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Elastic Block Modeling of Fault Slip Rates across Southern California

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Abstract

We present fault slip rate estimates for Southern California based on Global Positioning System (GPS) velocity data from the University NAVSTAR Consortium (UNAVCO), the Southern California Earthquake Center (SCEC), and new campaign GPS velocity data from the San Bernardino Mountains and vicinity. Fault slip-rates were calculated using Tdefnode, a program used to model elastic deformation within lithospheric blocks and slip on block bounding faults [2]. Our block model comprised most major faults within Southern California. Tdefnode produced similar slip rate values as other geodetic modeling techniques. The fastest slipping faults are the Imperial fault (37.4 ± 0.1 mm/yr) and the Brawley seismic zone (23.5 ± 0.1 mm/yr) in the SW section of the San Andreas fault (SAF). The slip rate of the SAF decreases northwestward from 18.7 ± 0.2 mm/yr in Coachella Valley to 6.6 ± 0.2 mm/yr along the Banning/Garnet Hill sections, as slip transfers northward into the Eastern California Shear zone. North of the junction with the San Jacinto fault (10.5 ± 0.2 mm/yr), the San Andreas fault slip rate increases to 14.2 ± 0.1 mm/yr in the Mojave section. Tdefnode slip rate estimates match well with geologic estimates for SAF (Coachella), SAF (San Gorgonio Pass), San Jacinto, Elsinore, and Whittier faults, but not so well for other faults. We determine that the northwest and Southeast sections of the SAF are slipping fastest with slip being partitioned over several faults in the central model area. In addition, our modeling technique produces similar results to other geodetic studies but deviated from geologic estimates. We conclude that Tdefnode is a viable modeling technique in this context and at the undergraduate level.

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Cover Page Footnote

Editors of the Macalester Journal of Physics and Astronomy. Please consider this revised manuscript for publication.

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Abstract

We present fault slip rate estimates for Southern California based on Global Positioning System (GPS) velocity data from the University NAVSTAR Consortium (UNAVCO), the Southern California Earthquake Center (SCEC), and new campaign GPS velocity data from the San Bernardino Mountains and vicinity. Fault slip-rates were calculated using Tdefnode, a program used to model elastic deformation within lithospheric blocks and slip on block bounding faults [2]. Our block model comprised most major faults within Southern California. Tdefnode produced similar slip rate values as other geodetic modeling techniques. The fastest slipping faults are the Imperial fault (37.4 ± 0.1 mm/yr) and the Brawley seismic zone (23.5 ± 0.1 mm/yr) in the SW section of the San Andreas fault (SAF). The slip rate of the SAF decreases northwestward from 18.7 ± 0.2 mm/yr in Coachella Valley to 6.6 ± 0.2 mm/yr along the Banning/Garnet Hill sections, as slip transfers northward into the Eastern California Shear zone. North of the junction with the San Jacinto fault (10.5 ± 0.2 mm/yr), the San Andreas fault slip rate increases to 14.2 ± 0.1 mm/yr in the Mojave section. Tdefnode slip rate estimates match well with geologic estimates for SAF (Coachella), SAF (San Geronio Pass), San Jacinto, Elsinore, and Whittier faults, but not so well for other faults. We determine that the northwest and Southeast sections of the SAF are slipping fastest with slip being partitioned over several faults in the central model area. In addition, our modeling technique produces similar results to other geodetic studies but deviated from geologic estimates. We conclude that Tdefnode is a viable modeling technique in this context and at the undergraduate level.

I. Introduction

Due to its large population and geologic setting, Southern California is particularly vulnerable to seismic activity. It is, therefore, imperative to understand local fault activity in order to protect residents. The results of this paper contribute to the overall understanding of fault activity in Southern California. This data is relevant to numerous parties. Energy companies, land developers, municipalities, residents, and a plethora of other groups need this basic information in order to conduct their business safely.

Faults are cracks in the earth's crust that show displacement of one side with respect to the other. Faults often occur near tectonic plate boundaries where two pieces of the earth's crust come together. There are several types of plate boundaries, each with their own characteristic fault types. In Southern California, the Pacific and North American tectonic plates come together along the San Andreas Fault (SAF) as shown in figure 1. In this region, relative plate motion is "transverse". This means that relative velocity vectors along opposing plates are mostly parallel and in opposite directions. The Pacific plate is moving to the northwest while the North American plate is moving SE. There are no major compressional forces.

Fault motion in Southern California is mostly stochastic. Friction between the two sides of the fault prevent it from sliding while the tectonic plates continue to move. Faults that do not slip are called "locked". Locking is measured on a scale from zero to one, zero being freely slipping and one being fully locked. This is also referred to as the locking or coupling fraction and is represented with the symbol ϕ . Locking results in the earth bending around the fault, building stress. This stress released in the form of earthquakes, sometimes causing widespread damage. The interval between earthquakes along faults can be anywhere from tens to thousands of years. For example, the last major earthquake on the SAF occurred in 1857 [1].

The fault slip rate is an important metric for understanding the activity of a fault. Slip rate is the rate at which one side of a fault moves with respect to the other. It would be the rate of motion of points along the fault boundary if the fault were slipping continuously. For example, a slip rate of 40mm/yr could be the result of one 4-meter slip event every 100 years. In Southern California, slip rates range from approximately 1mm/yr to 40mm/yr. The slip rate of a fault is directly correlated to the amount of stress built up in the earth around it. Stress data can then be used to predict earthquakes, for example. The stress around the SAF is so great that not only does it cause bending in the earth but results in many smaller faults forming in the area. Major faults are shown in Figure 1.

There are two major ways to measure fault slip rate; geologic and geodetic. Geologic rates are determined by examining offset surface features such as stream channels or alluvial fans to determine the distance a fault moved during an earthquake. Geologic methods are especially useful for gathering information about earthquakes that occurred in the past and are generally considered to be the most accurate. As seen in Table 1, however, geologic studies rarely cover a large area, as specific features must be studied at length to obtain a single slip rate. Our research uses geodetic methods to calculate fault slip rates. Geodetic methods use GPS surface velocity data, fault geometry, and modeling software to estimate slip rates and other parameters.

GPS surface motion data is one of the main constraints in geodetic modeling programs. There are thousands of permanent GPS receivers all over Southern California. Receivers calculate position continuously, producing a highly accurate record of surface motion at their location over time. In addition to permanent installations, various agencies send out groups on yearly “campaigns” to collect GPS data. Campaigns mobilize groups to install temporary GPS units at known locations. Locations are often in protected wilderness areas that will not allow for

installation of permanent units. After several years of going to the same locations, one can determine accurate surface velocities. These surface velocities can then be used to model fault slip rates. In this project, we use public GPS data provided by UNAVCO and the Southern California Earthquake Center.

Through a grant from the Southern California Earthquake Center, California State San Bernardino has conducted a 15-year GPS campaign in the San Bernardino Mountains and surrounding desert. Due to the remote nature of these field sites, there was previously no GPS data from the region. We continued the campaign in 2015 and used data from previous years to supplement our research project. Joshua Spinler at the University of Arizona processed the data collected by our receivers.

Our project applies an elastic block modeling technique and new GPS data to a large area in Southern California. No group has published research applying our modeling program to Southern California. In addition, no SCEC undergraduate team has successfully used the program thus far. With this in mind, we set out to answer three major questions. How does distribution of plate boundary slip vary across the region? Are our slip rates consistent with other studies done on the region? Is Tdefnode an appropriate modeling program for this context and at the undergraduate level? We determine that the northwest and Southeast sections of the SAF are slipping fastest with slip being partitioned over several faults in the central model area. In addition, our modeling technique produces similar results to other geodetic studies but deviated from geologic estimates. We conclude that Tdefnode is a viable modeling technique in this context and at the undergraduate level.

II. Methodology

We use a geodetic modeling program called Tdefnode. Tdefnode is a Fortran program written by Robert McCaffrey of Rensselaer Polytechnic Institute and Portland State University. Tdefnode takes GPS velocity data and fault geometry as inputs to a control file. The program then splits the region into fault-bounded elastic blocks. Fault and block geometry in our area of interest is shown in Figure 1. The following is an abbreviated description from an article written by Dr. McCaffrey detailing the elastic block modeling technique [2].

In general, the Tdefnode uses GPS surface velocity data and fault geometry to predict rotation rates of blocks, slip rates, and locking fractions. It then predicts its own surface velocities using these modeled parameters. To determine the best fit parameters, the program tests its modeled surface velocities against observed surface velocities and selects the set of parameters that minimizes the difference between the two [2].

To determine slip rates, the program first estimates the location of a Euler pole for each block in the model. Euler poles mark the center of rotation of an object on the surface of a sphere [3]. In this case, the objects are our fault-bounded blocks rotating on the surface of the earth relative to the stationary North American plate. The program begins by creating a velocity field, $V(x, y)$, from the GPS data on every block. It then estimates a velocity gradient tensor from the velocity field. The velocity field is broken up as follows:

$$V(x, y) = \mathbf{L}\mathbf{X} + \mathbf{T} + \mathbf{E}(\mathbf{X}) \quad (1)$$

Here, \mathbf{L} is the velocity gradient tensor, \mathbf{X} is a position vector, \mathbf{T} is a translation vector, and $\mathbf{E}(\mathbf{X})$ is an error vector field. \mathbf{L} and \mathbf{T} and $\mathbf{E}(\mathbf{X})$ are estimated using weighted least squares.

\mathbf{L} is structured as follows:

$$\mathbf{L} = \begin{vmatrix} \delta V_x / \delta x & \delta V_x / \delta y \\ \delta V_y / \delta x & \delta V_y / \delta y \end{vmatrix}$$

\mathbf{L} can be further broken down into symmetric and antisymmetric matrices. The symmetric matrix represents the strain rate tensor, ϵ , of the velocity field while the antisymmetric matrix represents the rotation rate tensor, θ . From θ , the program extracts the angular velocity, ω , of each rotating block [2].

Using the angular velocity one can solve for the location of the Euler pole using the following formula:

$$V(x, y) = \omega R_e \sin \Delta \quad (2)$$

Here, V represents the velocity of a point on the block, R_e is the radius of the earth, and Δ is the angle formed between the Euler pole, the center of the earth, and the point on the earth's surface. This can be visualized using figure 2. The program determines Δ for every point in the velocity field and can then solve for the location of the Euler pole [2].

Knowing the location of the Euler pole and ω , Tdefnode uses equation 2 to calculate the velocity of the rotating block on points along the boundaries. Fault slip rates are the difference in velocity of points on opposite sides of fault boundaries. This definition uses the second way to think of fault slip rate: the rate at which points along the fault would move if the fault were not locked [2].

In reality, however, most faults in Southern California are at least partially locked. Because of this, equation 2 cannot accurately predict surface velocities at any point. To correct for this, Tdefnode applies a technique called backslip. Along faults,

$$B_f = -\phi V \quad (3)$$

Where B_f is the backslip along the fault, ϕ is the locking fraction of the fault, and V is the velocity calculated using equation 2. The program considers all faults fully locked at the outset, determining more accurate values later in the sequence [2].

To determine how much backslip to apply to points within the blocks, it is necessary to understand how Tdefnode interprets fault geometry. Tdefnode sees faults as a series of points, or nodes, on the surface of the earth and below. The program then connects the nodes with straight lines to bound blocks and create faults as seen in figure 2. Backslip is applied to each node to a degree determined by the locking fraction. The program then determines the effect of that backward motion on surface points. The problem is akin to bending the end of a steel beam a certain distance and wanting to know the position of other points along the beam [2].

To relate nodes to surface points, Tdefnode applies a unit slip to each node and calculates the effect of this motion on each GPS surface point using Okada integration [4]. This process generates Green's functions for each node. Green's functions are the response of surface points to a unit slip at a specific node. Green's functions are denoted $G(X, X_{nk})$. G is the affect that a unit slip at node location X_{nk} has on surface point X . Because the same unit slip is used for each node, the Green's functions become a proportionality factor for applying backslip. Each node at location X_{nk} applies a backslip of

$$B_s = G(X, X_{nk})\phi V \quad (4)$$

to a surface point at X . The total backslip on a surface point is determined by summing the effects on the surface point from of all nodes that bound the block [2].

The program then goes back and varies certain parameters, each time recalculating surface velocities. These parameters include locking fraction which is varied around 1 and slip

rate which is varied around its calculated value. Tdefnode then chooses the combination of these parameters that minimizes the difference between predicted and observed surface velocities [2].

III. Discussion

Due to time constraints, we were only able to run a handful of models. In our final run, we input the most recent GPS data and best estimations for fault geometry. The results of the final run of our model are summarized in Figures 5, 6, 7, and 8 and Table 1. Our slip rates are consistent with previous geodetic studies but not geologic studies. Table 1 compares our rates with those from other studies. Based on our results, we conclude that Tdefnode is a viable modeling technique for use on the undergraduate level.

We first look to Figure 5 to compare our calculated surface velocities with observed velocities. Observed velocities are the only known quantity other than fault geometry in our model, and serve as a benchmark with which to test the model. Our calculated velocities are in good agreement with those observed by GPS. Vectors are generally of the correct direction and magnitude. We are then confident with further results from the model such as slip rates and coupling fractions.

We now compare our data with other geodetic and geologic studies and attempt to explain any discrepancies. The Pacific plate is well known to be moving toward the northwest while the North American plate is moving to the southeast. This means that we expect predominantly right-lateral strike slip motion. Our slip vectors are generally northwest pointing, indicating right-lateral motion. In addition, most slip is accommodated parallel to fault planes, indicating predominantly strike slip motion. Both of these observations are in agreement with predictions from the underlying geology. Known thrust faults have convergent fault-normal slip rates with the exception of the North Frontal fault.

The Pinto Mountain fault is well known to be left lateral though our model indicates right-lateral motion. This can be seen in figure 8. Spinler et al also obtained this result using a similar block modeling technique [6]. These results could be due to post seismic deformation in the area north of the fault following the 1992 Lander's earthquake. Because geodetic models only have access to data from the last ~20 years, anomalies such as a few years of more northerly motion of a block can skew models.

The northwest and southeast sections of the SAF accommodate the most slip within the model area. Slip is highest in the southeast sections of the fault on the Imperial strand (37.4 ± 0.1 mm/yr) and in the Brawley seismic zone (23.5 ± 0.1 mm/yr). Slip then decreases as the SAF moves to the northwest to 6.6 ± 0.2 mm/yr on the Banning and Garnett hill strands. In this section of the model, slip is transferred to the Eastern California Shear Zone with rates of 9.4 ± 0.3 mm/yr and 3.4 ± 0.5 mm/yr on the Camprock-Emerson-Homestead Valley faults and the Calico-Pisgah-Bullion-Mesquite Lake faults respectively. Further to the northwest, slip on the SAF increases after the junction with the San Jacinto fault to 14.2 ± 0.1 mm/yr on the Mojave strand. This information can be visualized in figures 6, 7, and 8.

High slip rates on the southeast sections of the SAF are most likely due to slip transfer between faults [5]. Slip transfer is the partitioning of plate motion along several faults. When several strands come together the slip rate on the remaining strand is simply the sum of the rates from the feeder strands. This can be seen clearly, for example, in the northwest section of the SAF where the San Jacinto and San Andreas faults merge. Here, fault parallel slip on the SAF increases from ~4mm/yr to ~14mm/yr. On the southeastern side, slip is transferred from the SAF to the Eastern California Shear Zone. These are the faults to the North of the SAF in our model.

In general, our rates are similar to those obtained geodetically but not geologically. Our results in the Mojave, Coachella Valley, and Imperial sections of the SAF, for example, are in good agreement with previous geodetic studies. However, only results in Coachella Valley agree with geologic studies. In the Mojave section, our model predicted a slip of 14.2 ± 0.1 mm/yr while Meade and Hager predict 14.3 ± 1.2 mm/yr [17]. Geologic studies found faster rates in the Mojave section, from 24.5 ± 3.5 mm/yr to 36.8 ± 8 mm/yr [23], [13]. In Coachella Valley, we found a rate of 18.7 ± 0.2 mm/yr while Spinler et al predict 18.1 ± 0.1 mm/yr [6]. Meade and Hager, however, predict a rate of 36.1 ± 0.7 mm/yr [17]. Geologic studies find similar rates as our study and that of Spinler et al; from 14-17 mm/yr [7], [8]. On the Imperial strand we predict a rate of 37.4 ± 0.1 mm/yr while geologic studies predict slower rates, from 15-20 mm/yr [22]. Our uncertainty values are low due to the quantity of input data we used in the model. This is a characteristic of many geodetic studies.

This trend of agreeing with geodetic rates but not geologic rates is uniform across our model area, as seen in table 1. This could be due to several factors. For one, geodetic studies assume fault geometry and only include faults deemed relevant. Fault geometry can change over time and previously inactive faults can suddenly become important players. In addition, data in certain sites is limited. As can be seen in figure 5, we lack data in certain regions, notably under the ocean and in remote areas of the desert. This can skew the model. Lastly, the timescales of geologic studies are much longer than geodetic studies. Geologic studies study features produced over thousands of years. Geodetic studies, on the other hand, use data from the last 15 years or so. On a geologic timescale, geodetic studies are highly localized and we may see geologic and geodetic results merge as time goes on and we have more GPS data.

With the exception of the Hollywood and Sierra Madre faults, all faults in our model are mostly to strongly locked. This is what one would expect in a region that experiences earthquakes.

While our model's slip values do not agree with geologic studies in general, they are in good agreement with geodetic studies. In addition, general trends such as right lateral slip, correctly predicting thrust faulting, and high locking fractions are in agreement with previous knowledge. We conclude that Tdefnode is a viable modeling program for use in this context on the undergraduate level. It appears that Tdefnode is on par with other block modeling programs and is simple enough to be used by undergraduates.

IV. Conclusion

We used elastic block modeling to estimate fault slip rates in Southern California. General trends in our model are consistent with established knowledge. We find highest slip rates at the northwest and southeast ends of the SAF with slip more evenly partitioned in the rest of the model area. This is in agreement with most studies on the area. Our slip rate values are consistent with previous geodetic studies but do not agree with geologic studies, in general. Thus, we consider Tdefnode as a viable modeling tool for undergraduates in this context and should be used in future work. Future work could include more faults in the model, giving a more nuanced look at distribution of slip. In addition, future groups could improve on certain modeling parameters and techniques outside of the scope of this paper. These include improving the optimization technique used by the program as well as initial adjusting initial conditions on locking fractions, for example.

Tables

Fault Number	Fault Name	Coupling Fraction	This study Fault-slip rate (mm/yr)	Medda and Jager, [17] Fault-slip rate (mm/yr)	McCull et al., [8] Fault-slip rate (mm/yr)	Sponler et al., [8] Fault-slip rate (mm/yr)	Geologic slip rate (mm/yr)	Geologic slip-rate reference
2	SAF (Inverell)	0.7860/0.07	37.40/1	36.1/0.7			15-20	[22]
3	SAF (Erewhin)	140/0.11	23.40/1	36.1/0.7				[22]
4	SAF (Coocella)	0.6950/0.48	18.74/0.2	36.1/0.7		14-17	17-20	[7], [8]
5	SAF (Banning and Garnet Hill)	140/0.03	6.60/2	5.1/1.5		9.5/0.4	11/3	[12]
6	SAF (San Gabriel Pass)	0.6930/0.1	5.60/2	5.1/1.5		8.1/0.2	8/4	[18]
45	SAF (San Bernardino)	0.7780/0.46	4.30/2	5.1/1.5	6.5/3.6	8.1/0.2	7/16	[14], [15]
7	SAF (Mojave)	0.7860/0.07	10.20/1	11.9/2.1		13/3	24.3/3.5	[23], [13]
8	San Jacinto	0.8880/0.82	10.20/1	11.9/2.1	14.1/2.9	12.5/0.3	9.5-15.5	[9]
9	Ehime	0.9170/0.056	12.00/2	11.2/1.2		12.5/0.3		[17]
10	Whittier	140/0.03	3.60/1	2.7/0.6	1.7/1.7		5/2	[21]
11	Montebello	0.8970/0.059	3.60/1				1.3-3.0	[21]
14	Neoport-Riverwood-Rose Canyon	140/0.07	3.60/1	0.2/2.5		10.4/0.2	0.48	[11]
38	Camp Rock-Empire-Hornet Valley	140/0.03	3.60/2	1.9/1.0	1.3/1.9	10.4/0.2	1.4	[20]
49	Colton	140/0.03	3.60/3	1.9/1.0	1.1/1.8	5.2/0.5	1.8	[20]
23	Colburn-S. Bristol	140/0.46	-9.40/3	-2.5/0.8	0			[20]
17	Johnson Valley	140/1.17	9.20/3	1.9/0.6	0.4/2.9	10.4/0.2		[20]
48	Eureka Peak	140/0.9	10.60/5	21.3/1.6		8.6/0.4		[10]
18	Eureka Peak	140/0.86	11.10/3	21.3/1.6		9.4/0.4		[10]
22	Primo Mtn.	140/1.16	13.40/5	-9.4/0.9		5.2/0.3		[10]
29	San Jacinto	0.7280/1.21	4.60/5	-4.4/2.2		-2.2/0.3		[10]
40	Blue Cut	140/0.48	-1.60/5			-1.7/0.4		[10]
16	North Frontal Thrust	140/0.52	-1.60/5					[10]
37	San Jose	0.8590/1.56	-1.60/3					[10]
13	Cuddeback	0.9290/0.95	2.70/1	-4.0/1.3				[10]
36	Serra Madre	0.5380/0.99	1.60/3	3.2/1.5				[10]
15	Hollywood	0.2460/0.52	3.40/3	-2.4/1.1				[10]
47	Santa Monica	1.50/0.7	3.40/2	-2.4/1.1				[10]

Table 1

Results from the final run of our model including coupling fraction, fault parallel slip rate in mm/yr, and a comparison of our rates with other geodetic and geologic studies. Meade and Hager, McGill et al, and Spinler et al are geodetic studies while the final column details geologic rates from several different sources.

Figure Captions

Figure 1

Figure showing the basic structure of the SAF in California. To the left of the fault is the Pacific plate and to the right is the North American plate.

Figure 2

Visualization of the euler pole-surface point relation. The circle represents the earth. $R_e \sin \Delta$ represents the distance between the Euler pole and the surface point.

Figure 3

Faults and blocks used in our model. Bold colored lines indicate faults. Thin blue lines indicate block boundaries. Block names used in the model are also labeled. Colored map area is the state of California.

Figure 4

Node structure of faults used by Tdefnode. Figure illustrates the 2-dimensional nature of the faults. The black dots represent nodes connected by red lines forming the fault plane while the green parallelogram represents the surface. A backslip of $-\phi V$ is applied at each fault node while a Green's function determines the backslip applied at surface nodes.

Figure 5

Observed velocities using GPS compared with calculated velocities from the final run of our model. Results are for every GPS data point used in the model

Figure 6

Fault parallel slip rates generated by Tdefnode. Fault parallel rates are the portion of the slip vector in the direction of the fault. Positive numbers indicate right-lateral motion while negative indicate left-lateral.

Figure 7

Fault normal slip rates generated by Tdefnode. Fault normal slip is normal to the plane of the fault. Positive values represent divergence.

Figure 8

Slip rate vectors generated by Tdefnode. Vectors indicate the direction of the fault footwall. The footwall, in this case, is the southern portion of the fault. Color and arrow size indicate magnitude.

Figure 1



Figure 2

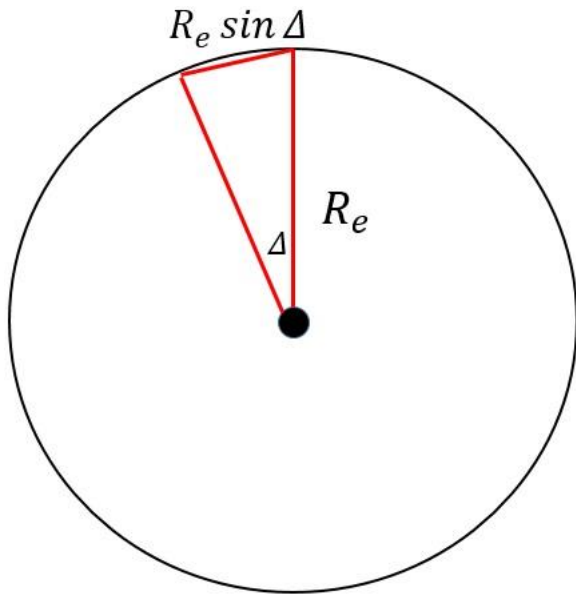


Figure 3

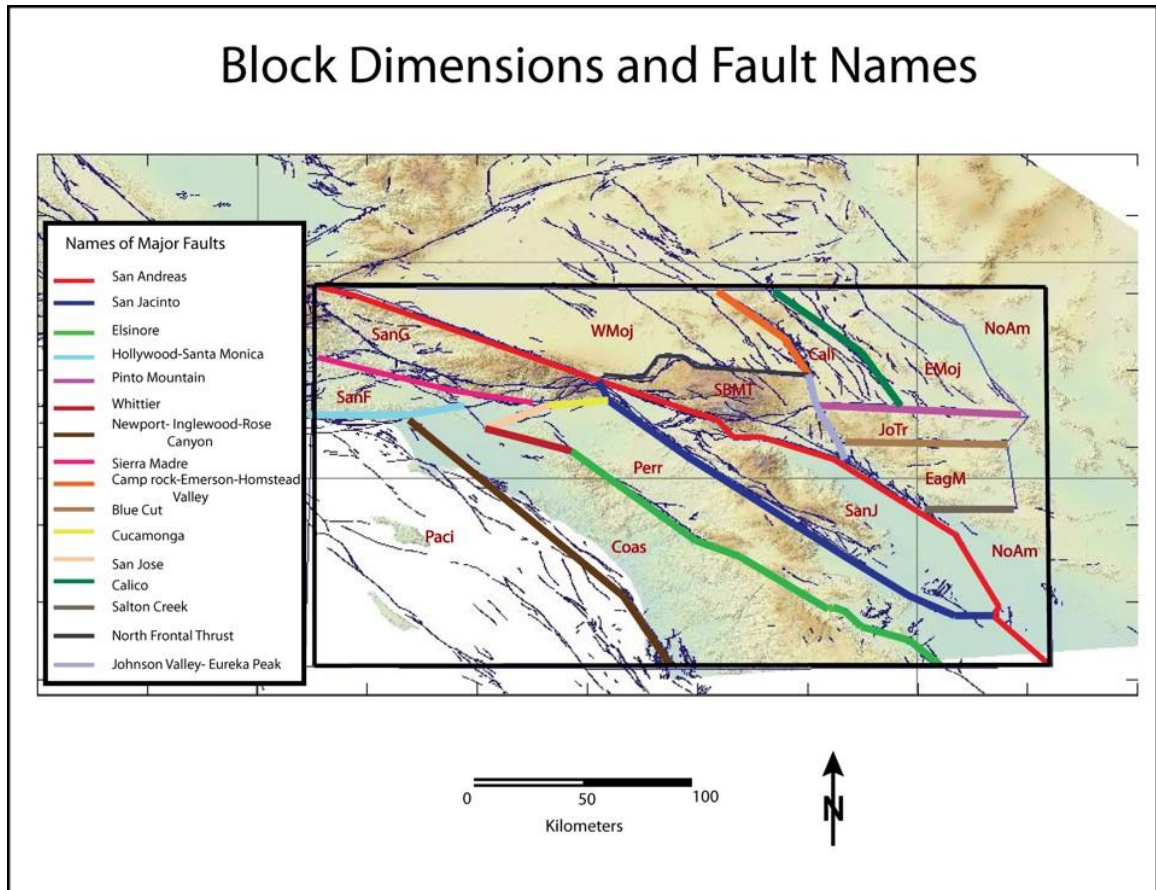


Figure 4

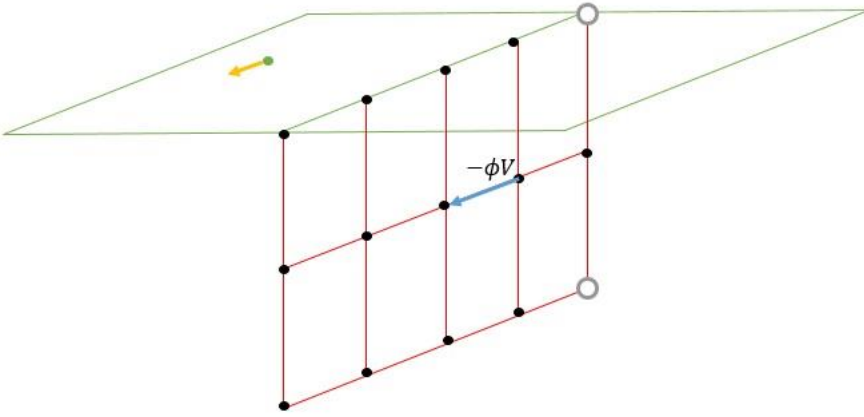


Figure 5

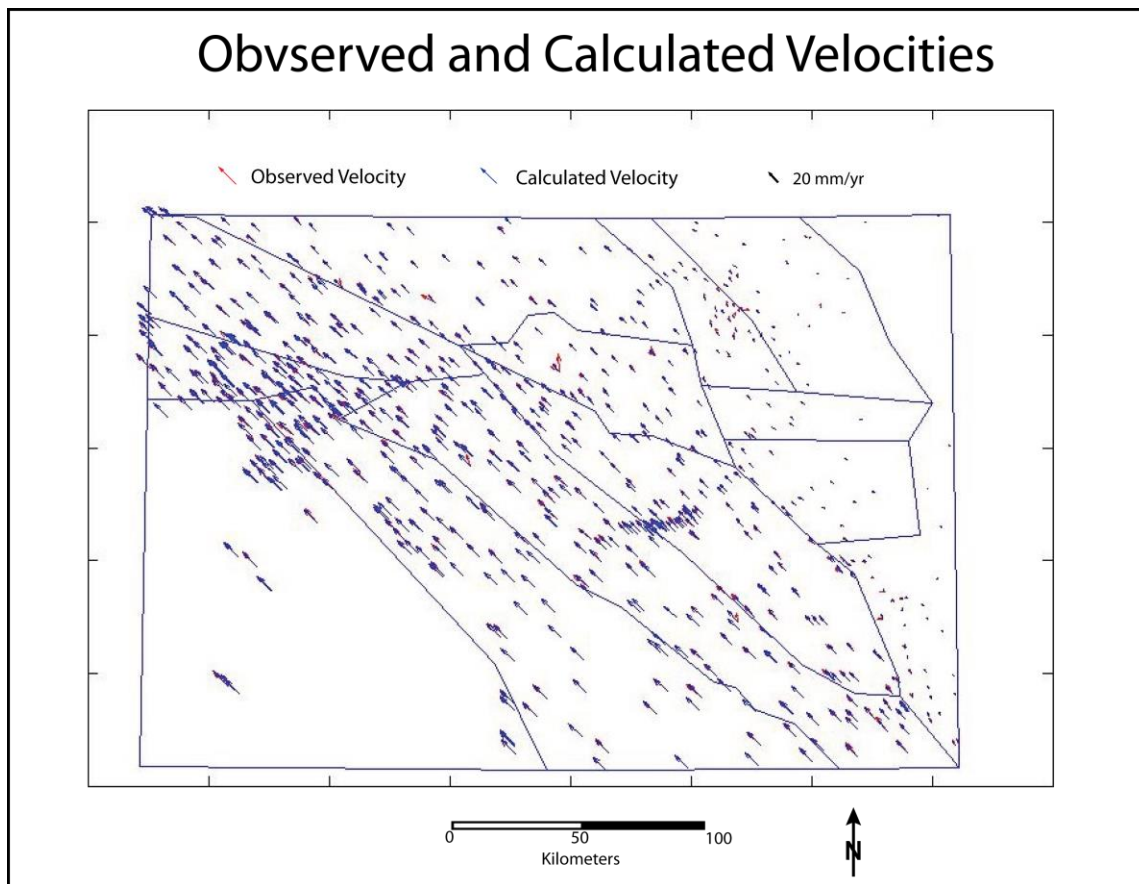


Figure 6

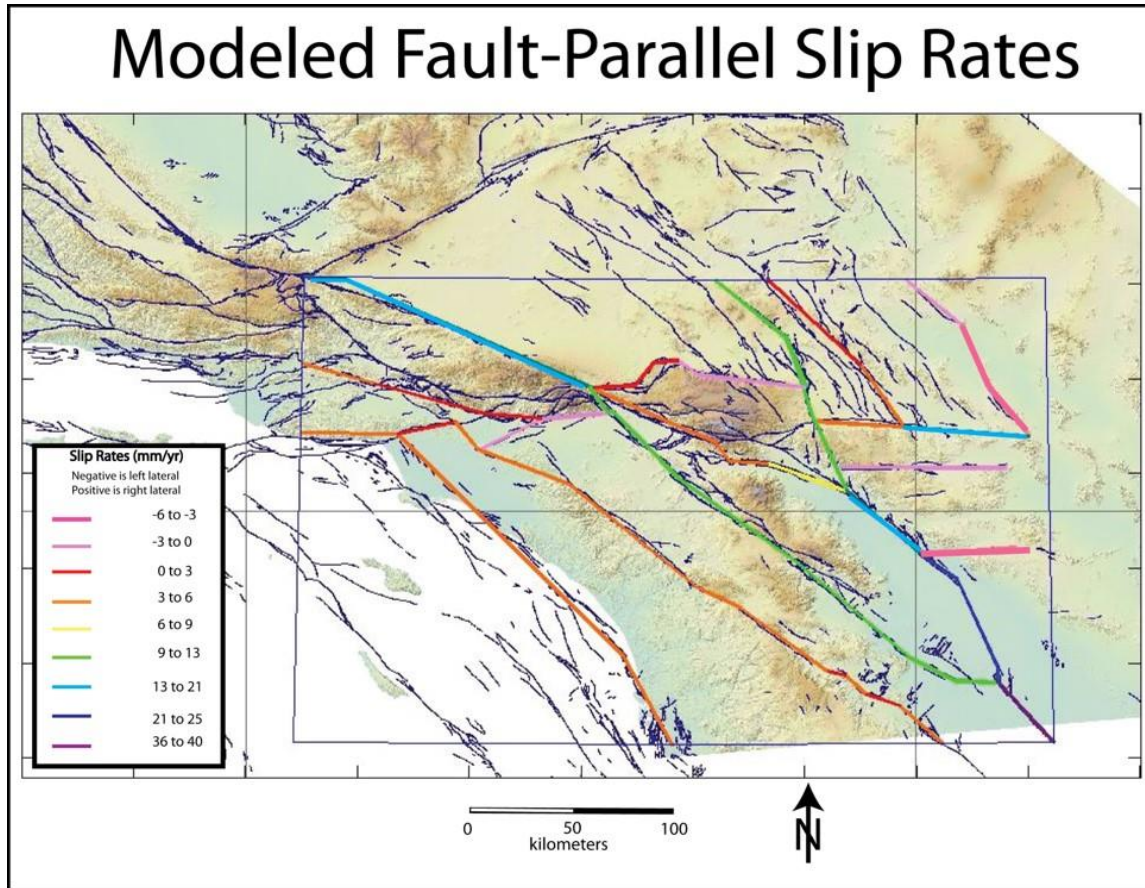


Figure 7

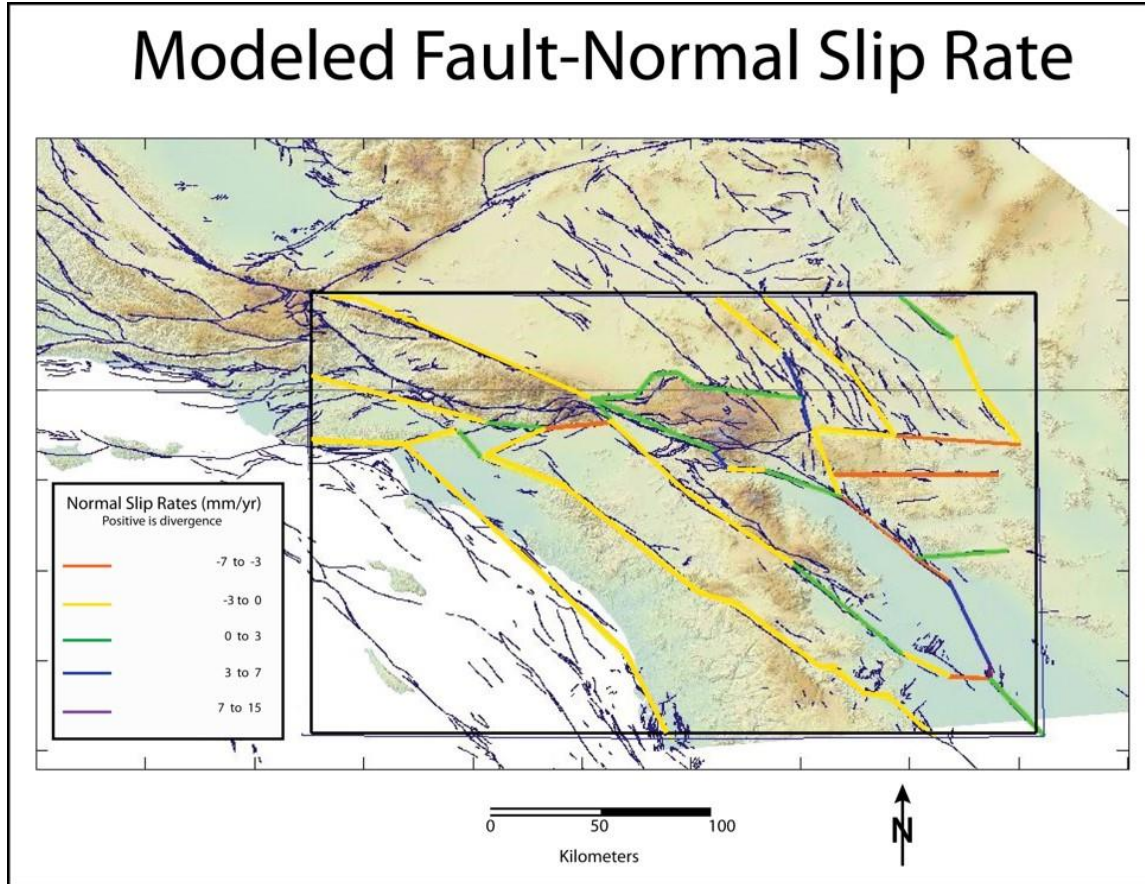
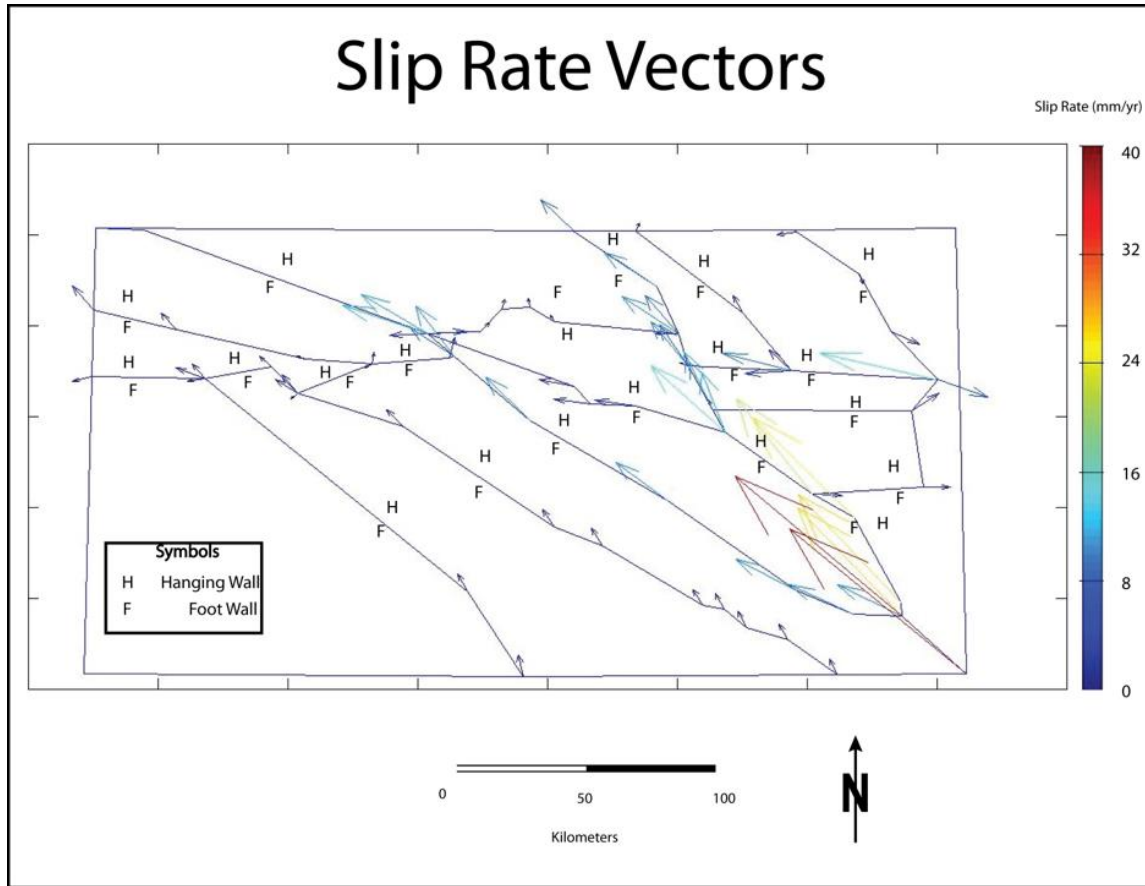


Figure 8



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