Inception of the Eastern California Shear Zone and evolution of the Pacific-North American plate boundary: From kinematics to geodynamics

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SUMMARY

The San Andreas Fault (SAF) is the transform boundary between the Pacific and the North American plates, yet up to 25% of the relative plate motion is now accommodated by the Eastern California Shear Zone (ECSZ). Here we investigate the inception of the ECSZ and its geodynamic interactions with the SAF using a three-dimensional viscoelastoplastic finite element model. For a given fault configuration of the plate boundary zone, the model simulates long-term slip on the faults and plastic strain outside the faults. The results show that the formation of the Big Bend of the SAF around 5-12 Ma impeded fault slips and caused strain localization along the ECSZ. Development of the ECSZ was further enhanced by the activation of the Garlock Fault (GF) and lithospheric weakening due to the encroachment of the Basin and Range extension. Similarly, the San Jacinto Fault (SJF) in southern California developed along a belt of localized strain, which resulted from the formation of the restraining bend along the San Bernardino Mountains segment of the SAF ~2 Myr ago. Once activated, the SJF reduced slip on both the southern SAF and the ECSZ across the Mojave Desert. These results indicate causative relationship between the SAF, the ECSZ, the GF, and the SJF. The inception of the ECSZ is the consequence of the evolving SAF plate boundary zone that continuously adjusts itself to accommodate the relative plate motion.

Key words: San Andres Fault, Eastern California Shear Zone, Pacific-North American plate boundary, finite element modeling, strain localization

1 INTRODUCTION

As the transform boundary between the Pacific and the North American plates (Fig. 1), the San Andreas Fault (SAF) proper accommodates 20-75% of the relative plate motion along its various segments (Powell and Weldon, 1992; CGS, 2002; Becker et al., 2005; Meade and Hager,
2005). The rest of the relative plate motion is taken up by a system of fault strands subparallel to the SAF proper, collectively referred to as the San Andres Fault system (Wallace, 1990). Furthermore, up to 25% of the present-day relative plate motion is accommodated by the Eastern California Shear Zone (ECSZ) (Dokka and Travis, 1990; Sauber et al., 1994; Reheis and Dixon, 1996; Gan et al., 2000; McClusky et al., 2001; Miller et al., 2001; Peltzer et al., 2001; Savage et al., 2001; Dixon et al., 2003), which include a set of NW-trending dextral faults cutting across the Mojave Desert (Dokka and Travis, 1990) and the Walker Lane belt along the western edge of the Basin and Range province (Hearn and Humphreys, 1998; Cashman and Fontaine, 2000; Wesnousky, 2005) (Fig. 1).

The inception and development of the ECSZ and other young faults in the SAF system is part of the history of the evolving San Andres Fault system that started ~29 Myr ago, when subduction of the Farallon plate brought the encounter of the Pacific plate with North America (Atwater, 1970; Atwater and Stock, 1998) (Fig. 2). The San Andres Fault formed as the transform boundary between the Pacific and the North American plates, and lengthened as the remaining of the Farallon plate continuous to subduct under the North American plate. The Pacific spreading center migrated eastward into the subduction zone in mid-Miocene, leading to fragmentation of the borderland of the North American plate and ~ 90° clockwise rotation of the Transverse Ranges. Around 5-12 Ma the SAF jumped inland as the result of the opening of the Gulf of California, in the process producing the “Big Bend” of the SAF (Atwater and Stock, 1998; Oskin and Stock, 2003) (Fig. 2).

The ECSZ initiated around the same time as the opening of the Gulf of California and the formation of the Big Bend of the SAF (Stock and Hodges, 1989; Holt et al., 2000; Oskin and Stock, 2003) (Fig. 2); development of the ECSZ may also be associated with a kinematic change around ~8 Ma when the Great Valley-Sierra Nevada block switched from moving westerly, driven by the extension in the Basin and Range province, to its modern NW-directed motion (Wernicke and Snow, 1998). Such kinematic changes are also witnessed by a change in stress direction in the Walker Lane belt about 7-10 Ma (Zoback et al., 1981; Bellier and Zoback, 1995).

How these kinematic changes led to the inception of the ECSZ, however, is unclear. Furthermore, lithospheric heterogeneity could also have contributed to the development of the ECSZ. The Walker Lane belt straddles the boundary between the rigid Great Valley-Sierra Nevada block and the weak and extending Basin and Range province, and is marked by high gradients of heat flow and many other geophysical properties (Lachenbruch and Sass, 1978). Dixon et al. (2000) show that the ECSZ is spatially correlated with a steep gradient of GPS site velocities.

In this study, we investigate how fault configuration changes of the San Andres Fault may have contributed to the initiation of the Eastern California Shear Zone and other younger faults. This work is a continuation of our previous studies of the geometrical impact of the SAF proper on fault slip rates and seismicity in California (Li and Liu, 2006) and the long-term mechanical interaction between the San Jacinto Fault and southern SAF (Li and Liu, 2007), using a three-dimensional (3D) viscoelasoplastic finite element model. We have further developed this model to systematically explore strain partitioning and crustal deformation around restraining
bends on strike-slip faults (Li et al., 2009). Here we apply this model to simulate the long-term geodynamic interaction between the SAF, the ECSZ, and other major faults in southern California by sequentially incorporating these faults in the model and exploring the consequent changes of stresses and strain partitioning in the SAF plate boundary zone. We show that the inception of the ECSZ is the consequence of the self-adjustment of the evolving SAF plate boundary zone as it continuously seeks the most efficient way to accommodate the relative plate motion.

2 Finite Element Model

The formulation and numerical schemes of our three-dimensional viscoelastoplastic finite element model of steady-state fault slip and lithospheric dynamics have been described in Li et al. (2009). In this study we modified the model to explicitly incorporate the SAF, the ECSZ, the Garlock Fault (GF), and the San Jacinto Fault (SJF) in southern California with their first-order geometric features (Fig. 3). The faults are represented by 400-m thick vertical plastic layers; the ECSZ is treated as a broad rheological weak zone.

The model consists of a 20-km thick upper crust with an elastoplastic rheology, and an underlying 40-km thick viscoelastic layer representing the ductile lower crust and mantle. The model simulates plastic deformation both within the fault zones (plastic sliding) and outside fault zones when stress reaches the respective yield criteria (non-associated Drucker-Prager model). For the viscoelastic layer, we used viscosities in the range of $10^{19}$-$10^{21}$ Pa s, based on the inferred values for the lower crust and upper mantle in California (Hager, 1991; Flesch et al., 2000; Kenner and Segall, 2000; Pollitz et al., 2001). The plastic yield criteria for the upper crust, outside the faults, are characterized by the values of cohesion (50 MPa) and internal frictional coefficient (0.4). For the fault zones, the cohesion is taken to be 10 MPa (Lachenbruch and Sass, 1980), and the internal frictional coefficient is set to zero, reflecting weak fault zones suggested by previous studies (Bird and Kong, 1994). In some cases we also tested the effects of variable fault strength. The elastic constants for the entire model domain are conventional values for the lithosphere: $8.75 \times 10^{10}$ Pa for the Young’s modulus, and 0.25 for the Poisson’s ratio (Turcotte and Schubert, 2002). Using different values of these parameters does not significantly change the model results.

The eastern side of the model, set in the stable North American plate, is fixed. The western side is loaded by a shear velocity of 49 mm/yr, reflecting the relative motion between the Pacific-North American plates (DeMets et al., 1994). To minimize artificial boundary effect, we added a 300-km wide extra model domain with straight fault zones to the northern and southern ends, which are free to move in the direction of relative plate motion and restricted in other directions.

To simulate the long-time evolution of the faults, we run the model for more than 100,000 years with 5-year time steps till the system reaches a quasi-steady state. By then the impact of initial stresses, which are arbitrarily chosen to be zero, is negligible, and the stress state of the model is controlled by the rheological structure, the geometry and properties of the faults, and
the tectonic loading. We then explore how the initiation of new faults changes the long-term regional stress and strain fields. Because we are interested in the steady-state results, addition of each fault zone is run as a new model; the transient processes are not simulated. In doing so, we also avoid the need to re-mesh the finite element model.

3 MODEL RESULTS

We have conducted a series of forward models to explore the geodynamic impact of the changing fault configuration, based on the geological reconstructions (Fig. 2), on crustal deformation within the SAF plate boundary zone. Specifically, in the model we sequentially incorporated the Big Bend of the SAF, the Garlock Fault, the Eastern California Shear Zone, and the San Jacinto Fault in their chronological orders of formation, and explored the geodynamic impact of each fault.

3.1 Impact of the fragmentation of the California Borderland

Before the fragmentation of the rim of the California borderland, the San Andres Fault was probably relatively straight, parallel to the direction of the relative Pacific-North American plate motion (Atwater and Stock, 1998) (Fig. 2a). We use such a SAF configuration as a starting model both to test our numerical model and to see the impact of changing configuration of the SAF on crustal dynamics in the plate boundary zone.

In this model, the only fault is a straight SAF parallel to the relative plate motion. Figure 4 shows the predicted velocity of the crustal motion and the maximum shear stress (capped by the plastic yield strength of the crust outside the fault). The results are what we would expect for an ideal plate model: the relative plate motion is accommodated entirely by the SAF; the Pacific plate moves as a coherent, rigid block relative to the fixed North American plate; and the shear stress is uniformly distributed outside the fault zone.

The fragmentation of the California borderland, especially the rotation of the Transverse Ranges (Fig. 2b), can significantly influence the crustal dynamics in the SAF plate boundary zone. To illustrate the basic effects of the changing configuration of the SAF, we started with a simplified restraining bend of the SAF (Fig. 5). As expected, in the North America-fixed reference framework, the restraining bend impedes the motion to the Pacific plate while pushes the North American side of the bend to move with the Pacific plate (Fig. 5a). In this case the long-term slip rate on the SAF is less than the relative plate motion, so some of the plate motion has to be accommodated by crustal deformation (simulated as plastic strain) outside the SAF (Fig. 5b). The plastic strain is concentrated around the restraining bend and along two belts extending from the bend. These belts of localized strain are not artifacts of boundary conditions but results from the changes of both shear and normal stresses caused by the restraining bend, as detailed by Li et al (2009). In essence, the restraining bend causes stress build-up in its surroundings. While shear stress moves the crust toward plastic failure, increasing of pressure, or the compressive normal stress, inhibits plastic deformation. Hence the highest plastic strain rates do not simply conform to regions of the highest shear stress (Fig. 5c). Rather, the plastic strain is localized
where the shear stress is high but the mean normal stress is relatively low. Note that the localized plastic strain in Fig. 5b is optimally oriented to accommodate the relative plate motion.

The restrain bend causes high shear stresses around it (Fig. 5c). However, once the crust has reached the plastic yield strength, the stress is capped, and further loading is accommodated by plastic deformation in the crust. Thus our model avoids the pathogenic stress buildup encountered by viscoelastic models when used to simulate long-term lithospheric deformation (Li et al., 2009).

3.2 Impact of the Big Bend

The development of the Big Bend was related to the opening of the Gulf of California between 12 to 5 Ma (Stock and Hodges, 1989; Holt et al., 2000; Oskin and Stock, 2003), which caused inland jump of the plate boundary (Fig. 2). Around the same time, the Great Valley-Sierra Nevada block changed from moving westerly to its modern NW-directed motion, perhaps also related to the inland-jump of the SAF plate boundary. From the results shown in Figure 5, we expect significant impact on crustal dynamics by the formation of the Big Bend.

To illustrate the impact of the Big Bend, we started with a model that includes only the SAF proper, with the first-order geometry of its surface trace. The model setting is essentially identical to that in Li and Liu (2006), except that we now focus on the role of the Big Bend in the inception of the ECSZ. This case also serves as a test of the numerical stability of the codes, because the models in this study use different finite element meshes and rheologic structures than those in our previous models (Li and Liu, 2006; Li and Liu, 2007). We also use this case as a reference model for comparison with subsequent cases which include more fault zones.

Figure 6a shows the predicted velocity of long-term crustal motion. Most part of the Pacific plate moves coherently at 49 mm/yr relative to the fixed North American plate, as expected for rigid plates. However, near the plate boundary the relative velocity changes within both plates because of the irregular geometry of the SAF, especially the Big Bend. To the south of the Big Bend, the motion of the Pacific plate is impeded; while to its north, the Great Valley-Sierra Nevada block within the North American plate is being pushed to move with the Pacific plate. Note that the predicted surface velocities differ from those measured by the GPS (Global Positioning System) (e.g., Bennett et al., 1999), because what we calculated here is the long-term crustal motion; the fault motion is approximated by steady-state plastic creeping. The results are similar to those of a simple straining bend (Fig. 5).

The Big Bend’s impendence to the relative plate motion causes high shear stresses in the surrounding crust (Fig. 6b), spatially correlating to the diffuse seismicity in southern California. These results are the same as reported in Li and Liu (2006).

The predicted long-term slip rates vary significantly along the strike of the SAF (Fig. 6c) as a result of the variable geometry of the San Andreas Fault. The values of the predicted slip rates depend on the fault strength and viscosity of the model. The fault strength is given by the plastic yield strength in the fault elements, measured by the cohesion and international friction coefficient (Li and Liu, 2006; Li et al., 2009). A higher fault strength reduces slip rates and cause more relative plate motion to be absorbed by plastic deformation in crust outside the fault.
Similarly, a higher viscosity for the viscoelastic layer (ductile lower crust and upper mantle) tends to lower slip rates along the SAF (Li and Liu, 2006), and vice versa. In this simple model we assumed a homogeneous viscosity of $2 \times 10^{20}$ Pa s for the entire model domain, and adjusted the fault strength to fit the observed geological slips rates on the SAF (CGS, 2002). The spatial patterns of the slip rates, however, are not affected by the chosen fault strength and viscosity values. The highest slip rates are always found in the central and northern segments of the SAF, while the lowest slip rates are over the Big Bend. This is generally consistent with geological estimates of slips rates along the SAF, which vary from ~$34$ mm/yr along central California to less than 18 mm/yr over the Big Bend (CGS, 2002).

Figure 6c shows that <70% of the relative plate motion is accommodated by the San Andreas Fault, the rest has to be taken up by other parts of the plate boundary zone, simulated as plastic deformation in crust outside the faults (Fig. 6d). Note that high plastic strain is associated with each bend of the San Andreas Fault, but most noticeably in two broad belts of localized plastic strain associated with the Big Bend, similar to those around the restraining bend in Figure 5b. One of the high-strain belt extends offshore of southern California, roughly aligned with the Palos Verdes Fault and the Coronado Bank Fault (Fig. 1); the other extends along the Eastern California Shear Zone.

Because no lateral variations of lithospheric rheology or fault properties are considered in this case, the predicted localization of plastic strain along the ECSZ is entirely due to the geometric impact of the Big Bend. To ensure that this strain localization along the ECSZ is not an artifact of the boundary conditions of the model, we tested cases with the fixed eastern boundary 100 km further away from the San Andreas Fault, and the results remain the same. The pair of high-strain belts always starts from the two ends of the Big Bend and extend subparallel to the direction of relative plate motion. These results indicate that the inception of the ECSZ were a consequence of the formation of the Big Bend.

### 3.3 Impact of the Garlock Fault

The Garlock fault probably formed around the same time as the Big Bend (Burbank and Whistler, 1987; Monastero et al., 1997). Figure 7 shows the effects of including the Garlock Fault in the model. Whereas the general results are similar to those in Figure 6 (without the Garlock Fault), the impact of the Garlock Fault is noticeable. First, the Garlock Fault further impedes the relative plate motion, causing a broader velocity gradient across the plate boundary zone (Fig. 7a). Second, with the Garlock Fault, the high shear stresses are more concentrated in the Mojave Desert (Fig. 7b). Third, because of the stronger impedance to relative plate motion, the predicted long-term slip rates on the SAF proper is reduced, while the dextral shearing along the ECSZ increased (Fig. 7c). This is also evident from the predicted plastic strain rates outside the faults (Fig. 7d).

### 3.4 Rheological Contribution to the Initiation of the ECSZ

Lithospheric rheology may be another important factor for the initiation of the ECSZ. The Walker Lane part of the ECSZ straddles on the boundary between the extending Basin and Rang
province and the relatively rigid Sierra Nevada-Great Valley block (Fig. 1). At present the Sierra Nevada-Great Valley block moves as a rigid microplate, producing a high gradient of surface crustal motion as measured by the GPS (Dixon et al., 2000). In the past few million years extension in the Basin and Range province has been encroaching into the Sierra Nevada-Great Valley, causing maximum thinning of the lithosphere under the ECSZ (Lachenbruch et al., 1994; Fliedner et al., 1996; Wernicke et al., 1996; Surpless, 2002).

To explore the rheological influence on the initiation and development of the ECSZ, we modified the reference model (Fig. 6), which has a homogeneous lithosphere, by reducing the viscosity from $2 \times 10^{20}$ Pa s to $1 \times 10^{20}$ Pa s beneath the Basin and Range province and $1 \times 10^{19}$ Pa s beneath the ECSZ. The weak rheology under the ECSZ and the Basin and Range province promotes strain localization along the ECSZ (Fig. 8a), which is further enhanced by including the Garlock Fault in the model (Fig. 8b). As the ECSZ absorbs more relative plate motion, the slip rates are reduced along the northern and central segments of the SAF, but increased on the southern SAF (not shown here), presumably because the activation of the ECSZ eases the impedance of the Big Bend on slip along the southern SAF.

The lateral rheological variations are difficult to quantify, but their role is clear in the model. Both the rheological contrast across the ECSZ and rheological weakening under the ECSZ helps to localize strain in the ECSZ, hence promoting its initiation and development.

### 3.5. Impact of the San Jacinto Fault

In a local scale model (Li and Liu, 2007), we found that the development of the restraining bends along the San Bernardino Mountains segment of the SAF may have caused the initiation of the San Jacinto Fault (SJF). Similar results are predicted in this regional scale model. In all the cases shown in Figures 6-8, the SJF is not included, yet the location of the SJF is shown as a belt of localized strain. Such strain localization results from the bending of the SAF along the San Bernardino Mountains segment and near the southern end of the Coachella Valley segment (Li and Liu, 2007). These restraining bends were developed 1.5-2 Ma, about the same time the SJF initiated (1.5 - 1.0 Ma), as inferred from geological and stratigraphic evidence (Morton and Matti, 1993; Albright, 1999; Dorsey, 2002).

Once initiated, the SJF accommodates some of the relative plate motion, hence reducing slip rates on the southern SAF. Assuming the same fault properties for these two faults leads to higher slip rates on the SJF than on the southern SAF (Li and Liu, 2007), because the SJF is better oriented for accommodating the relative plate motion. The present-day slip rates on the SJF is $15 \pm 9$ mm/yr (Becker et al., 2005), comparable to but less than those on the southern SAF (Rockwell et al., 1990; Morton and Matti, 1993; Meade and Hager, 2005). To fit these observed slip rates, we have to make the SJF nearly three times stronger (higher plastic yield strength). This is consistent with the notion that the nascent secondary faults in southern California are stronger than the mature SAF (Bird and Kong, 1994).

In this regional scale model with the ECSZ explicitly included as a rheological weak zone, we can also see the impact of the SJF on the ECSZ. With a strong SJF as required to fit the present-day slip rates on the SJF and the southern SAF, the SJF’s impact on strain localization...
along the ECSZ is insignificant, as indicated by a comparison of Figures 9a and 8a. However, if the SJF is as weak as the southern SAF, more relative plate motion will be accommodated by the SJF, consequently reducing the shear strain along the ECSZ (Fig. 9b).

3.6 Present-day crustal dynamics of the SAF plate boundary zone

In the final case we included the SAF, the SJF, the Garlock fault, and the ECSZ to simulate the present-day regional crustal dynamics of the SAF plate boundary zone (Figure 10). The rheological structure in this case is the same as that in Figures 8-9, with the ECSZ as a rheological weak zone, and the SJF is three times stronger than the SAF, as in Fig. 9b.

The model results shows that the ECSZ takes up ~9.5 mm/yr relative plate motion along the Walker Lane and up to 13 mm/yr long the eastern Mojave Desert (Fig. 10a). Along the SAF proper, the slip rates are around 30 mm/yr along the central and northern segments but less over the Big Bend. South of the Big Bend, the relative plate motion is shared by the SAF (~26 mm/yr) and the SJF (~11 mm/yr), comparable to the geological and geodetic data (Petersen and Wesnousky, 1994; Bennett et al., 1996; CGS, 2002; Becker et al., 2005). Although changing local fault properties and lithospheric rheology may improve the fits to local observations, the general agreement with the regional slip rate patterns, despite of the relatively uniform fault properties and rheological structure in the model, indicates that fault geometry and orientations largely control the present-day fault slip rates and crustal dynamics in the SAF plate boundary zone.

Figure 10b shows the spatial distribution of the maximum shear stresses. The results are similar to those in Figures 6b and 7b, showing that the Big Bend causes a broad concentration of high shear stress in southern California. The stress distribution is further modified by the Garlock Fault and the San Jacinto Fault.

The predicted strain localizations outside the faults are shown in Fig. 10c. These results, together with those in Figures 7d and 8, all indicate that strain localization along the ECSZ is caused by the Big Bend, and promoted by the rheological weakening under the ECSZ and along the western margins of the Basin and Range province. The Garlock fault enhances strain localization along the Walker Lane while weakens it across the eastern Mojave Desert.

Finally, the model predicts broad uplift, up to 1.5 mm/yr, around the Transverse Ranges (Fig. 10d), consistent with compressive fault structures around the Transverse Ranges (Spotila et al., 2007) and indicating a causative relationship between the Transverse Ranges and the fault development in southern California. The predicted subsidence near the northern end of the SAF may be an artifact. By assuming a fixed direction of relative plate motion in the entire model domain, the bend near the northern end of the SAF becomes a releasing bend, whose impacts are opposite to the restraining bends. In reality the direction of the relative plate motion rotates somewhat to N-NE near the northern end of the SAF (DeMets et al., 1994; Bennett et al., 2002), so the effects of the releasing bend may not be as strong as in the model.
4 DISCUSSION

The San Andres Fault system is perhaps the best studied plate boundary zones in the world (e.g., Wallace, 1990; Powell and Weldon, 1992). Intensive geological investigation and space-based geodetic measurements have provided great details of the kinematic evolution of the plate boundary zone. In this study, through modeling a sequence of “snapshots” of the evolving plate boundary, we have shown how changes of fault configuration and lithospheric rheology may have influenced subsequent development of the SAF plate boundary zone. The opening of the Gulf of California between 12 to 5 Ma (Oskin and Stock, 2003), which caused the inland jump of the southern SAF and formed the Big Bend, had hindered fault slip on the SAF and caused strain localization along the Eastern California Shear Zone. Rheological weakening due to the encroaching of the expanding Basin and Range extension, as well as the activation of Garlock fault, further contributed to the development of the ECSZ. Similarly, the development of the restraining bend along the San Bernardino Mountains segment of the SAF may have led to the initiation and development of the San Jacinto Fault. These modeling results provide some insights into the crustal dynamics behind the observed kinematic evolution of the SAF plate boundary zone.

To better illustrate the impacts of the fault configurations, we tried to keep the model simple. We used uniform lithospheric rheology and fault properties in most cases; only in a few selected cases did we vary these model inputs to test their effects. In general, higher fault strength reduces the slip rates on the given fault, hence increases slip rates on other subparallel faults and plastic strain rates in unfaulted crust. Higher viscosity for the viscoelastic layer in the model, representing the ductile lower crust and upper mantle, has similar effects (Li and Liu, 2006; Li et al., 2009).

As for any numerical models, the results can be affected by the chosen boundary conditions. In our model we applied a velocity condition on the western side of the model domain, simulating the motion of the Pacific Plate relative to the fixed North American Plate. In our numerical experiments, we varied the width of the model, including extending the velocity boundary hundreds of kilometers further away from the SAF, and found that the results are not significantly affected by the lateral boundary conditions (Li et al., 2009). In some previous models, the SAF plate boundary zone is loaded by prescribed velocities in the lower crust (Bourne et al., 1998; Roy and Royden, 2000b; Roy and Royden, 2000a). Whereas these models have their own merits, we prefer the side loading to bottom loading, because the side loading is well constrained and the bottom loading is not.

Less constrained are the boundary conditions on the northern and southern ends of the model domain. In our model these two ends are fixed in the tangential direction and free in the direction of relative plate motion. To minimize the boundary effects we added 300 km lithosphere on both ends of the SAF, within which the SAF is extended straightly, parallel to the direction of relative plate motion (Fig. 3).

Our investigation of the evolution of the SAF plate boundary zone focused on the initiation of the ECSZ while ignored some other important fault development, such as the initiation of the Garlock Fault, which is probably around the same time as the opening of the Gulf of Californian
and formation of the Big Bend or earlier (Burbank and Whistler, 1987; Monastero et al., 1997), certainly before the development of the ECSZ. The bending of the Garlock Fault (Fig. 1) is thought to result from the dextral shear along the ECSZ (Dokka and Travis, 1990), and have been used for estimating the age and slip rate of the ECSZ (Gan et al., 2003). It is not clear why none of the faults in the ECSZ cross cuts the older Garlock Fault (Fig. 1).

Our results show that initiation of new faults and change of the configuration of existing faults would change slip rates on other faults in the plate boundary zone. This may be one explanation for some of the observed long-term temporal variations of fault slip rates in the SAF system. For example, our results show that the initiation of the San Jacinto Fault would reduce slip rate on the southern SAF, consistent with the codependent trend between these two faults since the initiation of the SJF around 1 Ma to about 90 ka (Bennett et al., 2004). The increasing of slip rate on the SJF during this period is consistent with fault weakening as it matures (Bird and Kong, 1994). However, the reverse trend of slip rates on these two faults since then, as suggested by Bennett et al (2004), cannot be readily explained by the model results. Prediction of decreasing slip rates on the SJF would require either strengthening of the SJF or further weakening of the SAF since 90 ka, both are possible but without evidence.

In general, our model results show that the part of the relative plate motion not accommodated by the SAF proper is distributed over the plate boundary zone and absorbed by slip on subparallel faults or by plastic strain in the unfaulted crust, which in reality would be slip on smaller faults not included in our model. These results are consistent with the understanding that the relative plate motion between the Pacific and North American plates is absorbed by slip on the SAF as well as other faults over a broad boundary zone including the ECSZ; the right-oblique extension of the Basin and Range may also accommodated some of the relative plate motion (e.g., Powell and Weldon, 1992). Hence within any swath perpendicular to the strike of the plate boundary, the slip rates or rates of seismic moment release on the faults are expected to be codependent, with the total values equal or close to those of a single plate boundary fault. This codependence follows the simple principles of mass (volume) and energy (seismic moment) conservation, and is show by the fault slip between the SJF and the southern SAF over thousands of years (Bennett et al., 2004), and by the seismic moment release between the ECSZ and faults in the Los Angeles region over hundreds of years (Dolan et al., 2007).

Perhaps the most important insight provided by the model results is how the plate boundary zone has continuously evolved to accommodate the relative plate motion. The most efficient transform fault is a straight fault parallel to the direction of relative plate motion, but evolving plate boundary conditions and intrinsic lithological heterogeneities can change the configuration of the plate boundary fault. When the Big Bend formed, it impedes the relative plate motion on the SAF, causing strain localization along the ECSZ to absorb the extra strain. Similarly, the restraining bend along the San Bernardino Mountains causes localized strain along the SJF to make up the reduced slip rates on southern SAF. Both the ECSZ and the SJF provide an alternative, and more optimally oriented, paths for accommodating the relative plate motion. They are the results of the evolving SAF plate boundary zone as it continuously seeks the best ways to accommodate the relative plate motion.
5 CONCLUSIONS

We have investigated how change of fault configurations may influence the initiation of new faults in the SAF plate boundary zone using a three-dimensional viscoelastoplastic finite element model. Major conclusions we may draw from this work include the following.

1) The formation of the Big Bend had a major impact on the evolution of the SAF plate boundary zone. It reduced slip rates on the SAF proper, forced strain partitioning over a broad plate boundary zone, and caused broad stress concentration in southern California, including compression across the Transverse Ranges.

2) The initiation and development of the Eastern California Shear Zone is largely a consequence of the formation of the Big Bend, which localized strain along the ECSZ to compensate for the reduced slip rates on the SAF. Rheological weakening due to the encroaching of the Basin and Range extension, and the activation of the Garlock Fault, further contributed to the development of the Walker Lane part of the ECSZ.

3) Initiation of the San Jacinto Fault was genetically related to the development of the restraining bend over the San Bernardino Mountains segment of the SAF. Slip on the SJF tends to reduce that on the southern SAF.

4) The SAF proper and the secondary faults in the SAF plate boundary zone, including the ECSZ, collectively accommodate the relative plate motion between the Pacific and the North American plates. Hence all these faults are kinematically connected and mechanically coupled. All faults within a swath perpendicular to the strike of the plate boundary are expected to show some codependence, because their total slip rates or seismic moment release should be close or equal to those for a single plate boundary fault between these two plates.

5) The initiation of the ECSZ, the SJF, and some other young faults in the SAF system is the manifestation of a continuously evolving and self-adjusting plate boundary zone. When the fault configuration in the plate boundary zone is not optimal for accommodating the relative plate motion, the strain not accommodated by the faults tends to localize where new faults would provide better paths to accommodate the relative plate motion.

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REFERENCES


Figure Captions

Figure 1. Topographic relief, active faults, and seismicity in the San Andres Fault plate boundary zone. Numbers show geological slip rates on segments of the SAF (data from Calif. Geol. Survey, 2002). Thick lines are the faults incorporated into the model.

Figure 2. Simplified kinematic history of the San Andres Fault (SAF) plate boundary zone, redrawn after Atwater (http://emvc.geol.ucsb.edu/download/conejovolcanics.php). Thick lines are the active plate boundaries at the time. SB, Santa Barbara block (western Transverse Ranges); GL, Garlock Fault; SJF, San Jacinto Fault; ECSZ, Eastern California Shear Zone.

Figure 3. Numerical mesh and boundary conditions of the finite element model. The entire San Andreas Fault, the San Jacinto Fault (SJF), the Garlock Fault (GF), and the Eastern California Shear Zone (ECSZ) are included in the model.

Figure 4. The testing model with a straight transform fault parallel to the direction of relative plate motion. (a) Predicted surface velocity relative to the fixed North American Plate. (b) Predicted maximum shear stress. In this case the two plates moves as coherent rigid blocks, and the stress is uniformly distributed outside the plate boundary fault.

Figure 5. Results of a simplified restraining bent. (a) Predicted surface velocity relative to the fixed North American Plate. (b) Predicted plastic strain rates outside the fault. (c) Predicted maximum shear stress.

Figure 6. Results with only the SAF proper included in the model. (a) Predicted surface velocity relative to the fixed North America. (b) Predicted maximum shear stress. (c) Predicted slip rates at various segments of the SAF proper. Also shown here is the predicted shearing rate along the Eastern California Shear Zone, although it is not included in the model. (d) Predicted plastic strain outside the SAF proper. Circles are seismicity explained in Fig. 1.

Figure 7. Results with the SAF proper and the Garlock Fault included in the model. (a) Predicted surface velocity relative to the fixed North America. (b) Predicted maximum shear stress. (c) Predicted slip rates along the SAF proper, the Garlock Fault, and the Eastern California Shear Zone (not included in this model). (d) Predicted plastic strain outside the SAF proper and the Garlock Fault. Circles are seismicity explained in Fig. 1.

Figure 8. Results showing the impact of lithospheric weakening in the Basin and Range and the Eastern California Shear Zone (bounded by the dashed lines). The viscosity is $2 \times 10^{19}$ Pa s under the ECSZ, $1 \times 10^{20}$ Pa s under the Basin and Range, $2 \times 10^{20}$ Pa s for the rest area of the model domain. (a) Predicted plastic strain rates outside the faults. (b) Same as (a), but with the Garlock
Fault included in the model.

**Figure 9.** Results showing the impact of the San Jacinto Fault on the predicted plastic strain rates outside the faults. (a) The SJF is three times stronger than the SAF. (b) The SJF is as weak as the SAF. In this case more strain can be accommodated by the SJF, hence less needs to be accommodated by the ECSZ (bounded by the dashed lines).

**Figure 10.** Model results of present-day crustal dynamics in the SAF plate boundary zone. The SAF proper, the Garlock Fault, the San Jacinto Fault, and the Eastern California Shear Zone are included in the model. (a) Predicted slip rates along the faults and the ECSZ. (b) Predicted maximum shear stress. (c) Predicted plastic strain rate outside the SAF, the GF, and SJF. (d) Predicted vertical velocities. Circles are seismicity explained in Figure 1.
Figure 1. Topographic relief, active faults, and seismicity in the San Andres Fault plate boundary zone. Numbers show geological slip rates on segments of the SAF (data from Calif. Geol. Survey, 2002). Thick lines are the faults incorporated into the model.
Figure 2. Simplified kinematic history of the San Andres Fault (SAF) plate boundary zone, redrawn after Atwater (http://emvc.geol.ucsb.edu/download/conejovolcanics.php). Thick lines are the active plate boundaries at the time. SB, Santa Barbara block (western Transverse Ranges); GL, Garlock Fault; SJF, San Jacinto Fault; ECSZ, Eastern California Shear Zone.
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