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Tectonophysics 436 (2007) 1–8
TECTONOPHYSICS
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Vertical-axis rotation controlled by upper crustal stress based on force balance analysis: A case study of the western Transverse Ranges of California

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Received 27 June 2006; received in revised form 21 February 2007; accepted 2 March 2007
Available online 12 March 2007

Abstract

This paper evaluates driving mechanisms of vertical-axis rotation using data from the western Transverse Ranges in southern California. Simple force balance considerations and comparison of torque applied to a rotating block indicate that shear forces applied to the base of the block are not strong enough to produce the motions and deformation observed at the surface. For the measured dimensions of the crustal blocks and crustal viscosities in southern California, stresses transmitted through the upper crust are one to three orders of magnitude stronger than forces generated in the ductile lower crust. These results suggest that the kinematics of crustal blocks in continental deformation zones are primarily controlled by forces within the upper crust rather than a flow field beneath.

Keywords: Vertical-axis rotation; Western Transverse Ranges; Continental

1. Introduction

A recurring question regarding continental tectonics is what controls the relative motions of crustal fault blocks in diffuse plate boundary zones. Are the motions of crustal blocks, and the associated deformation, driven by stresses transmitted through the upper brittle crust, or by penetrative ductile shear below the seismogenic layer? Evolving fault patterns, seismicity, and geophysical data have led some authors to attribute block movements to stresses transmitted through the upper crust (e.g., Nur et al., 1986; Jackson, 2002). Others have proposed that the block motions and deformation observed at the surface are merely a discrete approximation of ductile flow occurring below the seismogenic layer and are directly controlled by shear forces at the base of the blocks (e.g., McKenzie and Jackson, 1983; Lamb, 1994). These two hypotheses have typically been explored by comparing observed crustal movements at the surface in a deforming zone with the regional velocity field estimated from plate tectonic reconstructions or geodetic data (e.g., Jackson and Molnar, 1990; Bourne et al., 1998).

Rotation of crustal blocks is often used to test models of continental dynamics. Areas where crustal blocks have been rotated about a vertical-axis provide a more continuous view of the velocity field across a zone than can be obtained by evaluating discrete faults alone, and interactions between rotating blocks and nonrotating zone boundaries may help distinguish the dynamic processes

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doi:10.1016/j.tecto.2007.03.002

driving the deformation. In addition, physical quantities such as the rotation amount and rate are expected to be different depending on whether the motion is driven from the sides or the base of the blocks (McKenzie and Jackson, 1986; Molnar, 1988). One of the best-studied areas where vertical-axis rotation has occurred is the western Transverse Ranges of southern California, which are commonly used as a testing ground for various models of crustal rotation and continental deformation.

In this paper, I use geologic observations of vertical-axis rotation from the western Transverse Ranges to evaluate the relative influence of upper and lower crustal forces that control the motion and deformation of crustal blocks. Using two independent arguments based on physical principles and geologic observations, I propose that rotation in southern California cannot be the result of basal traction forces imposed on the upper crust from beneath and must be primarily driven by stresses transmitted through the upper brittle crust. These findings also apply to other areas of vertical-axis rotation, as well as distributed continental deformation zones, where crustal block dimensions are on the order of tens of kilometers. This analysis holds implications for general continental dynamics as well as the mechanisms of vertical-axis rotation as a specific mode of crustal deformation.

2. Rotation of the western Transverse Ranges

Vertical-axis rotation of crustal blocks in southern California has occurred within the diffuse transform boundary zone between the North American and Pacific plates. The most dramatic rotated domain is the western Transverse Ranges (WTR), which has rotated clockwise about 90° since 18 Ma (Fig. 1) as indicated by paleomagnetic data and geologic evidence (e.g., Crouch, 1979; Kamerling and Luyendyk, 1985; Hornafius, 1985; Luyendyk, 1991). The block is approximately 180 km by 70 km across and has rotated as a relatively coherent piece adjacent to nonrotated crust to the north and south (Crouch and Suppe, 1993; Nicholson et al., 1994).

This remarkable tectonic occurrence has spurred the development of several models of vertical-axis rotation. Luyendyk and others (1980) proposed a geometric model in which rotation occurred along left-lateral strike-slip faults while nonrotating crust to the north and south slid out of the way along northwest-striking right-lateral faults. This model was later adjusted to include changes in the width of the shear zone boundary during the rotational episode, and oblique slip faults between blocks (Luyendyk, 1991). Nicholson et al. (1994) proposed a more dynamic model that inferred rotation

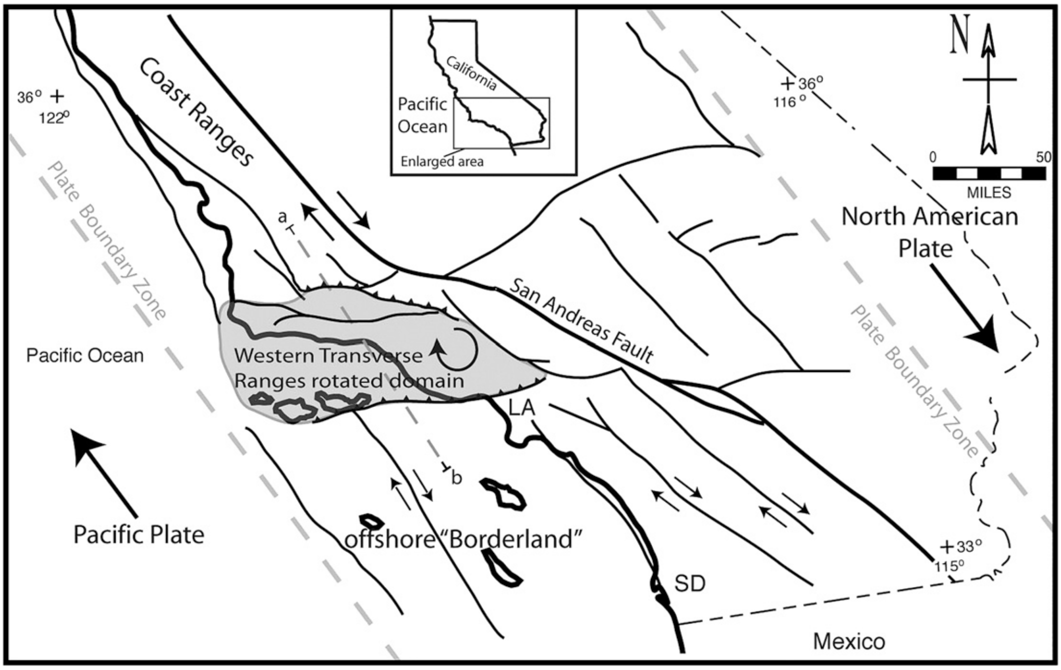

Fig. 1. Fault map of the Pacific–North American plate boundary in southern California showing the rotated western Transverse Ranges (shaded area). The coastline (in bold) and the cities of Los Angeles (LA) and San Diego (SD) are shown for reference. The western Transverse Ranges block has rotated approximately 90° about a pivot point at its eastern end within the right-lateral shear couple of the plate boundary.

of the western Transverse Ranges was caused by fault orientations in the upper crust and shear forces at the base of the block due to partially subducted oceanic crust being pulled out from underneath. However, most vertical-axis rotation models specific to southern California (e.g., Luyendyk, 1991; Crouch and Suppe, 1993; Dickinson, 1996) have been mainly kinematic and have not attempted, or have not been able, to resolve the driving mechanisms for rotation.

3. Rotational deformation and implications

Tectonic movements result in crustal deformation that is observed at the Earth's surface. Therefore, the deformation style, direction, and magnitude in plate boundary zones can be used to infer the driving forces of tectonic processes. The interaction of the WTR block with the surrounding crust has resulted in a significant amount of deformation at the block edges. Crouch and Suppe (1993) presented evidence that the south side of the WTR rifted away from the northern Peninsular Ranges in early Miocene time creating the Los Angeles Basin and Inner Borderland extensional zones to the south and southeast (Fig. 1). Extension in the earlier stages of rotation was succeeded by thrusting and uplift along the southern boundary that is still continuing today (Crouch and Suppe, 1993; Tsutsumi et al., 2001). Along the northern boundary, rotation was accommodated by a set of large thrust faults and folds that define a transition zone between the rotated WTR and the nonrotated Coast Ranges to the north (Onderdonk, 2005). This contractional deformation started with the onset of rotation in the eastern half of the boundary, but was preceded by an earlier phase of extension to the west in the Santa Maria basin (Hornafius, 1985). The contractional deformation at the boundaries of the rotated domain is consistent with the observation that the amount of right-lateral strike-slip on northwest trending faults north and south of the WTR are far less than needed by the original geometric models (i.e., Luyendyk et al., 1980), indicating that the nonrotating crust is not slipping out of the way, but rather colliding with the rotating block.

Several recent studies have noted that rotation is occurring primarily along dip-slip faults (Crouch and Suppe, 1993; Levi and Yeats, 2003; Onderdonk, 2005) and many of these major dip-slip faults in the WTR most likely sole out into large regional detachments that have been imaged beneath the area (e.g., Nicholson et al., 1992; Huang et al., 1996, Seeber and Sorlien, 2000, Prindle and Tanimoto, 2006). A regional detachment at 10 km to 15 km depth separates continental crust rocks from either mantle rocks or underplated oceanic crust (Nicholson et al., 1992; Huang et al., 1996) and most of the measured rotation may be occurring along this surface. The presence of this regional detachment surface, which may be a relic feature from earlier subduction along the western edge of the continent (Nicholson et al., 1994), implies that the transition from the lower to upper crust is discrete.

Analysis of the amount and mode of deformation present along the edges of the rotated domain provides constraints on the dynamics of rotation. The thrusting and folding along the block boundaries indicate that the driving mechanism must generate enough stress to fold and break the upper brittle crust. The blocks are not passively moving past each other or even moving with the same velocities, but are instead being subjected to large amounts of deformation with areas of shortening, extension, and rotation, which vary both spatially and temporally. These tectonic blocks are not perfectly rigid, but have experienced significant deformation, especially at the block boundaries.

Although the recent studies discussed above suggest that rotation is occurring along discrete detachments at depth, the following physical arguments are not dependent on the mode of attachment between the upper brittle crust and any ductile flow beneath. The transfer of forces between the ductile lower crust and the upper brittle crust is represented herein by viscosity and holds no assumptions as to whether the boundary is a discrete detachment or a transitional zone.

4. Force balance

In the following argument, observed deformation patterns and simple force balance considerations are used to test the hypothesis that basal traction is the driving force of vertical-axis rotation in California.

Rotation of the western Transverse Ranges occurred during crustal extension throughout the region in the earlier stage and was accompanied by north–south oriented contraction during the later stage. The forces responsible for both stages of deformation must obey basic physical principles of force balance. Here I evaluate the later stage during which rotation was accommodated by shortening deformation that is evident in the present-day structural framework of the area. Any compressive force at the northern edge of the rotated domain (point Y in Fig. 2) that is generated within the rotating block must be equal and opposite to the force generated by the southern Coast Ranges blocks to the north. If these forces are due to traction imparted to the base of the brittle crust by ductile shear below,

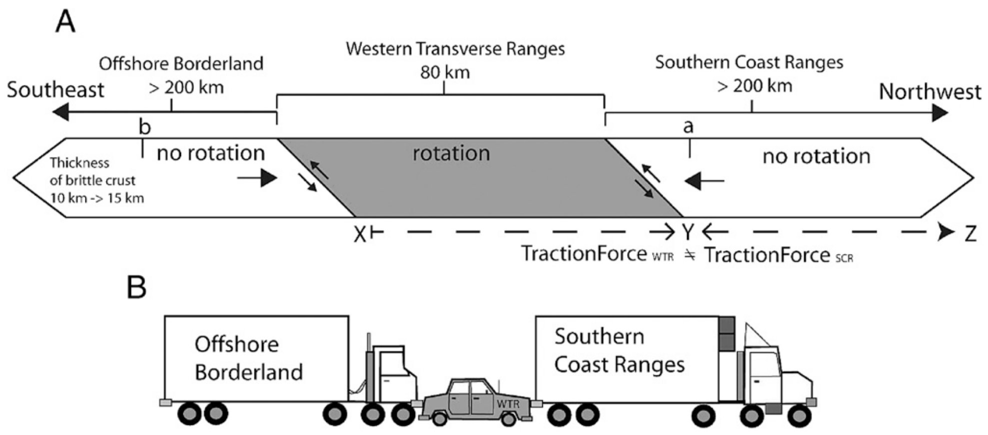

Fig. 2. A. Block model cross-section across the western Transverse Ranges (WTR) and the nonrotated blocks to the north and south. Refer to Fig. 1 for location of cross-section. B. Trucks and car analogy for the relative influence of basal traction forces depending on block size.

then the shear forces at the base of the southern Coast Ranges (line YZ) must be balanced with basal shear forces beneath the WTR (line XY). Since the basal area of the WTR (about 12,600 km^2) is far less than the southern Coast Ranges (>20,000 km^2), these forces cannot be equal and the smaller WTR block would be accelerating away from the Coast Ranges. This situation is obviously not occurring, and could not, because the WTR block is "supported" by (in contact with) the larger Borderland blocks to the south. Basal shear forces from beneath the Borderland blocks must be transmitted through the upper brittle crust to maintain force balance across the deforming boundary zones of the rotating block. Therefore, "local" basal shear forces at the bottom of the rotating block are irrelevant. Driving forces generated by basal shear must be far-field and are transmitted through the brittle crust to create the observed rotational deformation.

This force balance argument may be roughly likened to evaluating the relative role of basal traction generated by the tires of a small car sandwiched between two large trucks (Fig. 2B). The forces generated by the tire traction of the small car would be irrelevant when compared to the forces imposed on it by the larger trucks on either side. It is important to note that the cars and trucks in Fig. 2B, like the crustal blocks, are not "bumping" into each other. They are always in contact, so there is no inertia. Consequently, it is the big blocks (or trucks in the analogy) that dictate the motion of the smaller blocks (cars) in between.

This analysis is not dependent on the tectonic regime and would not change if we evaluated the earlier stage of rotation accompanied by extension. In both cases the forces that cause deformation at the boundaries of the rotated domain must be balanced. In order to rip the crust apart, it must be held with an equal force, just as one must push with equal force to deform it by contraction. The observation that the rate of rotation did not change throughout Neogene time (Luyendyk, 1990) supports this assertion that the mechanism controlling rotation is independent of tectonic regime.

The force balance considerations in this simplified two-dimensional analysis also apply to the three-dimensional plate boundary shear zone as a whole. Any movements of isolated blocks that are relatively small compared to larger blocks in a shear zone, or the shear zone bounding plates, are the results of forces transmitted through the upper crust. Because crustal blocks in any zone of deformation are constantly in contact with one another, or the shear zone boundaries, any forces applied to the base of a block must be in balance with the forces applied to the sides. When we consider the magnitudes of forces that can be imparted to the sides of fault blocks by the larger shear zone boundary plates, the forces imparted to the base of smaller fault blocks becomes irrelevant.

5. Comparison of torque forces

Lamb (1994) used basic physical principles to compare the vertical torque exerted on the sides of a crustal block to the torque exerted at the base by shear in a ductile flow beneath. Here I apply Lamb's method to crustal rotation in southern California by using values and dimensions specific to the WTR.

The torque exerted on a body is:

$$T = RF_{\perp} \quad (1)$$

where R is the length of the moment arm and $F_{\perp}$ is the magnitude of the force perpendicular to the moment arm

(Fig. 3). Integrating the torque over a block of characteristic dimension l, the torque applied to the base is;

$$T_b \sim 1^3 S_b \tag{2}$$

where S_b is the shear stress on the base of the block. The torque applied to the sides is;

$$T_s \sim hl^2 S_s \tag{3}$$

where h is the thickness and S_s is the resistive stress of the brittle crust. If we assume a Newtonian rheology for the underlying fluid, then;

$$S_b = \eta\dot{\varepsilon} \tag{4}$$

where η is the effective viscosity of the underlying ductile flow (and can be considered a measure of the degree of linkage between the flow and the brittle crust above), and $\dot{\varepsilon}$ is the strain rate of the shear zone. Substituting S_b into Eq. (2) we can compare the torque applied to the base to the torque from the sides of the block with the following equation:

$$T_b/T_s \sim 1\eta\dot{\varepsilon}/hS_s. \tag{5}$$

To evaluate the torque on the WTR, a characteristic length of 125 km is used, and an estimated thickness of 13 km (Huang et al., 1996; Prindle and Tanimoto, 2006). This estimated thickness might vary by as much as 5 km, but any variation on the same order of magnitude will not affect the calculations presented here. Using a shear zone width of approximately 300 km, and a displacement rate across the zone of approximately 4 to 5 cm/yr (e.g., Demets et al., 1990; Argus and Gordon, 2001), a strain rate of about 4.8×10^{-15} 1/s is calculated for the North American–Pacific plate boundary in California. Crustal shear stresses range from 10^6 and 10^8 Pa (e.g., Hanks, 1977; Kirby, 1980; Mount and Suppe, 1987; Molnar and England, 1990). Upper mantle/lower crustal viscosities calculated for the western US are consistently lower than upper mantle viscosities in other parts of the world (see Dixon et al., 2004 for discussion) and vary between 2×10^{17} Pa s (Kaufmann and Amelung, 2000) and 3×10^{19} Pa s (Bills et al., 1994). Here I use an average value of 4×10^{18}, which also corresponds to a recent determination from southern California (Pollitz, 2003).

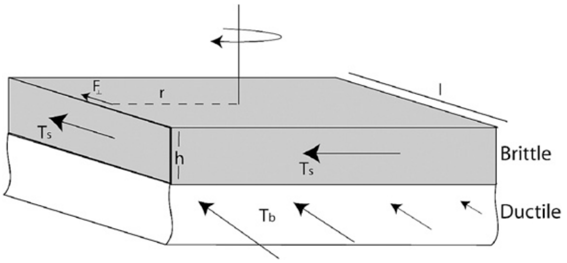

Fig. 3. Diagram illustrating the torque applied to a crustal block.

The resultant ratio, T_b/T_s, ranges between .18 (using 10^6 Pa) and .0018 (using 10^8 Pa). This indicates that torque applied to the sides of a crustal block is one to three orders of magnitude stronger than can be applied at the base by ductile flow beneath, and suggests that stresses transmitted though the brittle crust govern the movements of crustal blocks in a shear zone. This result holds true for other plate boundary zones such as the Aegean, and the Alpine fault in New Zealand. Reported values for crustal thickness, block dimensions, strain rate, and expected asthenospheric viscosities in these areas do not vary enough from those used above to significantly affect the calculated torque ratio (e.g., Vickery and Lamb, 1995; Westaway, 2002; Tirel et al., 2004). In fact, in both these areas the characteristic size of the blocks are smaller, and the average crustal thicknesses are slightly larger than in California, thereby making the deformation even more dependent on upper crustal stresses.

Lamb's (1994) analysis yielded T_b/T_s ratios of .01 to 1000, which led him to conclude that, "the underlying ductile flow may have an overwhelming influence on crustal deformation". The primary reason for this divergence from the values calculated here is that Lamb (1994) assumed that the viscosity of the ductile lithosphere was 10^{21} or greater, which is a value typically calculated for the middle to lower mantle (e.g., Cathles, 1975; Mitrovica and Forte, 2004). Although the lower lithosphere in thick continental regions may reach this value, it is most likely not appropriate for most plate boundary zones.

Both the analysis here and by Lamb (1994) are only rough approximations of torque balance and must be regarded as theoretical arguments. These analyses assume circular blocks, whereas crustal blocks may be a variety of shapes. More importantly, both analyses assume maximum torques, which require that the applied forces are always in a direction perpendicular to a line between the center of mass and the point at which the force is applied. This is clearly not the case in any tectonic shear zone. Instead, torque will vary dramatically according to position along the base of the block and the angle of the side surface with respect to the shear vector. However, these variations will apply to both the torque applied at the base and the sides in a similar manner. Consequently, the analysis of torque balance is a valuable approach to comparing possible driving forces for block rotation.

6. Discussion

In the calculation above, torque is used to evaluate the relative influence of forces transmitted through the upper brittle crust versus lower ductile crust on block motions. Simple translation or nonrotational deformation of crustal blocks can also be addressed in a similar analytical manner and the results will ultimately depend on the relationships between lower crustal viscosity and strain rate to block dimensions. The influence of basal shear forces increases with block size. At the scale of tectonic plates, basal shear forces are large enough to overcome upper crustal strength and result in deformation and relative movements between plates. However, the analytical analysis presented here suggests that the movements of crustal blocks with a characteristic length scale of hundreds of kilometers or less, are dominated by forces transmitted through the upper brittle crust, especially in plate boundary zones where low viscosity material directly underlies the brittle crust.

Although there is a significant amount of Pliocene and younger deformation within the rotated domain, the available geologic data indicates that the WTR moved as a relatively coherent block during most of its rotational history (e.g., Yeats, 1983; Crouch and Suppe, 1993; Shaw and Suppe, 1994). For this reason, the rotated domain is evaluated as a single block in the analysis presented here. If the WTR is treated as multiple rotating panels, as it is in several kinematic models (e.g., Jackson and Molnar, 1990; Dickinson, 1996), the dominance of upper crustal driving forces is only enhanced, according to force balance principles, due to a reduction in block size. This result questions the assumption that a larger number of smaller blocks, which closely represents continuous deformation, is indicative of basal traction dynamics (Molnar, 1988; Lamb, 1994).

Upper mantle and lower crust viscosities in some active plate boundary zones, such as southern California, are orders of magnitude lower than those measured in continental interiors. For this reason, the link between the lower ductile and brittle parts of the crust in these areas is not strong enough to overcome upper crustal stresses and control block motions at the surface. The complex pattern of deformation along the San Andreas plate boundary in southern California, and the existence of isolated rotated domains, may itself be an indication of the dominance of upper crustal forces. If the linkage between the ductile lower crust and the upper brittle crust was strong enough to fold and break the upper crust, why would the upper crust exhibit such a complex deformation pattern with individual nonrotating and rotating blocks, instead of producing a clean shear boundary that more closely mimics a shear flow below? Why would the crust deform by folding and thrust faulting, when a simple set of boundary-parallel strike-slip faults would require less effort?

The question of why some parts of the plate boundary have undergone rotation, while others just translate also relates to the dynamics at work. Nicholson and others (1994) presented a model of southern California tectonics in which rotation of the WTR was associated with a partially subducted slab being pulled out to the northwest from underneath. They infer that rotation was the result of a combination of basal shear from the translating slab and upper crustal interactions related to complications in the main plate boundary zone. Although the results presented here indicate that basal shear cannot drive the observed rotations (especially when the traction must be transferred across a former subduction surface where crustal stresses are typically low), the influence of the structural geometry hypothesized by Nicholson et al. (1994) warrants more investigation. In southern California, localization of rotation is more likely to be the result of anisotropies in the upper crust or complications in the structural geometries of the evolving plate boundary rather than lower crustal heterogeneity. This is supported by the inference that the WTR lacks a lower continental crust (Nicholson et al., 1992, 1994). Prior to the Late Miocene to Present transform motion, the plate boundary at the western edge of North America was a subduction zone and the WTR block lay in the relatively thin crustal wedge of the over-riding plate. The lower crust in coastal southern California appears to be underlain by remnant subducted oceanic lithosphere (e.g., Nazareth and Clayton, 2003; Prindle and Tanimoto, 2006). Several studies have observed large heterogeneities in the upper mantle below southern California (e.g., Humphreys and Clayton, 1990; Tanimoto and Prindle Sheldrake, 2002), however, these anomalies have developed since rotation began and have been attributed to convergence in the area of the Big Bend of the San Andreas fault, which is an upper crustal feature (Humphreys, 2004). At the time rotation of the WTR began, the upper crust was underlain by either a subduction surface with oceanic crust beneath, or fresh asthenosphere. The presence of this significant discontinuity makes it unreasonable to assume that any effect lower crustal variations may have on the displacement field in the lower crust could be transferred across the paleosubduction boundary between the underplated oceanic lithosphere and the upper crust.

To move forward in our understanding of vertical-axis rotation, we must begin to evaluate the conditions necessary to initiate and facilitate this form of crustal deformation. The development of paleomagnetic techniques has led to the recognition of vertical-axis rotation as a common occurrence in every type of tectonic environment. However, the distribution of rotated crust is often localized, as in southern California, and the factors governing where, when, and why rotation is preferred by tectonic mechanisms are not understood. An examination of present and past structural geometries, block motions and deformation, and modeling may reveal possible situations in which rotation is preferred.

7. Conclusion

The geologic observations and physical analysis presented here provide insight into the dynamics of vertical-axis rotation in southern California. Faults and folds at the boundaries of the rotated domain indicate that the driving forces must be capable of deforming the upper crust. Simple force balance considerations and comparison of torque that can be applied to the edges and base of the rotated block indicate that basal shear forces are not strong enough to produce this deformation. Therefore, stresses transmitted through the upper brittle crust must be the dominant control on the observed motion. This result is dependent primarily on block dimensions and viscosity of the ductile part of the crust and can be applied to other continental deformation zones where similar relationships exist.

Acknowledgements

Dani Schmid and Yuri Podladchikov are gratefully acknowledged for their helpful discussions and insightful suggestions. Reviews by C. Sorlien and S. Giorgis helped improve the manuscript and are greatly appreciated. This work was funded by the Norwegian Science Foundation while the author was employed by the Physics of Geological Processes research center at the University of Oslo in Norway.

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