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Effects of active folding and reverse faulting on stream channel evolution, Santa Barbara Fold Belt, California

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ABSTRACT

The Santa Barbara Fold Belt (SBFB) is an area of active crustal shortening comprising younger east–west and older southeast-northwest oriented reverse faults and folds. Changes in channel position and stream incision are the result of active fold growth and uplift. Rates of incision range from 0.4 ± 0.1 m/ka to 1.2 ± 0.04 m/ka. Lateral stream diversion from fold and fault growth varies from 6.7 to 0.4 km. Minimum uplift of western Mission Ridge anticline is 0.8 ± 0.1 m/ka and minimum uplift on the Mesa fault is 0.3–0.4 m/ka. The hypothesis that east-to-west folds are younger is suggested by a cross-cutting relationship and is tested using geomorphic indices of active tectonics including: valley width to height ratios (Vf), mountain front sinuosity (Smf) and drainage densities (Dd). East-to-west trending structures have mean values of Vf, Smf, and Dd of 2.7, 1.2, and 2.2 km/km^2, respectively, while southeast-to-northwest trending structures have mean values of 5.0, 1.5, and 3.7 km/km^2, respectively. We present a new geomorphic tool, the stream diversion index, which uses diversion timing and distance to assess relative tectonic activity; these values range from 6 to 260 m/ka. All of these values support the hypothesis that the east-to-west folds are younger and more active. Clockwise rotation of the Western Transverse Ranges is probably the process that produced the two sets of structures. With rotation the older set that started out east-to-west eventually became northwest-to-southeast, and more difficult to maintain with the north-to-south contractional (shortening) associated with the Big Bend of the San Andreas fault 80 km to the north. The second set of younger structures formed with a more favorable (east-to-west) orientation to the shortening.

1. Introduction

1.1. Research objectives, purpose and importance

Strain is accommodated in active fold and thrust belts primarily by offset along faults and secondarily by folding in the hanging wall. The geometry of the fault controls the shape and style of the overlying fold, which in turn controls the shape of the landscape (Keller and Pinter, 2002; Burbank and Anderson, 2012). Our ability to infer the presence and geometry of blind faults from the landscape is important because of the large seismic hazard they present (e.g. Keller and Gurrola, 2000; Keller and Pinter, 2002; DeVecchio and Keller, 2008; DeVecchio et al., 2012). We can also use hanging wall fold geometry and geomorphology to decipher the most-recent history of deformation in complex fold and thrust belts.

Because hanging wall folds represent a significant portion of strain it is important to understand their evolution when analyzing the development of an orogenic system as a whole. However, many active fold and thrust belts occur in urban settings, e.g. Los Angeles, or are covered by vegetation, e.g. foreland fold and thrust belts in the northern Andes. In such cases one tool we have at our disposal is a remote sensing based detailed geomorphic analysis of folds. One of the most important tools within this geomorphic toolbox is the analysis of stream patterns (e.g. Jackson et al., 1996; Keller et al., 1998, 1999; Keller and Pinter, 2002; Ramsey et al., 2008).

Analysis of river or stream incision and diversion provides valuable information about the development and evolution of folds and their underlying faults (e.g. Jackson et al., 1996; Boudiaf et al., 1998; Keller et al., 1998, 1999; Walker, 2006; Ramsey et al., 2008). The balance of stream power and erosional resistance define a relationship in which streams respond to tectonically induced changes in topography by either incising into or diverting around growing structures (Bull, 1991). Erosional resistance is influenced by surface or rock uplift, lithologic characteristics, and sedimentation (Burbank et al., 1996; Sklar and Dietrich, 1998; Humphrey and Konrad, 2000); slope and drainage area determine stream power (Gilbert, 1877; Howard and Kerby, 1983; Seidl and Dietrich, 1992). If erosional resistance is greater than incision, streams will be defeated and deflected along the active fold. In this process the drainage area will increase until the stream power overweighs erosional resistance and the stream

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incises a new channel across the active structure. In this paper we refer to stream diversion in the sense of a tectonic diversion rather than a non-tectonically caused diversion such as stream capture and rerouting (e.g. Bishop, 1995).

Defeated streams leave a lasting imprint on the landscape in the form of geomorphic paleochannels. The topographic breaks in fold profiles formed where paleochannels and active streams traverse the axial hinge are termed “wind gaps” and “water gaps”, respectively (Burbank et al., 1996, 1999; Keller and Pinter, 2002). We note that the term “wind gap” has been applied in situations where headward incision causes the abandonment of channels (Bishop, 1995); we use this term as described above in the sense of Keller and Pinter (2002). These geomorphic features provide valuable strain markers when unraveling the Quaternary tectonic history of a fold belt.

Previous studies have used stream and paleochannel patterns as geomorphic tools to identify folds (e.g. Gupta, 1997; Boudiaf et al., 1998), determine fold propagation direction (Jackson et al., 1996; Keller et al., 1998, 1999), determine fold growth rates (Medwedeff, 1992), differentiate between fault tip propagation and slip accumulation (e.g. Amos et al., 2010), determine fault slip rates (e.g. Sieh and Jahns, 1984), and assess seismic hazard in fold belts (e.g. Keller and Gurrola, 2000). Keller et al. (1999) mapped paleochannels on the backlimb of western Mission Ridge anticline in Santa Barbara, California; they recognized that drainage pattern, drainage density, and backlimb rotation all indicate a westward propagation direction. But they did not expand the study past this one anticline.

Geomorphic indices of active tectonics developed by Bull and McFadden (1977) are a set of tools that utilize landscape morphology to quantitatively assess landscape evolution in active tectonic settings. Some of these metrics include valley width to height ratio, mountain front sinuosity and drainage density (described below). For example, Silva et al. (2003) used geomorphic indices to test the morphologic properties of different styles of faulting and assign a tectonic activity class to different mountain fronts. Azor et al. (2002) applied geomorphic indices to a hanging wall anticline on a reactivated normal fault in southern California, and determined that the morphology of the fold was controlled by a decrease in fault slip rather than propagation of the fault tip. A detailed analysis using geomorphic indices has not been applied in the Santa Barbara Fold Belt (SBFB).

Many orogenic systems involve complex deformation patterns and previous geomorphic studies focus mostly on individual structures. The SBFB contains two coevally interfering sets of active structures oriented roughly 30° from each other. In this paper we use drainage patterns, the strain markers of paleochannels and alluvial fans, as well as geomorphic indices of active tectonics to determine stream incision, fold propagation direction and the relative timing of structural overprinting in the SBFB. We test the hypotheses that: 1) incision and uplift are approximately equal and thus the landscape is in steady state; 2) folds in the SBFB generally propagate westward; and 3) east–west oriented folds are the most recent manifestation of north–south shortening in a clockwise rotating micro-block.

1.2. Tectonic geomorphology background of the SBFB and field area

The SBFB is a zone of continental shortening in an urban setting with a uniform climate and well-mapped geology where we can perform a detailed geomorphic analysis to understand Quaternary tectonic evolution. The geology comprises steeply dipping sandstone and shale striking sub-parallel to the Santa Ynez Mountains and perpendicular to the streams draining to the Pacific Ocean (Dibblee, 1966; Minor et al., 2009). Average annual precipitation increases two fold from the coast to the crest of the Santa Ynez Mountains from 43 cm/yr to 79 cm/yr (Gibbs, 1990). For a given elevation, precipitation is uniform across the range; drainages are of similar size and elevation.

The field area is located on the coastal piedmont around Santa Barbara, California between the towns of Ellwood and Montecito, approximately 145 km (90 miles) north of Los Angeles (Fig. 1). The SBFB is structurally bound by two left lateral faults: the Santa Ynez fault to the north and the Santa Cruz Island fault to the south (Fig. 1), and is a westward continuation of the Ventura Fold belt (Gurrola, 2006). Within the field area the SBFB consists of a series of topographic ridges and valleys that are the surface expression of anticline-syncline pairs resulting from reverse faulting associated with crustal shortening (Yeats, 1986; Keller and Gurrola, 2000). These folds have either a southeast–northwest or an east–west orientation, where east–west folds truncate southeast-northwest folds.

The overlapping deformation pattern within the SBFB is a product of a complex tectonic history. Paleomagnetic data show that since early Miocene time the western Transverse Ranges (including the field area) have rotated as much as 100° in a clockwise direction (Hornafius et al., 1986). Luyendyk et al. (1980) propose a geometric model by which continued dextral shear along the San Andreas boundary is accommodated by sinistral slip and clockwise rotation of the western Transverse Ranges. This requires that the SBFB first experienced extension and then compression while undergoing continued clockwise rotation (see palinspastic reconstructions of Hornafius et al. (1986) and the “Southern California Breakup and Paleomagnetic Vector Rotations, 20 Ma to Present” animation by Tanya Atwater). The later compressional phase of deformation was enhanced due to the formation of the Big Bend in the San Andreas system during the late Neogene (Crowell, 1979). Recent GPS studies reveal continued clockwise rotation of the region (Meade and Hager, 2005).

1.2.1. Faults

The Mission Ridge fault system, which dominates the onshore portions of the SBFB, extends about 70 km from Ojai to Ellwood where it continues offshore. If the entire length of the fault were to rupture in one event it could create a M7.2+ earthquake (Wells and Coppersmith, 1994). Within the SBFB the Mission Ridge fault system is characterized by three predominant styles of active faults. These are east–west trending blind reverse faults, southeast–northwest trending blind reverse faults, and north–south lateral tear faults (Keller and Gurrola, 2000; Gurrola, 2006; Minor et al., 2009). Blind reverse faults dip 60–70° to the south (Gurrola, 2006) and associated hanging wall anticlines are north vergent. East–west faults include the More Ranch fault; southeast–northwest faults include the Mission Ridge fault, Mesa fault, Lavigia fault, and the San Jose fault; tear faults do not significantly divert stream channels, and are not included as part of this study (cf. Fig. 1). More Ranch fault develops a northeast–southwest orientation between Hope Ranch and the city of Santa Barbara; we include this in our results and discussions of east–west structures because the overall strike of the fault is east–west (see geologic map of Minor et al., 2009).

1.2.2. Previous work: geochronology, uplift rates and mapping

Previous workers have collected and analyzed a suite of geochronologic data in the area that provide us a powerful tool when evaluating the evolution of the SBFB. The techniques used include cosmogenic ^{21}Ne exposure dating, optically stimulated luminescence and uranium series analysis. Zepeda (1987) estimated the age of the alluvial fan deposit to the north of the Goleta Valley anticline, labeled Qf2b in this study, to be between 70 and 100 ka. Subsequently Keller and Gurrola (2000) used optically stimulated luminescence (OSL) and uranium-series analysis on marine terrace sands and shells to estimate the ages of marine terraces and uplift rates of the SBFB. OSL samples, within the field area, were collected from four marine terrace locations: the Cemetery anticline terrace, the Mesa terrace, the Hope Ranch terrace and the Campus terrace (Gurrola, 2006). Samples for U-series analysis were collected at the Mesa terrace and the Campus terrace. Landis et al. (2002), performed a series of six