Originally published as:

Schelle, H., Grünthal, G. (1996): Modeling of Neogene Crustal Block Rotation: Case Study of South-Eastern California. - *Tectonics*, 15, 2, pp. 700–710.

DOI: <http://doi.org/10.1029/95TC03687>

Modeling of Neogene crustal block rotation: Case study of southeastern California

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Abstract. Numerical modeling using a two-dimensional distinct element method (DEM) was performed to give an additional understanding of the mechanism of crustal block rotation in a highly active portion of the Pacific-North America transform plate boundary. Paleomagnetic and structural investigations have shown that large (30°-50°) horizontal rotations of crustal blocks occurred in the Eastern Transverse Zone and the Northeast Mojave Block (southeastern California) since the end of early Miocene. The main aspect of the modeling was to investigate whether an anisotropic horizontal stress state can be responsible for the rotation of crustal blocks with a length of 100 km or not. The simulations were performed using different stress boundary conditions and different parameters of the fault strength. Applying an assumed ratio of 2 for the horizontal stress components as boundary condition, block rotations in the order of 40° only occur if (1) the major horizontal stress S_H is oriented N20°E with a maximal deviation of 15° to the east or west, and (2) the fault strength described by the friction coefficient is smaller than 0.12, or 14% only of the value 0.85 for intact rocks (Byerlee's law). For a weakening model of the fault strength an initial friction coefficient of 0.85 allows also rotations of about 40° if the friction coefficient decreases rapidly due to an increasing shear displacement to a basic friction coefficient of 0.12 or smaller. For the same amount of rotation (40°) a decreasing stress ratio requires a lowering of the friction coefficient used, whereas an increase of the ratio allows a higher friction coefficient. The simulation also show that the modeling with elastic blocks can adequately describe the observed main features of the crustal deformation, especially the cumulative slip values. Discrepancies in the observations and modeling results for the western parts of the Mojave Desert are the result of a neglect of the three-dimensional deformation in our two-dimensional modeling.

Introduction

Since the development and acceptance of plate tectonic theory and the recognition of the San Andreas fault system as a major plate boundary, it has often been assumed that

deformations near the fault necessarily reflect right-lateral motions along parallel northwest oriented wrench faults [Nicholson *et al.*, 1986a]. Seismological investigations show that secondary dextral faults as well as many secondary sinistral faults exist in the proximity of the San Andreas fault [cf. Nicholson *et al.*, 1986a, b].

Paleomagnetic and structural evidence indicates that large (30°-50°) and very large (70° and more) horizontal rotations of crustal blocks occurred between parallel fault sets on both sides of the San Andreas fault since the end of early Miocene time [cf. Carter *et al.*, 1987; Luyendyk, 1991; Valentine *et al.*, 1993]. The paleomagnetic data for the Western Transverse Ranges suggest a 70° to 90° rotation [Kamerling and Luyendyk, 1979; Luyendyk *et al.*, 1985], which is necessarily connected with the partial destruction of the initial block structure, because [after Nur *et al.*, 1986] block rotations larger than 45° require the development of multiple sets of rotating faults with angles of 20° to 45° between them.

The Eastern Transverse Ranges experienced a rotation of only about 40° according to paleomagnetic data [Carter *et al.*, 1987]. For the Northeast Mojave Block there are also paleomagnetic data suggesting that this area rotated simultaneously with the Eastern Transverse Ranges in a clockwise sense [Ross *et al.*, 1989; MacFadden *et al.*, 1990a; Dokka *et al.*, 1991]. Contrary to the area west of the San Andreas fault, no additional fault sets resulting from larger block rotations should have superimposed on the initial fault pattern. For this reason the area east of the San Andreas fault, including the Eastern Mojave Desert, the Northeast Mojave Block, and the Mojave Desert between the Garlock and Pinto Mountain faults, has been selected for the modeling.

Common to all the mechanisms of block rotation in southern California is the concept that crustal blocks have to be detached at depth, thereby permitting them to translate and rotate about an approximately vertical axis [Nicholson *et al.*, 1986a, b; Carter *et al.*, 1987]. Therefore the crustal deformation should be essentially characterized by two-dimensional horizontal deformation processes. To give some additional understanding of the mechanism of block rotation, and to verify the applicability of the distinct element method (DEM), a computational model representing the most important structures for crustal deformation east of the San Andreas fault was analyzed by the two-dimensional program UDEC [Lemos *et al.*, 1985] using different boundary stress states and varying parameters of fault strengths.

Geological and Tectonic Settings

General

The San Andreas fault is one major component of the Pacific-North America transform plate boundary. Displacement

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Paper number 95TC03687.
0278-7407/96/95TC-03687\$12.00

and strain related to the relative motion along this plate boundary are distributed over a wide zone rather than along a single fault [Atwater, 1970]. The major surface faults mapped in southern California are illustrated in Figure 1 [after Luyendyk, 1990, 1991]. The Mojave Desert, the Northeast Mojave Block, and the Eastern Transverse Ranges form a triangle-shaped area bounded on the north by the left-lateral Garlock fault and on the southwest by the right-lateral San Andreas fault. Within this triangle, right-lateral northwest trending and left-lateral east-west trending faults occur. The structural geology and fault pattern within this area are nearly uniform, internally consistent, however, and distinctly different from the structural geology and fault pattern of the areas to the north and south.

The Eastern Transverse Ranges and the Northeast Mojave Block (shaded in Figure 1) had their main rotation phase since the end of early Miocene time [Luyendyk, 1991]. All the clockwise rotated blocks are bounded to the north and to the south by faults striking approximately east-west. Most of these faults are characterized by predominantly left-lateral components of motion.

Since middle Miocene the geological development of the whole Mojave region has been influenced mainly by the San Andreas strike-slip fault system [Cheadle *et al.*, 1986]. The lateral displacements along both the San Andreas and the Garlock faults have resulted in a nearly north-south oriented compressive stress regime [Hill, 1954; Bohannon and Howell, 1982] and in the development of northwest trending dextral faults within the Mojave Desert [Dibblee, 1968; see Figure 1].

Midcrustal Detachment and Block Structure

Midcrustal detachments are characteristic for many areas in the southwestern part of the United States and have been suggested previously for southern California by earthquake travel time residuals [Hadley and Kanamori, 1977], by geodetic constraints on the effective elastic thickness of the upper crust [Turcotte *et al.*, 1984], and by the presence of moderate to large earthquakes near the base of the seismogenic zone showing a low-angle nodal plane in their fault plane solutions [Webb and Kanamori, 1985; Nicholson *et al.*, 1986b]. Other evidence for low-angle detachments has been found by deep seismic reflection studies in the Mojave Desert [Cheadle *et al.*, 1986]. Velocity structures determined from earthquake arrival times also show a pattern suggesting a possible regional decollement [Nicholson and Simpson, 1985].

The distribution of microearthquake hypocenters ($M_L < 5.5$) in California suggests that the transition from brittle or frictional behavior to quasi-plastic deformation processes in quartz-bearing crust (defined as the depth above which 90% of the microearthquakes take place) occurs at a depth of around 10 km in the area of high to normal heat flow, such as the Mojave Desert region [Sibson, 1982]. It is possible that this transition correlates with the midcrustal detachments in southern California.

The heterogeneous strain and the nonuniform displacement fields, characteristic for the Pacific-North America transform plate boundary, can be interpreted as a manifestation of the deformation of rootless upper lithospheric flakes, nearly 15 km

Figure 1. Simplified fault pattern for southern California. Shaded areas are believed to have been rotated in clockwise direction since the end of early Miocene time [after Luyendyk, 1991]. The maximum rotation west of the San Andreas fault is between 70° and 90° clockwise; east it is about 40°. The area east of the San Andreas fault, including the Eastern Mojave Desert, the Northeast Mojave Block, and the Mojave Desert, has been selected for the modeling of the crustal block rotation. RPB fault system is Rodman/Pisgah/Bullion fault system.

thick, which are at least partly decoupled from the lower lithosphere [Sedlock and Hamilton, 1991]. This decoupling should be realized along the postulated midcrustal detachments or decollements that mark a significant strain discontinuity [Yeats, 1981; Hearn and Clayton, 1986a, b].

Paleomagnetism and Block Rotation

The paleomagnetic data collected from the Eastern Transverse Ranges region by Carter *et al.* [1987] indicate that the region has undergone a net clockwise rotation of about 40° since late Miocene, because the age of the investigated basalt rocks was dated as late Miocene and implying that deformation processes in the region began at that time [Carter *et al.*, 1987]. Revised isotopic data constrain the rotation found there to be post-6 Ma [cf. Ross *et al.*, 1989]. This clockwise rotation of the Eastern Transverse Ranges constrains a cumulative slip of the northwest trending faults of the Mojave Desert to adjust the deformation of the Eastern Transverse Ranges and the clockwise rotation of the Northeast Mojave Block.

Paleomagnetic data from Miocene rocks in the northwest part of the Mojave Desert, immediately south of the Garlock fault, show that no significant rotation has taken place since middle Miocene time [Kanter and McWilliams, 1982], whereas a post-early Miocene rotation of 30° to 50° appears to have taken place in the southern part of the Northeast Mojave Block [Ross *et al.*, 1989]. The investigation and discussion of Ross *et al.* [1989] suggest that the clockwise rotations of the Eastern Transverse Ranges and the Northeast Mojave Block occurred simultaneously post-6 Ma. Further data of a relevant rotation are given for the Cady Mountains located along the Cady fault. A paleomagnetic study of MacFadden *et al.* [1990a] suggests that rocks from these mountains have rotated about 21° since 16 Ma. Data of Dokka *et al.* [1991] show much higher values of rotation for approximately the same area [cf. also Valentine *et al.*, 1993].

Paleomagnetic studies in the southwestern Mojave Desert give contradictory results. Data from Burke *et al.* [1982] and J. Morton and J. Hillhouse (unpublished data 1987) [see Carter *et al.*, 1987] suggest 15° ± 11° of net counterclockwise rotation of the Mojave region since middle Miocene. Weldon *et al.* [1984] have provided paleomagnetic evidence indicating that the southwestern Mojave Desert has rotated less than 4° since middle Miocene time. Middle Miocene or younger rocks investigated by MacFadden *et al.* [1987, 1990b] and Valentine *et al.* [1993] also show no evidence of rotation in the Barstow area in the center of the Mojave Desert. Paleomagnetic results from Miocene volcanic rocks in the western Mojave Desert suggest only small counterclockwise rotations in middle Miocene or later times [Golombek and Brown, 1988].

Rotations in the Mojave Desert predating middle Miocene time (about 15 Ma) are found by several authors but are not important for our modeling as the northwest striking faults in the Mojave Desert developed after 13 Ma and have probably been most active since about 5 Ma [cf. Valentine *et al.*, 1993; Ross *et al.*, 1989 and Dokka, 1989].

Fault System and Regional Stress State

Numerous observations for the San Andreas fault are based on heat flow measurements indicating that the fault zone itself is relative weak in comparison with the surrounding crust [cf.

Hickman, 1991]. The apparent absence of a heat flow anomaly along the fault has been interpreted as an evidence of a relatively low absolute shear strength of not more than 20 MPa [Lachenbruch and Sass, 1988, 1992]. In situ stress orientations along the San Andreas fault [Mount and Suppe, 1987; Zoback and Healy, 1992; Shamir and Zoback, 1992] show that the major horizontal compressive stress S_H in the immediate vicinity of the San Andreas fault is oriented at angles of 60° to 80° to the nearly vertical fault plane. Nevertheless, the low shear strength on the fault and the stress orientations are consistent with high local deviatoric stress magnitudes of about 100 MPa [Mount and Suppe, 1992]. Inferences for the stress state on the secondary faults are not directly possible from the heat flow measurements related to the immediate vicinity of the San Andreas fault.

Measurements of the stress magnitudes are known for some sites near the San Andreas fault. Based on stress measurements in the Cajon Pass Scientific Research Borehole [Zoback and Healy, 1992] a lateral stress ratio S_H/S_v (S_H is major horizontal stress component; S_v is vertical stress) of 0.9 to 1.35 can be obtained, whereas the lateral ratio S_h/S_v is about 0.45 to 0.6 (S_h is minor horizontal stress). Similar results are calculated for the data summarized by Zoback [1992].

Apart from the immediate vicinity of the San Andreas fault, the stress state in southern and easternmost California is almost unknown. Due to the lack of stress orientation data in these regions, stress trajectories are not plotted for this part of California [Mount and Suppe, 1992]. The data collected by Zoback and Zoback [1989] show for southern California an orientation of S_H in the range between about N-S and N40°E. Most of the data based on the World Stress Map (WSM) [Zoback, 1992] show an orientation of the maximum horizontal compressive stress in the range between N-S and N50°E for southern California, whereas some stress directions derived from data taken near the San Andreas fault correspond approximately with the fault direction.

For the southwestern part of the Mojave Desert, the earthquake focal mechanisms associated with the three relatively large, strike-slip events that occurred in April and June 1992 all indicate a NNE-SSW compressive stress regime [Zoback, 1993; Hauksson, 1994]. For modeling the Coulomb failure stress changes as a result of the Landers earthquake, King *et al.* [1994] used a regional principal compressive stress oriented N7°E.

New observations of the internal structure of the San Gabriel fault, which are combined with previous characterizations of other faults in this area, show that these faults have an internal zonation [Chester *et al.*, 1993]. Most of the dislocations on these faults were confined to the core of the principal faults, which typically consists of a narrow layer (less than tens of centimeters) of ultracataclasite within a zone of foliated cataclasite several meters thick [Chester *et al.*, 1993]. The structural, mechanical, and hydrologic characteristics of the San Gabriel and other faults support the model for a weak San Andreas fault.

Dip values of these faults are available for the San Andreas and the Garlock fault. According to the Consortium for Continental Reflection Profiling (COCORP) deep seismic reflection profiling in the Mojave Desert the San Andreas fault is a major, vertical feature traceable to a depth of about 20 km,

whereas the Garlock fault seems to be also vertical but shallower reaching a depth of only 9 km [Cheadle *et al.*, 1986].

Distinct Element Modeling

Distinct Element Code UDEC

The distinct element method (DEM) was first proposed by Cundall [1971] and has been developed in the last two decades, mainly for the purpose of modeling regularly and highly jointed rocks. It has become more widely used recently with the availability of the two-dimensional program Universal Distinct Element Code (UDEC) [Cundall, 1980; Lemos *et al.*, 1985]. This method is ideally suited to modeling jointed rock masses where the deformation mechanism is mainly a result of block separation, rotation, and slip, whereby large relative motions may occur. At present, the method appears to be extremely useful in explaining qualitatively the deformation and failure mechanisms of jointed rock masses [Pande *et al.*, 1990]. Sometimes UDEC was also used for modeling of crustal deformation processes [Jing and Stephansson, 1990; Schelle and Grünthal, 1994].

Rock masses in this method are represented as a discontinuous system of interacting blocks. Discontinuities are treated as internal boundaries with defined conditions, and blocks as finite difference zones, respectively. The solution algorithm is based on an explicit time-marching procedure, and the response of the system is calculated by numerical integration of the equations of motion for each block. Due to the explicit solution procedure the CPU times required can be exceedingly large.

The explicit procedure is similar to other explicit calculations in the time domain, and an explicit central difference scheme is used to integrate the equations of motion of the block assemblage at each grid point. For one grid point the equation can be expressed in the form

$$\frac{\partial \dot{u}_{ij}}{\partial t} + \alpha \dot{u}_{ij} = \frac{F_{ij}}{m_j} + g_i \quad i = 1, 2; j = 1, N \quad (1)$$

where $\dot{u}_{ij}$ are the components of the velocity at grid point j ; N is the number of finite difference zones; α is the parameter for the viscous damping; m_j is the lumped mass at this grid point; and g_i are the components of the gravitational acceleration. F_{ij} is the sum of forces acting at grid point j given by

$$F_{ij} = F_{ij}^z + F_{ij}^e + F_{ij}^c. \quad (2)$$

F_{ij}^z represents the internal forces caused by elastic deformations of the finite difference zone surrounding grid point j and F_{ij}^e are the external loads. The contact force F_{ij}^c is obtained by integrating the constitutive equations for the discontinuities along the displacement increments. In the central difference scheme velocities at time $(t + \Delta t/2)$ become

$$\dot{u}_{ij}^{(t+\Delta t/2)} = \dot{u}_{ij}^{(t-\Delta t/2)} + \left(\frac{\Sigma F_{ij}^{(t)}}{m_j} + g_i \right) \Delta t \quad (3)$$

where Δt is the initial time step. The new velocities in (3) are now used to determine the new block locations according to

$$x_{ij}^{(t+\Delta t/2)} = x_{ij}^{(t)} + \dot{u}_{ij}^{(t+\Delta t/2)} \Delta t \quad (4)$$

where x_{ij} are the coordinates of zone j . Analogous equations to (3) and (4) have to be used for the angular velocities and rotations of the finite difference zones around the grid points.

For the block constitutive behavior there are different basic constitutive laws provided in UDEC. The most important are (1) elastic, isotropic model, (2) elasto-plastic models based on Mohr-Coulomb plasticity or (3) Drucker-Prager plasticity. Models 1 and 2 are used in our modeling.

The deformability of the discontinuities between the blocks and the frictional characteristics is represented in the DEM by spring-slider systems with prescribed force-displacement relation that allow evaluation of shear and normal forces between blocks. Two rate-independent constitutive models are assumed for the strength of the faults.

An elastic-perfectly plastic fault behavior is assumed with the yield function and the plastic potential based on the following Mohr-Coulomb equation:

$$F = |\sigma_s| - \left(\tan(\varphi) \sigma_n^{eff} + c \right) \quad (5)$$

and

$$Q = |\sigma_s| - \left(\tan(\psi) \sigma_n^{eff} + c \right), \quad (6)$$

respectively. The effective normal stress on the fault σ_n^{eff} is simply

$$\sigma_n^{eff} = \sigma_n - P_p \quad (7)$$

where σ_n is the normal stress on the discontinuity, P_p is the fluid pressure in the same discontinuity, σ_s is the shear stress, and c is the cohesion. The angles φ , ψ are the residual friction angle and the dilation angle, respectively. For equal angles an associated flow rule is assumed. The friction coefficient μ is defined as $\tan \varphi$.

This model can still simulate stick-slip movement. Applying the continuously yielding model describing the weakening during shear the consideration of the post-peak shear strength degradation is possible. The behavior of the faults is now described by an initial friction angle φ_i and a basic friction angle φ_b , and the higher value of φ_i is decreasing continuously to φ_b mainly depending on the magnitude of the shear displacement along the discontinuity. The continuously yielding joint model simply simulates the internal mechanism of progressive failure damage of the joint under shear and can simulate the decrease in the shear strength of discontinuities after the peak strength has been reached and the surface damage during shear has occurred.

Two-Dimensional Rotation Model

A two-dimensional reference model and two modified models (compare Figure 2) were used for the numerical

Figure 2a. Reference model A for modeling the deformation processes in southeast California. The block southwest of the San Andreas fault remains fixed as a "boundary condition". The Eastern Transverse Ranges, the Northeast Block, and the Mojave Desert are shown in different shades of grey. The recent orientation of the maximum horizontal stress S_H is also indicated.

simulation of rotating the wrench fault system including the Eastern Transverse Ranges, the Northeast Mojave Block, and the Mojave Desert. Several prerequisites are necessary for the two-dimensional modeling of such a real three-dimensional structure: a wrench fault system with nearly vertical dipping of the faults, a regional detachment of the rotating blocks at some depth, and an anisotropic regional stress state with a distinct orientation. The different investigations described in the foregoing text show that all these prerequisites are seemingly fulfilled approximately in the area under investigation.

The main objectives of the numerical calculations were (1) to determine whether the paleomagnetically observed rotations can be simulated with a distinct element method, (2) to test over what range the material parameters to be assumed or assessed for computation can vary and retain a match with the observations, and (3) to investigate the influence of the boundary stress state and its orientation on the deformation mechanism on the area of interest. Finally, the applicability of

Figure 2b. Modified model B considering an additional northwest trending set of faults in the Northeast Mojave Block. The boundary conditions are the same as for model A.

the distinct element method for the modeling of large crustal deformations was tested.

The first model (Figure 2a) shows the reconstructed representation of the situation before rotation. A reconstruction that restores the slip on the sinistral faults while backrotating the Eastern Transverse Ranges was presented by *Carter et al.* [1987]. Only one set of nearly parallel faults is characteristic for each modelled region in this model: (1) a northwest trending fault set for the Mojave desert, (2) a northeast trending set for the Eastern Transverse Ranges, and (3) a slightly different orientated northeast trending fault set for the Northeast Mojave Block. The only difference between the model used and the model of *Carter et al.* [1987] is that the San Andreas fault, acting as the left boundary in our model, is not assumed to have rotated simultaneously with the deformation of the Mojave Desert. This feature agrees with newer geological findings [*Meisling and Weldon*, 1989].

In a second model (Figure 2b), two different fault sets were considered for the modeling of the Northeast Mojave Block, as it is in discussion, what fault set is responsible for crustal deformation in this area since middle Miocene time [*Dokka and Travis*, 1990]. The first fault set is assumed to have a northeast

Figure 2c. Model C based on model B but taking into account further the Sleeping Beauty fault in the eastern Mojave Desert. For model C the same boundary conditions are also used as for the reference model.

orientation, as in the first model; the second fault pattern is approximately oriented in a northwest-southeast direction, as proposed by *Dokka and Travis* [1990]. This aspect of the *Dokka and Travis* model is in marked contrast to previous models that emphasize the role of the northeast striking sinistral faults in the deformation of the Northeast Mojave Block. Modeling of the two different orientated fault sets may give some hints about which of the sets was more active during the deformation processes since the middle Miocene.

Another aspect of the *Dokka and Travis* [1990] structural model (the importance of the Sleeping Beauty fault) was investigated in a third model (Figure 2c). In the opinion of *Dokka and Travis* [1990] this fault, located south of the Cady fault, had significantly influenced the deformation of the western part of the Mojave Desert.

Different joint and block constitutive models and parameters are tested in the numerical calculations for the block rotation. For the joints a Coulomb slip model, with and without displacement weakening, and a continuously yielding joint model were selected. For the crustal blocks, different constitutive models were assumed: rigid, quasi-rigid, elastic, and elasto-plastic, with Mohr-Coulomb plasticity and dilation.

Rigid blocks have no deformability, whereas quasi-rigid blocks have elastic moduli 10 times higher than for the elastic blocks.

Assumed block and joint constitutive parameters are of the order given by typical textbook values for crystalline rocks (Table 1) [e.g., *Jumikis*, 1979; *Carmichael*, 1989]. The strength of the discontinuities was first described according to the friction law of *Byerlee* [1978] using a friction coefficient of 0.85. This value was varied to achieve crustal rotation processes depending on the used boundary stress anisotropy. The cohesion is presumably very small in faults and was neglected in our models.

As boundary conditions for the northern, the eastern and the southern boundary, horizontal stresses S_H and S_h of 300 MPa and 150 MPa are used. The major and minor stresses are governed by a crustal density of 2.5 g/cm³ and at first by lateral stress ratios of 1.2 for S_H and 0.6 for S_h , respectively, and correspond approximately to a depth of about 10 km. The assumed stress ratio of the major to the minor horizontal stress components was 2 for most of the calculations. Starting with the recent orientation of S_H , N20°E, at first the calculations were performed with different fault strengths to estimate the strength values allowing block rotations in the order of 40°. Additionally, a hydrostatic pressure at a depth of 10 km was used to calculate the effective normal stresses on the faults (equation (7)).

Based on the estimated parameter for the fault strength, in a second step the orientations of the applied stress field were varied from N10°W to N50°E. Finally, in a third step, the interaction between the anisotropy of the applied stress and the fault strength, necessary for block rotations of 40°, was investigated roughly.

The left boundary of the model is principally represented by the San Andreas fault. For the modeling, at least one point of the model has to be fixed in space. Therefore an additional triangle was incorporated in the model allowing a rational formulation of this condition (Figure 2a). Now, the San Andreas fault is part of the model itself, but it is the main aim of the modeling to get a better understanding of the mechanism of block rotation and not to investigate the slip along the San Andreas fault. (By the way, if slip along the San Andreas fault is initiated, nothing can stop the sliding blocks along this assumed linear fault in our model.) To avoid this slip, the fault

Table 1. Assumed Block and Joint Parameters for Crystalline Rocks

Parameter	Value
<i>Block</i>	
Bulk modulus	22.2 GPa
Shear modulus	16.7 GPa
Cohesion	20 MPa
Friction angle	30°
Dilation angle	0°
<i>Joint</i>	
Normal stiffness	20 GPa/m
Shear stiffness	20 GPa/m
Joint cohesion	0 MPa
Joint friction angle	40.36°

From *Byerlee* [1978], *Jumikis* [1979], and *Carmichael* [1989].

strength of the San Andreas fault is increased ($\mu = 1$). Generally, the crustal deformation processes in this area were probably characterized by changing activities of the different geological features in this area, phases of discontinuous slip processes along the San Andreas fault were followed by phases of deformation in the vicinity of the San Andreas. In our modeling, the times of an active San Andreas fault are faded out.

Results and Discussion

Rigid Modeling

At first, a Mohr-Coulomb behavior with identical constitutive parameters was used for all faults, except the San Andreas fault. When starting the modeling with an orientation of the major horizontal stress component S_H of N20°E, a ratio between S_H and S_h of 2, and a fault strength of $\mu = \tan \varphi = 0.85$ according to Byerlee's [1978] law no deformation, and especially no rotation of blocks, was calculated. Therefore the fault strength was reduced stepwise due to the lowering of the friction coefficient. Only friction parameters smaller than about 0.12 led to a block rotation of more than as 40° in our models. This low value (14% from the value of Byerlee) has the same order as the parameters of Bird and Kong [1994], which they had deduced also from computer simulations. For friction coefficients greater than 0.12, either block rotations with angles smaller than 40° or no block rotations occur. Using a continuously yielding behavior for the faults, the initial friction coefficient $\mu_i = \tan \varphi_i$ can be increased to the value according to Byerlee's [1978] law if the basic friction coefficient $\mu_b = \tan \varphi_b$ is small as 0.12. If the basic value is increased, block rotations do not reach the order of 40°.

These calculations were carried out with a stress ratio of 2 and an orientation of the major horizontal stress component of N20°E corresponding to an angle of about 80° between the San Andreas fault and the major component S_H . Based on these calculations with a friction coefficient of 0.12, similar results were obtained using stress orientations varying less than about 15°. However, if the orientation differs by more than about 15° from the initial one, no block rotations occur, and the whole deformation process is only characterized by slip on the faults. Such a deformation mechanism is obviously not realistic for the study area. Therefore it can be concluded that an orientation of approximately N20°E with a maximum deviation

of 15° has been characteristic for the time since the late Miocene. This orientation is in the range of the observed recent orientation of the major principal stress S_H and appears to be responsible for the deformation processes. This result could be used as a constraint for the area on a rather stable S_H orientation since the late Miocene.

Using an orientation N20°E of S_H and changing the boundary stress anisotropy according to the lateral ratios deduced from the stress measurements in the Cajon Pass Scientific Research Borehole [Zoback and Healy, 1992], a maximal stress anisotropy S_H / S_h of three was used for the calculations. This higher stress anisotropy only allows an increase of the friction coefficient to about 0.14 for block rotations of 40°. Contrarily, a lowering of the stress anisotropy also requires a weakening of the faults to values smaller than 0.1.

Applying a friction coefficient of 0.12, a S_H orientation of N20°E, and a S_H / S_h ratio of 2, the three models in Figures 3a-3c show the expected deformation behaviour: (1) clockwise block rotation and sinistral slip in the Eastern Transverse Ranges and (2) right-lateral slip without significant block rotation in the Mojave Desert.

The influence of an additional northwest trending fault set in the Northeast Mojave block is shown in Figure 3b. Using the prerequisite of equal fault parameters, the deformation in the Northeast Mojave Desert occurred mainly on the initial northeast trending faults that now show an east-west orientation, and the crustal deformation in this area seems to be mainly governed by the sinistral slip along these faults (Figure 3b). This left-lateral slip led to the separation of the original throughgoing northwest trending faults. Nevertheless, dextral slip on the northwest trending faults took place, but the slip on these faults is small in comparison with the northeast trending faults.

The incorporation of the Sleeping Beauty fault in our model results in some deviations from the other models (Figure 3c). Instead of a separation of the fault as established in the model of Dokka and Travis [1990], we modeled a lateral slip on this fault only (Figure 3c). Obviously, the separation of this fault cannot be modeled in our simplified simulation. Two possible explanations can be offered for the behavior of the Sleeping Beauty fault in our model: either (1) the geometry is oversimplified, especially in the eastern part of the Mojave Desert, or (2) geological structures at depth, in combination with the known faults, are responsible for the extension of this

Figure 3. Numerical results for the simulation with the three different rigid models. Calculations stopped when block rotation reached a value larger than 40°. The three models principally show the expected deformation behavior: (1) clockwise block rotation and sinistral slip in the Eastern Transverse Ranges and (2) dextral slip without significant block rotation in the Mojave Desert. Differences can be especially observed in the deformation of the Northeast Mojave Block and the eastern Mojave Desert.

fault. Further investigations based on a more detailed fault structure given by *Dokka and Travis* [1990] will test the influence of the model geometry on the deformation process of the Sleeping Beauty fault. A study of the influence of fault structures at depth using a three-dimensional model is not possible until now, due to the lack of information on the existing structures at depth. In contrast to the other models, Figure 3c also shows that dextral-shear processes along the northwest trending faults are dominant in the Northeast Mojave Block if the Sleepy Beauty fault is taken into consideration.

Another feature of the modeling illustrated in Figures 3a-3c is the slight block rotation and partial block separation of the three easternmost blocks of the Mojave Desert. Especially, such rotations were not observed in this part of the Mojave Desert.

Modeling With Deformable Blocks

To illustrate the influence of deformable blocks, we only used the simple shear model (Figure 2a). For the simulations an orientation of N20°E for S_H in combination with a stress ratio S_H/S_h of 2 was used. Applying the block and fault parameters listed in Table 1, the results of the numerical simulations with quasi-rigid, elastic, and elasto-plastic blocks are illustrated in Figure 4. All of them are stopped when block rotation in the Eastern Transverse Block exceeded a value of about 40°. This final value was chosen because it agrees with the observed rotation since late Miocene indicated by paleomagnetic data. Different calculations with changed block and fault parameters suggest a negligible influence on the fault strength necessary for block rotations in the order of 40°.

It is obvious from Figure 4a that for the quasi-rigid modeling the whole deformation of the area mainly results from strike-slip processes on the existing faults. On the other hand, the results of the elastic (Figure 4b) and elasto-plastic (Figure 4c) modeling suggest an increasing transition of the deformation from the faults to the blocks. As a result, it can be concluded that a clockwise rotation of the Eastern Transverse Ranges would be connected with a calculated cumulative slip in this area of the order of 50 km for quasi-rigid, 36 km for elastic, and 23 to 34 km for elasto-plastic modeling, respectively. These values are in the range of the 30 km to 35 km observed

cumulative left slip in the Eastern Transverse Ranges [*Dibblee*, 1968; *Richard*, 1993].

Due to the absence of observed data, a detailed discussion of the slip is not possible for the Northeast Mojave Block, where the calculated clockwise rotation is connected with a cumulative slip of the east-west-trending sinistral faults of the order of 28 km for quasi-rigid, 16 km for elastic, and 15-27 km for elasto-plastic modeling, respectively.

Furthermore, the clockwise rotation of these two regions constrains the deformation of the Mojave Desert in association with the requirement that the cumulative slip along the north-west oriented dextral faults must be at least of the order of some 10 km, in order to accommodate the clockwise rotation of the Eastern Transverse Ranges. This agrees generally with geological data, suggesting that the cumulative slip reaches similar values (compare Table 2).

Whereas the cumulative slip listed in Table 2 for quasi-rigid modeling is much larger than the observed value, the differences for elastic and elasto-plastic modeling are relatively small, as some part of the whole deformation has occurred within the blocks themselves. Both the degrees of deformation in the blocks and the slip on the faults are to some extent regionally inhomogeneous for elasto-plastic modeling.

A detailed analysis of the data listed in Table 2 shows different correspondences between the observed and calculated slip both west and east of the Blackwater/Calico fault. The calculated elastic cumulative slip of 34.7 km in the eastern part, when including the Blackwater/Calico, the Rodman/Pisgoh, and the Bristol Mountain faults, agrees very well with the geologically observed slip of 36.0 km. The agreement between the observed cumulative slip and the slip calculated with elasto-plastic blocks (35.2-38.2 km) is also good, but the differences for the individual faults are higher than for the elastic modeling (compare Table 2). It seems that the crustal deformation in the Eastern Transverse Ranges, the Northeast Mojave Block, and the eastern part of the Mojave Desert can adequately be described by strike-slip processes on the east-west trending and the northeast trending faults considered in the model in case of the elastic modeling.

The discrepancies in the western part of the Mojave Desert are much larger (observed cumulative slip of the order of 8 km and calculated slip values between 14 and 20 km for the

Figure 4. Results for (a) quasi-rigid, (b) elastic, and (c) elasto-plastic models. Calculations have been terminated when block rotation reached a value larger than 40°. For quasi-rigid blocks (Figure 4a) the total crustal deformation is mainly realized as slip processes of the different faults, block deformations are negligible. Contrary, for elastic (Figure 4b) and elasto-plastic blocks (Figure 4c) the block deformations contribute essentially to the total deformation.

Table 2. Observed and Calculated Slip Values for the Strike-Slip Faults of the Mojave Desert

Faults in the Southern Part of the Mojave Desert	Observed	Dokka- Modell ^a	Distinct Element Modeling		
			Quasi-Rigid	Elastic	Elasto- Plastic
Helendale	3.0 ^b	2.5	0.3	3.7	0.3-0.5
Lenwood	1.5-3.0 ^c	1.5	5.5	5.8	4.9-6.0
Camp Rock	1.6-4.0 ^c	3.8	14.3	9.7	8.7-12.5
Blackwater/ Calico	9.6 ^c	10.0	13.9	11.2	4.1-7.2
Rodman/Pisgoh/Bullion	6.4-14.4 ^c	10.5	16.5	9.5	13.5
Ludlow	small? ^c	2.0	- ^c	- ^c	- ^c
Bristol Mountains	>6.0 ^d	13.5	17.8	14.0	17.6
Cumulative net slip	28.1-40.0	43.0	74.2	53.9	49.1-57.3

^aDokka and Travis [1990].^bMiller and Morton [1980].^cDokka [1983].^dMiller et al. [1982].^eNot considered in the model.

Helendale, Lenwood, and Camp Rock faults). The situation in this region is much more complicated because of the existence of active reverse and thrust faults in the San Bernardino Mountains at the southwest edge of the Mojave Desert. Undoubtedly, a distinct part of the deformation in this area results in uplifts through movements along these low-angle faults. Such a deformation mechanism cannot be incorporated into our two-dimensional model. More realistic modeling in this area thus requires three-dimensional models which also take fault structures with depths into account. Nevertheless, the focal mechanisms of the Landers earthquake and its aftershocks in the San Bernardino county on June 28, 1992, have shown that strike-slip processes are also characteristic of the crustal deformation in this area [Hauksson et al., 1993]. Indeed, the main shock focal mechanism of this M_w 7.4 earthquake suggested right-lateral strike-slip faulting with a strike of N8°W on an almost vertical fault. It is noteworthy that in the 1970s, earthquakes took place along the line of the hypocentre location of the Landers earthquake sequence. In 1975, the Galaway earthquake ($M=5.2$) was accompanied by a 6.8-km-long surface rupture with right-lateral displacement on a previously unmapped fault trending N10°W [Hill and Beeby, 1977]. Furthermore, the fault plane solutions of the larger shocks of the 1979 Homestead Valley earthquake sequence suggest nodal planes trending N4°W [Hutton et al., 1979].

The Landers earthquake and the other earthquakes in this area show also that there are right-lateral faults in the eastern Mojave Desert that have not been considered in previous deformation models. Consideration of these additional faults may give better agreement between the observed and calculated cumulative slips in the eastern part of the Mojave Desert.

If a quasi-rigid or elastic constitutive block model is used, triangular-shaped gaps appear in the block structure. Isostatic gravity anomalies show gravity lows occurring just north and generally along the Pinto Mountain fault [Roberts et al., 1981]. These anomalies may be associated with sedimentary basins of lower density [Richard, 1993]. Such regions of alternating transtensional and transpressional features are also observed along the strike of the San Andreas fault.

Conclusions

The following conclusions can be drawn from the numerical modeling conducted here for the study area in southeastern California:

1. The numerical simulations show rotations of small crustal blocks caused by the impact of the regional stress state. This deformation requires low strength values of the involved faults, a fact often discussed for the San Andreas fault itself. In our model the low fault strength is expressed by friction coefficients smaller than 0.12, or 14% of the initial value 0.85 for intact rocks (Byerlee's law).

2. Variation of the stress boundary conditions for the numerical calculations show that realistic deformation occurs only for a major horizontal stress component S_H oriented at N20°E corresponding to the recent stress state. If the orientation differs by more than about 15° from the initial one, then no block rotations occur. An orientation of about N20°E with a maximum deviation of 15° seems to be characteristic for the area under study since late Miocene.

3. By using a simple shear model a comparison of calculated and geologically observed slip values makes sense only for cumulative values considering fault sets in distinct areas, since in reality the slip is distributed over more faults than those considered in our model. On the other hand, a larger calculated cumulative slip may give hints for the existence of undiscovered faults.

4. For elastic modeling the calculated crustal deformation in the Eastern Transverse Ranges, the Northeast Mojave Block, and the eastern part of the Mojave Desert can adequately describe the main features of the crustal deformation in the studied area.

5. The discrepancy between calculated and observed slip values in the western part of the Mojave Desert indicates that the deformation cannot be declared by strike-slip processes alone in this area. A distinct part of deformation appears to be due to slip on reverse faults, resulting in uplift processes. Therefore more realistic modeling requires treatment of the three-dimensional case. Nevertheless, the fact remains that strike-slip faulting is very important in this area.

6. With the exception of the clockwise rotation of crustal blocks in the Eastern Transverse Ranges and the Northeast

Mojave Block the calculations suggest no rotations in the Mojave Desert according to the simple shear model. The possibility of block rotations in the easternmost part of the Mojave Desert suggests that further calculations with a more detailed block structure will be necessary to investigate the possible counterclockwise rotation of crustal blocks.

7. In summary our modeling clearly supports the hypothesis that the deformation of great parts of the study area was mainly

characterized by strike-slip processes along a limited number of major faults and clockwise rotation of individual blocks in the Eastern Transverse Ranges and the Northeast Mojave Block.

Acknowledgments. We would like to thank M. Gölke, A. Nur, P. Wilson and an anonymous tectonics reviewer for careful and thoughtful reviews of this article.

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(Received June 13,1994;
revised August 24, 1995;
accepted September 5, 1995.)