GEOPHYSICAL RESEARCH LETTERS, VOL. 22, NO. 5, PAGES 547-550, MARCH 1, 1995

Plate Boundary Segmentation by Stress Directions: Southern San Andreas fault, California

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Abstract.
We propose a new method for defining segmentation of plate boundaries and faults, based on the directions of the stress tensor. Estimates for these directions are obtained by minimizing the average misfit between the theoretical and observed slip directions on fault planes of earthquake focal mechanisms. The misfit, f, for an individual earthquake is the parameter we use for defining the segmentation of plate boundaries. We hypothesize that the stress directions along plate boundaries, and faults, are uniform within segments, but different from other segments. If this is true, a cumulative plot of f as a function of space along strike will show constant, but different, slopes for each segment. The significance of the difference between segment-slopes can be estimated by the standard deviate z-test. Applying this method to the San Andreas fault from the Carrizo plains to its southern end, we identify quantitatively the same four boundaries between segments as proposed based on non-quantitative tectonic considerations, plus one additional segment boundary. We interpret the relatively uniform, but segmented, distribution of stress directions as due to the changing strike, and possibly changing fault surface properties. Whether great earthquake ruptures, or their major asperities, may terminate at segment-boundaries, should be determined along faults that recently generated large earthquakes. This method of defining fault segmentation also allows identification of volumes with uniform stress directions, suitable for inversion for stress orientations, with a minimum of computing time. And finally the method affords an alternative estimate of the significance of differences in stress directions.

Introduction

The relationship of plate boundaries and major faults, to the stress orientation is important for understanding seismo-tectonic and faulting processes. These boundaries are not infinitely sharp, but consist of zones, tens to hundreds of km wide, in which deformation and slip take place seismically and a-seismically along a multitude of faults, and by flow within the rock mass. Usually a dominant fault is present. In California this is the main strand of the San Andreas fault, in subduction zones like the Aleutians this is the mega-thrust plane. There is strong evidence that these planes slip in response to stresses unfavorably oriented according to the Coulomb fracture criterion (small ratio of shear to normal stress clamping the fault) [e.g. *Zoback et al.*, 1987; *Jones*, 1988; *Gillard et al.*, 1992, 1995]. Little can be learned about the stress-directions from the earthquakes located on these weak main faults, because the slip direction is the same for a wide variety of angles between the greatest (and least) principal stress and the fault surface [*McKenzie*, 1969]. Most of the constraint in inversions for the stress direction estimate comes from slip on relatively minor faults in the volume surrounding the major fault of the plate boundary.

Techniques to invert fault plane solutions for stress-tensor orientation minimize a measure of the misfit between the observed and theoretical slip directions on fault planes, and they assume that the stress-tensor is uniform in the volume from which the data are taken. We use the method of *Gephart and Forsyth* [1984; *Gephart*, 1990a, b] in which the average misfit, $F = \Sigma f_i/n$ $(i = 1, 2...n)$, is calculated from the sum of individual misfits, f_i, which are defined as the smallest angle of rotation that brings into coincidence the observed fault plane and slip direction with the theoretical direction of the shear stress in a theoretical fault plane. It is difficult to verify whether the assumption of uniform stress direction is fulfilled in any given data set. We have proposed that in some data sets $F > 6°$ may indicate that the assumption is violated, because $F < 6°$, but probably not more, can be explained by errors in the fault parameters [*Wyss et al.*, 1992; *Gillard and Wyss*, 1995]. Up to now the selection of the spatial limits of the data set was done subjectively based on tectonic considerations, such as clustering of epicenters, fault strike, style of faulting, and tectonic models [e.g. *Hauksson*, 1994]. In some data sets we noticed that misfits from earthquakes located at the periphery of the volume were often large. In such cases we then adjusted the dividing plane between volumes for which separate inversions were calculated, and found that F was reduced to a level where we could be more confident that the assumption of uniform stress-directions was fulfilled [*Gillard et al.*, 1992, 1995; *Wyss et al.*, 1992; *Neri and Wyss*, 1993]. Here we take the first step to develop a method by which we can define quantitatively the extent of volumes with uniform stress-directions.

Our experiment is the following. We hypothesize that the stress directions are uniform in limited segments of the plate boundary, but different in each sub-

Paper number 95GL00074
0094-8534/95/95GL-00074$03.00

segment. The extent of segments with homogeneous stress-directions will be determined from changes in slope of the cumulative misfit, $\Sigma f(x)$, calculated based on a reference-stress-tensor, which can be an assumed one approximately fitting the tectonic setting, or it can be the stress-tensor fitting any segment. Ends of segments will be considered as defined, if their relatively constant slopes of $\Sigma f(x)$ is different from that of the neighboring segment above the 95% confidence level, as judged by the standard deviate z-test [e.g. *Davis*, 1973] . The segmentation analysis will be considered successful if the inversions for the stress-directions in the individual segments yield $F_i < 6°$ and $F_i < F$ (over all), where i is the segment number. Finally the stress directions will be estimated for each segment separately by inversion from fault plane solutions within a limited crustal volume along the plate boundary.

Data and Analysis

The cumulative misfit (Figure 1) was calculated based on the fault plane solutions of *Jones* [1988], which include all earthquakes within 10 km on either side of the part of the San Andreas fault defined in Figure 2, and which occurred in the years 1978-1985. *Jones* [1988] divided this data set into five sub-sets separated by four segment-boundaries (Figure 2), based on the difference in strike along the fault, and on separation of epicenter clusters by volumes lacking seismic activity. *Gillard and Wyss* [1995] followed this somewhat subjective division in their comparison of the strain-directions with stress-directions. Both of these studies found differences in the tensor directions, but some of the differences could not be established at the 95% confidence level.

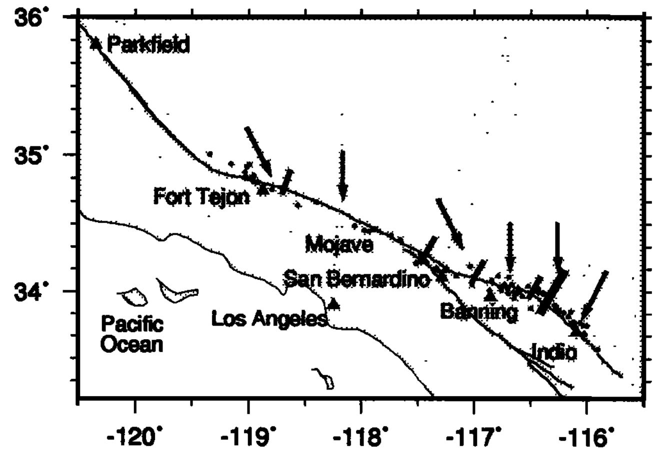


Figure 2. Map of southern California with epicenters of the earthquakes used (dots), and some main fault traces. Bars perpendicular to the fault mark segment-boundaries proposed by *Jones* [1988]. A heavy long bar marks the location of the additional boundary found by our method. Arrows indicate the direction of the greatest principal stress.

The cumulative misfit from north-west to south-east, using the Mojave stress-tensor as the reference-tensor, is shown in Figure 1 for all 125 earthquakes in the data set. Arrows pointing down mark the locations chosen by *Jones* [1988] as segmentation-boundaries; arrows pointing up mark the locations where we find a highly significant change in slope of $\Sigma f(x)$.

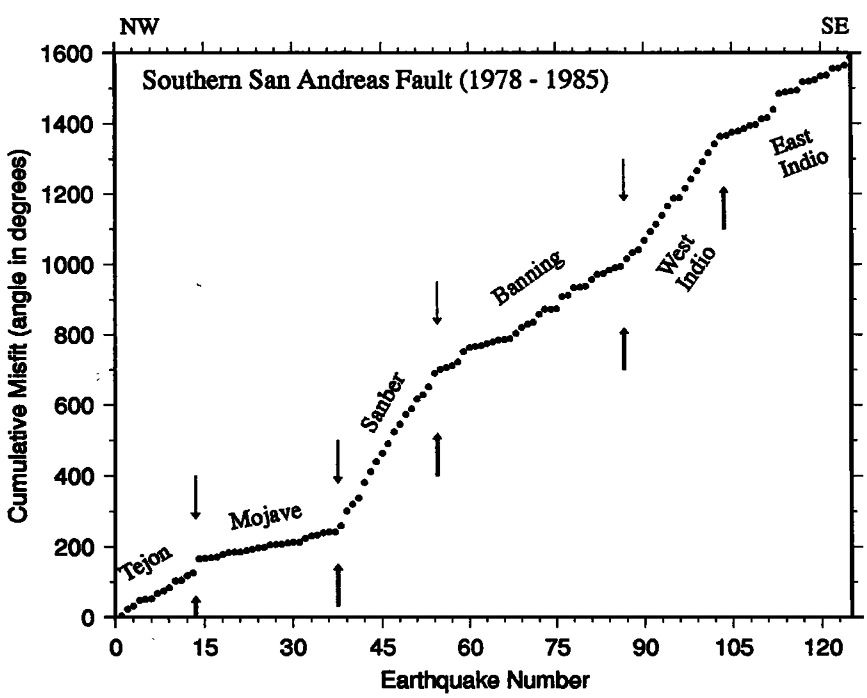
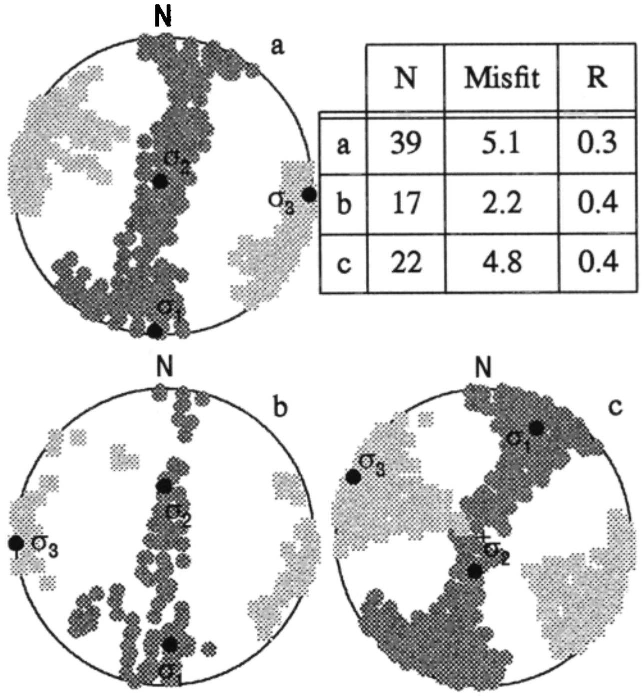


Figure 1. Cumulative misfit as a function of space along the San Andreas fault from north-west to south-east. Arrows pointing down and up mark segmentation-boundaries proposed by *Jones* [1988] and those found by our method, respectively. Note that the abscissa is in units of event numbers, which produces a variable distance scale.

The constancy of slope in individual segments is remarkable, and so is the contrast between segments (Figure 1). We interpret this to mean that our hypothesis is correct. Within segments of the southern San Andreas fault the stress directions are uniform, giving rise to a relatively constant misfit for all earthquakes within that segment, with respect to the slip directions expected, based on the reference-tensor. The strong differences of slope between the segments allow us to state with confidence levels above 99% that differences in stress directions exist along this part of the San Andreas fault. This supports the conclusions by *Jones* [1988].

All four segment-boundaries chosen subjectively by *Jones* [1988] are defined by our quantitative method also (Figure 1). In addition, our method finds a segment boundary not used by Jones. It occurs at earthquake number 103. The location of this boundary is marked by a heavy long bar on the map (Figure 2). The over-all inversion for the Indio segment yields $F = 5.1°$. The average misfit decreases to $F_{nw} = 2.2°$ and $F_{se} = 4.8°$ in the north-western and south-eastern Indio segments, respectively, when the data are inverted separately for the two segments.



	N	Misfit	R
a	39	5.1	0.3
b	17	2.2	0.4
c	22	4.8	0.4

Figure 3. Lower hemisphere stereographic projections of the best fitting estimates of the stress-tensor directions for the original Indio segment (a) and the newly defined segments north-west (b) and south-east (c). The best estimates of the greatest and least principal stresses are labeled as σ_1 and σ_3, respectively. Circles and squares show stress directions not distinguishable from the best estimate at the 95% confidence level for σ_1 and σ_3, respectively.

Discussion and Conclusions

The hypothesis we set out to test is confirmed by the results. Segments of constant slope of $\Sigma f(x)$ exist, and the slopes of neighboring segments differ strongly (Figure 1). The fact that our quantitative method picks all four segment-boundaries proposed by *Jones* [1988] based on common sense also supports our proposal that this method is capable of defining the segmentation of faults in a meaningful way. We propose that our method is superior to judgment by inspection, because it identified an additional segment-boundary. However, Jones's conclusions are not changed by our results. We only introduce a refinement in finding an additional boundary and moving slightly to the east the point where the greatest principal stress changes direction from approximately NS to N25E (Figure 2).

Comparing the stress tensor directions for the two new segments to the estimate for the original segment (Figure 3), we find that the results in one of the new segments is not different, and in the other it is different from the original result. Although the two solutions in the new segments are not confined well enough to be accepted as different at the 95% confidence level, based on the method by *Gephart and Forsyth* [1984], the difference is significant at the 99% level in the cumulative misfit curve.

The significance of a difference between two estimates of the stress directions is difficult to asses. We often find cases, as that in Figure 3, where the best estimate from two volumes differ by 20° to 30°, but the confidence areas [*Gephart and Forsyth*, 1984] overlap. In the cumulative misfit approach we can estimate the difference between the mean misfit of two segments as significant above the 95% confidence level, but we do not know the orientation of the stress-tensor. That is, we are confident that a difference exists, but we do not know which solution from those within the 95% confidence area is the correct one. Thus, we propose that the cumulative misfit method may give us a tool to identify the difference in stress directions between volumes, when the full inversion for stress-tensor is not well constrained. Our approach addresses a lower information level: a difference exists, but the directions are poorly known. The relationship between the two methods of testing the significance of apparent differences in stress directions will have to be clarified.

The stress directions along a weak fault like the San Andreas are probably controlled to a large degree by the presence of the fault. *Jones* [1988] pointed out that the attitude of the greatest principal stress with respect to the fault surface remained approximately the same, regardless of changes in strike. *Rebai et al.* [1992] showed the same for faults in southern France on various scales, and they presented a compelling model for these observations. Analyses of segmentation of stress directions along faults may contribute to understanding the role of faults in modifying the local stress field.

The consequences, which segmentation of plate boundaries have for the control of large ruptures, are not clear to us yet. It seems reasonable to propose that major ruptures and their asperities may terminate at segment-boundaries. In our analysis of the Aleutian subduction zone, ends of asperities seem to correlate with segment boundaries [*Lu and Wyss*, 1995]. Also, we see some correlation between ends of great ruptures and segment-boundaries. More information about the level of correlation of these phenomena can only be found by a systematic analysis of many plate boundaries.

The method we proposed here, to find segmentation of faults and volumes of uniform stress-directions, needs to be refined. The cumulative misfit curve does not bring out the contrast between segments equally clearly using any reference-tensor. Using as reference-tensor the solution for the San Bernardino segment we miss one, using any of the other segment's solution we miss two out of five boundaries. The solution to the entire, heterogeneous, data set affords the poorest resolution of the segment boundaries. We will have to explore systematically what conditions have to be met for the reference-tensor to bring out the segmentation optimally.

In future tests of our hypothesis we plan to use the sign of the misfit in addition to the absolute value. We will also expand the method to map the misfits in two dimensions, so that areas of uniform stress directions can be identified in tectonic settings of diffuse seismicity. In summary, we believe, once perfected, this method may provide a tool to map segmentation along most seismically active plate-boundaries and major faults, and it may be able to define crustal volumes of uniform stress directions.

Acknowledgments. This work was supported in part by NSF grant No: 9118086, and in part by the Wadati foundation at the Geophysical Institute of the University of Alaska, Fairbanks. We thank G. Neri for discussions which led to the development of this method, and D. Gillard for the data in electronic form, as well as his advice concerning computational methods. We also thank J. Lahr and S. Jaume for comments leading to improvements in the manuscript.

References

Davis, J. C., Statistics and data analysis in geology, John Wiley & Sons, NewYork, p 48, 1973.

Gephart, J. W., FMSI: A FORTRAN program for inverting fault/slickenside and earthquake focal mechanism data to obtain the original stress tensor, *Comput. Geosci., 16*, 953-989, 1990a.

Gephart, J. W., Stress and the direction of slip on fault planes, *Tectonics, 9*, 845-858, 1990b.

Gephart, J. W., and D. W. Forsyth, An Improved Method for Determining the Regional Stress Tensor Using Earthquake Focal Mechanism Data: Application to the San Fernando Earthquake Sequence, *J. Geophys. Res., 89*, 9305-9320, 1984.

Gillard, D., and M. Wyss, Comparison of strain and stress tensor orientation: Application to Iran and southern California, *J. Geophys. Res., 100*, in revision, 1995.

Gillard, D., M. Wyss, and J. S. Nakata, A Seismotectonic model for western Hawaii based on stress- tensor inversion from fault-plane solutions, *J. Geophys. Res., 97*, 6629-6641, 1992.

Gillard, D., M. Wyss, and P. Okubo, Stress and strain tensor orientations in the south flank of Kilauea, Hawaii, estimated from fault plane solutions, *J. Geophys. Res., 100*, submitted, 1995.

Hauksson, E., State of stress from focal mechanisms before and after the 1992 Landers earthquake sequence, *Bull. Seismol. Soc. Am., 84*, 917-934, 1994.

Jones, L. M., Focal mechanisms and the state of stress on the San Andreas fault in southern California, *J. Geophys. Res., 93*, 8869-8891, 1988.

Lu, Z., and M. Wyss, Segmentation of the Aleutian plate boundary derived from stress direction estimates based on fault plane solutions, *J. Geophys. Res., 100*, submitted, 1995.

McKenzie, D. P., The relation between fault plane solutions for earthquakes and the directions of the principal stresses, *Bull. Seismol. Soc. Am., 59*, 591-601, 1969.

Neri, G., and M. Wyss, Preliminary results from stress tensor inversion of earthquake fault-plane solutions in the southern Tyrrhenian region, *Bollettino di Geofisica Teorica ed Applicata, 35*, 349-362, 1993.

Rebai, S., H. Philip, and A. Taboada, Modern tectonic stress field in the Mediterranean region: evidence for variation in stress directions at different scales, *Geophys. J. Int., 110*, 106-140, 1992.

Wyss, M., B. Liang, W. R. Tanigawa, and X. Wu, Comparison of orientations of stress and strain tensors based on fault plane solutions in Kaoiki Hawaii, *J. Geophys. Res., 97*, 4769-4790, 1992.

Zoback, M. D. et al., New Evidence on the State of Stress of the San Andreas Fault System, *Science, 238*, 1105- 1111, 1987.

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(received November 24, 1994;
revised January 4, 1995;
accepted January 5, 1995.)