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Using orthographic projection with geographic information system (GIS) data to constrain the kinematics the Central Range Fault zone, Trinidad

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ABSTRACT

Fold geometry versus axis orientation can be used to constrain the kinematics of transpressional plate boundaries. This approach is typically based on bedding orientation data collected in the field, however, in some regions outcrop quality is insufficient to provide enough measurements. We extract orientation data from a georeferenced geologic map and a digital elevation model and to constrain the kinematics of a poorly exposed, active transpressional boundary: the Central Range Fault zone in Trinidad. Strike-and-dip orientations are calculated based on contact positions extracted from the digital geologic and topographic datasets. The uncertainties in the both horizontal position and elevation of the contact are propagated into the final kinematic analysis. Analysis of folds adjacent to the Central Range Fault suggests the angle of oblique convergence in transpression (α) varies from 20° to 85°. The majority of folds, however, are consistent with a large component of contraction (i.e. $\alpha > 50°$). The analysis also suggests folding in the Central Range records a minimum of 3–9 km of contraction, 3 km of strike-slip motion, and 4–9 km of total plate motion. The range of values reflects uncertainties in the position of the folded contacts. We interpret the overall kinematics of deformation, amount of shortening, and homogeneity of the finite strain field to indicate that active deformation on the Central Range Fault zone has not yet accumulated enough strain to overprint the effects of earlier (pre-strike-slip; pre-Middle Miocene) fold-and-thrust style tectonics.

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1. Introduction

High strain strike-slip fault systems with a component of oblique convergence, such as the San Andreas Fault system, typically partition deformation between the main fault the adjacent borderlands (e.g. Zoback et al., 1987; Jamison, 1991; Teyssier and Tikoff, 1998). In general, most of the strike-slip component of deformation is accommodated by the central fault, and the borderlands absorb most of the contraction (e.g. Teyssier and Tikoff, 1998; Titus et al., 2007). The kinematics of the borderlands can thus reflect a combination of convergence and strike-slip motion – i.e. transpression. The relative contribution of strike-slip motion vs. convergence has previously been investigated by examining folded strata in the borderlands (e.g. Jamison, 1991; Tikoff and Peterson, 1998; Titus et al., 2007). These studies provided important information about the kinematics and strike-slip partitioning across well-exposed, active transpressional plate boundaries.

Previous work on the San Andreas Fault system focused on well-exposed, arid segments and used bedding orientation data to characterize fold geometry and orientation in the borderlands (e.g., Jamison, 1991). In deeply weathered and heavily vegetated regions, such as in the Central Range in Trinidad, poor exposure limits how much bedding data can be collected. However, if detailed geological mapping exists, such as in Trinidad where the surface mapping was based on extensive micropaleontological augering (Kugler, 1960), it is possible to use the intrinsic relationship between contacts and topography to determine fold geometry. The utility of this approach is limited only by the accuracy of the geologic map and of the elevation data set.

We present a kinematic analysis of the Central Range Fault zone – i.e. the Central Range Fault itself and the adjacent borderlands – in Trinidad that used orthographic projection to analyze digital geologic map and elevation datasets using ArcGIS and MatLab. The approach developed and presented here includes a numerical method to propagate uncertainty in contact position into the final results. Our study of the Central Range Fault zone illustrates the potential and limitations of using GIS-based orthographic projection as a tool for kinematic analysis.

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2. Geologic setting

Trinidad is located along the South American-Caribbean plate boundary. Obliquely convergent motion of the Caribbean Plate relative to South America throughout much of the Cenozoic resulted in an orogen active first in western South America and then progressively further east (e.g., Speed, 1985; Pindell et al., 1998). Fig. 1 shows the generalized geology of Trinidad. The Northern Range, contains largely metasedimentary rocks with Mesozoic protolith ages and Cenozoic metamorphic ages, and comprises the exhumed hinterland segment of this orogen (Weber et al., 2001a). The Late Cretaceous sediments currently exposed in central Trinidad were deposited in a passive margin setting, while the Paleogene-Early Neogene section was deposited in a distal foreland basin in front of the advancing orogen. Late Pliocence to Pleistocence sediments and sedimentary rocks in Trinidad are largely deltaic deposits of the paleo-Orinoco system. On the north flank of the Central Range, the Late Neogene-Pleistocene section was deposited unconformably after intense folding and thrusting deformed the pre-Middle Miocene strata. In south Trinidad, folding continued into the Pleistocene.

Sometime between ~12 Ma and the present, Caribbean-South American plate tectonics changed from oblique convergence to transform motion, with local transpression and transtension; active transtension occurs in the Gulf of Paria pull-apart basin, and active transpression in expected in central Trinidad (Pindell et al., 1998; Weber et al., 2001b). Geodetic (GPS) analysis showed that the Caribbean plate is presently moving 20 mm/yr due east relative to a fixed South American plate (Perez et al., 2001; Weber et al., 2001b). West of Trinidad, in Venezuela, most of this motion is accommodated on the El Pilar Fault (Perez et al., 2001). In Trinidad, the locus of plate motion steps south off of the El Pilar Fault onto the Central Range Fault (Saleh et al., 2004; Weber et al., 2011). In addition, the geodetic analyses showed that 12 $\pm$ 3 mm/yr of the total 20 mm/yr relative plate motion is accommodated on the Central Range Fault (Weber et al., 2011). The Central Range Fault strikes 070°, which is ~20° oblique to the Caribbean-South American relative plate motion vector, and the modern elastic strain field centered on the fault is approximately 30 km wide (Weber et al., 2011). Motion at 12 mm/yr in this orientation resolves into 4 mm/yr of zone-normal convergence. Overall, the Central Range is characterized geologically as an anticlinal flower structure that exposes Late Cretaceous sedimentary rocks in its core and Oligocene to Miocene strata on its flanks (Fig. 1; de Verteuil et al., 2006). These units are generally unmetamorphosed, and reset apatite fission track data demonstrate these rocks reached temperatures greater 130 °C and experienced exhumation primarily in the Miocene (Sanguinito et al., 2010). The unconformably overlying Late Pliocene to Pleistocene section is tilted northward off the north flank of the Central Range and also forms most of the surficial geology and fill of the oil-rich Southern Basin (Fig. 1).

Folding and faulting in the Central Range clearly indicate this region has experienced Middle Miocene contraction, e.g. the geologic reconstructions of Pindell et al. (1998). The presence and spatial pattern of the Early to Middle Miocence shallow-water Tamana Limestone in the Central Range indicate limited emergence of the fold-thrust belt at paleo-topographic (and structural?) culminations (Erlich et al., 1993). Geodetic data suggest that contraction could be active today (e.g., Weber et al., 2011). The clear geomorphic expression of the Central Range Fault, observations from paleoseismic trenching, and offsets imaged in offshore 3D seismic data all suggest that transpressional activity was also likely active earlier in the Holocene (Soto et al., 2007; Prentice et al., 2010; Weber et al., 2011). It is uncertain, however, how much of the folding, faulting, and topography in the Central Range is due to pre-Middle Miocene convergence vs. Holocene transpression (Weber et al., 2011). Given this complexity, it is also likely that the Central Range may record more than one generation of deformation and/or reactivation.

In this study we used the macroscopic, second order folds on the flanks of the anticlinal flower structure in the Central Range to characterize the kinematics of deformation and estimate finite strain. The Central Range folds plunge gently, and are upright, tight-open, NE-trending, and outcrop in bands that are 1–2 km in length and several hundred meters wide. Outcrop is scarce in the Central Range, however good quarry exposures in the reef carbonates of the Tamana Formation suggest that open, sinusoidal, constant-thickness, flexure-slip folds predominate there. Our analysis, which focused on second order folds, does not take into account shortening due to thrust faults or larger order folding, therefore our results represent minimum strain estimates. Lastly, we calculate finite strain, which provides only a sum of Miocene and modern shortening.

3. Kinematic model of folding in transpression

3.1. Data collection

Our initial data set consisted of a georeferenced geologic map and a digital elevation model (DEM) of Trinidad (de Verteuil et al., 2006). Contact location data were collected in the Universal Transverse Mercator (UTM) system (Zone 20 for Trinidad). Our coordinate system is set with the x-axis oriented east–west, parallel to UTM easting, the y-axis north–south, parallel to UTM northing, and the z-axis up-down. Using ArcGIS, we generated a table of x, y, and z coordinate points that followed each folded contact (Fig. 2).

3.2. Contact orientation

The orientation of a folded contact can be determined at any locality along its trace using three adjacent points via orthographic projection. Assuming that the contact is locally planar, the trend and plunge of the pole to that plane can be calculated by converting those three points into two vectors (**A** and **B**), and then taking the cross product of those vectors (e.g. Ragan, 2009). Vector **A** was created by connecting the point with the highest elevation to the point with the lowest elevation. Similarly, vector **B** was created by connecting the intermediate elevation point with the lowest elevation point. The orientation of vectors **A** and **B** can be described using the direction cosines $[l\ m\ n]$. A vector with a trend T and a plunge P has direction cosines

$$[l, m, n] = (\cos P \cdot \cos T \quad \cos P \cdot \sin T \quad \sin P) \tag{1}$$

(e.g. Charlesworth et al., 1976). The cross product of these two vectors yielded the direction cosines of the pole to the plane containing these three points. These direction cosines were then converted back into trend and plunge. This process was then repeated along the contact using each possible combination of three consecutive points.

3.3. Fold axis

An analytical solution to the calculation of a fold axis from a population of poles to bedding is given by Charlesworth et al. (1976). Briefly, a population of p poles are converted to direction cosines using eq. (1) and then used to calculate the matrix

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