10}Be measurements from active channel deposits (Qac) and fluvial terraces (Qt) illustrate a complex history of erosion, sediment storage, and sediment transport in this environment. Beryllium-10 catchment-wide denudation rates range from 19.9 ± 3.2 to 149 ± 22.5 m/Ma and demonstrate strong correlations with mean catchment slope and with total active fault length normalized by catchment area. The lack of strong correlation with other geomorphic variables suggests that tectonic uplift and rock weakening have the greatest control. The currently measured topography and denudation rates across the Mecca Hills may be most consistent with a model of radial topographic growth in contrast to a model based on the rapid uplift and advection of crust.

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1. Introduction

Understanding the Quaternary evolution of fault systems in tectonically active environments is essential for evaluating both modern seismic hazard and the long-term tectonic processes of plate boundaries. Southern California is one such environment where the San Andreas Fault acts in concert with other major strike slip fault systems to form a dynamic and complex system (Fig. 1; Matti and Morton, 1993; Janecke et al., 2010; Dorsey et al., 2012). Part of this complexity is expressed by the interaction of the San Andreas Fault and San Jacinto Fault which have had a strong interplay in slip rates (Bennett et al., 2004; Janecke et al., 2010) leading to questions of how strain is partitioned between the two structures. Interestingly, the southern San Andreas Fault is host to the Durmid, Indio, and Mecca Hills which represent “restraining bends” where strike slip motion is converted into compression throughout the Quaternary (Sylvester and Smith, 1976; Bilham and Williams, 1985). The presence of the Bishop Tuff (Ware, 1958; Merriam and Bischoff, 1975; Rymer, 1991) define the uplift of the Mecca Hills to sometime prior to 767.1 ± 0.9 ka (Izett and Naeser, 1976; Reid and Coath, 2000; Crowley et al., 2007) but not earlier than 1.2–1.5 Ma (McNabb et al., 2013). The timing of uplift of the Mecca Hills, and possibly the

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http://dx.doi.org/10.1016/j.quascirev.2014.09.009
0277-3791/Published by Elsevier Ltd.

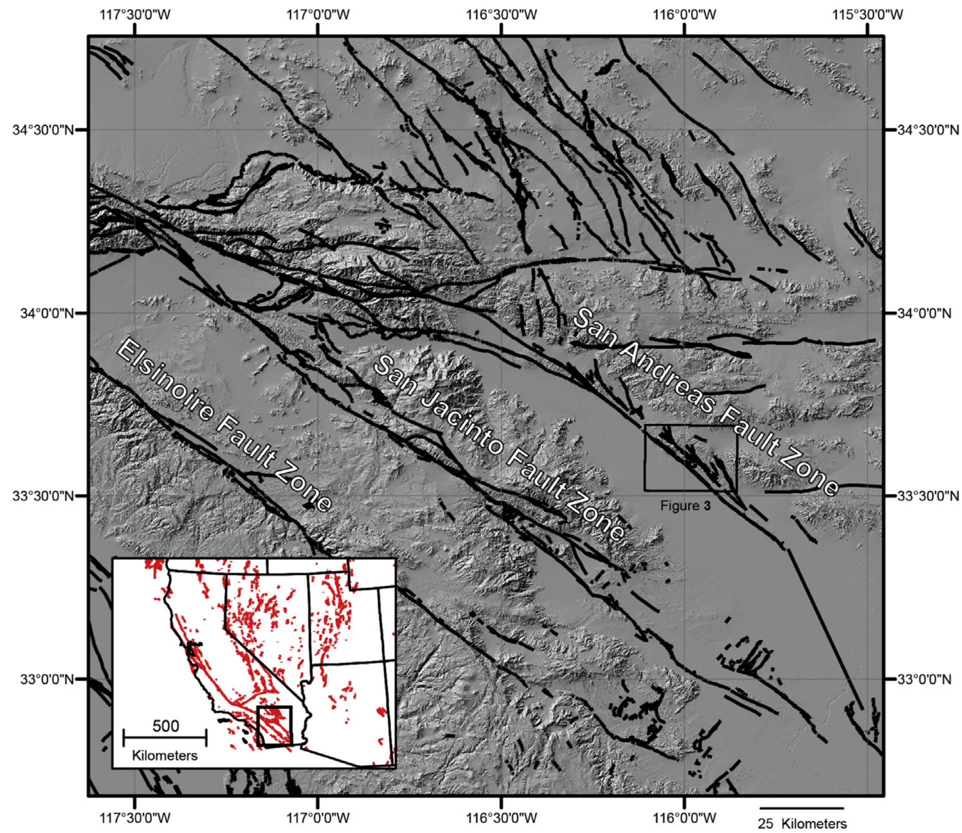

Fig. 1. Location of the Mecca Hills in southern California showing major faults. Background image is a hillshade derived from a 1-arc second digital elevation model (DEM) from the U.S. Geological Survey (USGS) National Elevation Dataset. Fault lines are sourced from the USGS fault data repository (Petersen et al., 2008).

timing of uplift of the Durmid and Indio Hills (Bilham and Williams, 1985), correlates with the initiation of the San Jacinto Fault. Contemporaneous origin of the restraining bends with the San Jacinto Fault initiation suggests that a significant change in the stress field on the southern San Andreas Fault occurred with San Jacinto Fault initiation which shifted motion from strike slip towards convergence (Fattaruso et al., 2013). Alternatively, the restraining bends observed along the southern San Andreas Fault may instead represent local fault plane heterogeneities or "structural knots" (Hilley and Arrowsmith, 2008) which have generated the uplifts. These two forms of restraining bend development can be distinguished by the spatial patterns of uplift rate (Fig. 2). In this paper, we conduct a quantitative geomorphic study of the Mecca Hills to determine if the observed spatial patterns of uplift and erosion are consistent with local fault plane heterogeneity or a possible reorganization of strain on the San Andreas Fault. Our approach utilizes: (1) geomorphic mapping with an emphasis on alluvial fans; (2) ^{10}Be geochronology to assess ages and fluvial incision rates of geomorphic surfaces; and (3) measurement of ^{10}Be in sediment to quantify catchment averaged rates of denudation.

In regions where reverse faulting is a significant component of slip partitioning, the record of vertical fault motion can be obscured by long-term denudation or a lack of fault surface expression (Aydin et al., 1992; Philip and Meghraoui, 1983). The long-term record of fault uplift, however, is expressed as elevated topography which in turn produces denudation rates in a pattern similar to the distribution of fault uplift rates at the watershed scale (Cyr et al., 2010; Binnie et al., 2008; Gudmundsdottir et al., 2013). One method to evaluate the spatial patterns of uplift and denudation is through the use of quantitatively defined landscape evolution models that provide useful limits for evaluating slip partitioning in tectonically active regions with a significant component of reverse faulting (Wobus et al., 2006; Kirby et al., 2008; Gudmundsdottir et al., 2013). However, the vertical motions of faults in the Mecca Hills are difficult to determine with traditional paleoseismic methods owing to the lack of preserved surface expression and depositionally complex stratigraphy. Instead, we construct and test two endmember landscape evolution models as working hypotheses to evaluate uplift patterns.

Our endmember models are based on previous research on the topographic development of transpressive "restraining bends" in strike slip tectonic systems (Fig. 2; Cunningham and Mann, 2007; Mann, 2007). The primary difference in the models is the location of the focal point of maximum uplift which plays a key role in the development of topography (Fig. 2; Anderson, 1994; Cowgill et al., 2004a; Hilley and Arrowsmith, 2008). Model 1 is developed from previous work in the Mecca Hills and from theoretical and analog models of restraining bend development (Sylvester and Smith, 1976; Woodcock and Fischer, 1986; McClay and Bonora, 2001). Conceptually, the focal point of maximum uplift is located in the center of the restraining bend and tapers toward the edges creating a domal pattern of uplift rate. Model 2 is constructed from research demonstrating that the topographic expression of restraining bends occurs from a focal point of uplift followed by advection of material (Fig. 2; Anderson, 1994; Bürgmann et al., 1994; Hilley and Arrowsmith, 2008). Note that restraining bends obey a spectrum of uplift styles depending on fault geometry and principal stress orientations (Cowgill et al., 2004; Cunningham, 2007; Mann, 2007). The data presented in our study favor Model 1 and seem to exclude the possibility of Model 2.