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Title: Correlation of Data on Strain Accumulation Adjacent to the San Andreas Fault with Available Models

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The purpose of this contract was to carry out theoretical and numerical studies of deformation on strike slip faults and to apply the results to geodetic observations carried out in the vicinity of the San Andreas Fault in California.

Our initial efforts were devoted to an extensive series of finite element calculations of the deformation associated with cyclic displacements on a strike-slip fault. Measurements of strain accumulation adjacent to the San Andreas fault indicate that the zone of strain accumulation extends only a few tens of kilometers away from the fault. Such a narrow zone of cyclic strain accumulation and release is consistent with the measured coseismic strain and inferred stress drop during the 1906 earthquake. The restricted zone of cyclic accumulation and release of elastic energy adjacent to major strike-slip fault has been attributed to the damping effect of a viscoelastic asthenosphere. However, to explain the narrowness of the zone on the San Andreas fault, it is necessary to conclude that the thickness of the lithosphere is 10-20 km. This does not appear to be consistent with the relatively low surface heat flow measurements. We proposed an alternative four layer model to explain the behavior of the San Andreas fault. An upper elastic plate extends to a depth of about 15 km, the depth of the deepest seismicity on and adjacent to the fault. Beneath this upper elastic plate is a soft, intracrustal asthenosphere that exhibits a viscoelastic behavior. The viscous behavior of these crustal rocks at relatively low temperatures is attributed to either the presence of quartz, which is known to have a very soft rheology, or the presence of water that can lead to pressure solution creep or to both effects. Beneath this soft layer is a second elastic layer made up of the tough lower crustal and upper mantle rocks. And beneath this second elastic layer is the asthenosphere. There is extensive geological and geophysical evidence for the existence of an intracrustal asthenosphere both in California and elsewhere. We showed that the damping due to the intracrustal asthenosphere can explain the observed narrow zone of cyclic strain accumulation and release on the San Andreas fault. This work was written up and published in the Journal of Geophysical Research (2).

Our work led us to be concerned about the tendency to make geodetic observations along the line to the source. This technique has serious problems for strike slip faults since the vector velocity is also along the fault. The tendency is to place observation stations at considerable distances along strike. Since there may be large variations in strain along strike this poses serious problems in interpretation. I would suggest using a series of stations lying perpendicular to the fault whose positions are measured relative to a reference station. If the measurements at the station are made relatively quickly then differential differences are easily obtained.

This work was also included in the 1982 William Smith Lecture to the Geological Society of London given by the P.I. This lecture was subsequently published in the Journal of the Geological Society of London (1). This work was also included in an invited paper that the P.I. gave at the XVIII General Assembly of the International Union of Geodesy and Geophysics, Hamburg, Germany, August 15-27, 1983 (8) and at a Chapman Conference of the American Geophysical Union (7).

The complexity of faulting adjacent to the San Andreas fault indicated to us that the homogeneous elastic and viscoelastic approach to deformation had serious limitations. This approach considered static and dynamic friction on a pair of roughened surfaces or to include granulated particulate material between the surfaces. Unfortunately, the frictional hypothesis makes several predictions that are not in agreement with observations. Most materials have a coefficient of friction near 0.7 which leads to high stresses on the fault and high heat flow that is not observed. Also, the stress drops predicted by friction theories are unreasonably small.

These difficulties led us to propose a new approach that assumes a fault is composed of a distribution of asperities and barriers on all scales. We consider a fault to be scale invarient. The observational evidence for scale invariance is the universal relationship between the frequency and magnitude of earthquakes. We thus treat an earthquake on a fault as the failure of a fractal tree. We assume a statistical distribution of asperity strengths and take into account the transfer of stress from a failed asperity to adjacent asperities. We then apply the renormalization method to the problem and find a bifurcation of the solution. At a critical value of the applied stress a catastrophic failure occurs, this is the earthquake.

Our initial work on this project was presented at the 1983 Fall Annual Meeting of the American Geophysical Union, San Francisco, Dec. 5-9, 1983 (9). The initial work was extended in a number of ways. By assuming a double peaked distribution of asperity strengths we found that we not only obtained a catastrophic failure of the fault (an earthquake) but we could also terminate the propagation of the rupture. This research was presented at the Meeting of the NASA Crustal Dynamics Working Group held at Boulder, Colorado, on March 27-28, 1984, at the Spring Annual Meeting of the American Geophysical Union, Cincinnati, Ohio, May 14-17, 1984 (11), the Spring Meeting of the American Physical Society, Washington, DC, April 23-26, 1984 (10), as part of an invited paper at the 14th International Conference on Mathematic Geophysics held in Loen, Norway, June 24-30, 1984 (12), as an invited paper at the NSF Sponsored Workshop on Instabilities in Continuous Media, Venice, Italy, December 3-7, 1984 (13) and at the Fall Annual Meeting of the American Geophysical Union, San Francisco, California, December 3-7, 1984 (14). This work was written up and published in the Journal of Geophysical Research (3) and in Nature (4).

Work continued on the development of a fractal based model for deformation in the western United States. The initial results were presented at the Texas A & M conference on Intraplate Deformation, College Station, Texas, April 10-12, 1985. Regional deformation is hypothesized to occur on a scale invariant matrix of faults. Deformation occurs on all scales of faults. The fractal dimension determines the fraction of the total regional displacement that occurs on faults of a particular scale. The value of the fractal dimension can be obtained from the frequency-magnitude relation for earthquakes. The results were applied to the San Andreas fault in central California. The model predicts that the relative velocity across the main strand of the fault is 2.93 cm/year while the remainder of the relative velocity of 5.5 cm/year between the Pacific and North American plates occurs on other faults in the system. The predicted value is in quite good agreement with the value 3.39 ± 0.29 cm/year inferred from geological studies. The concept that only a fraction of the relative velocity occurs on the primary strand of the fault has important implications regarding the occurrence of great earthquakes in California. Our model also predicts recurrence rates on smaller faults in southern

California. This work was written up and published in the proceedings of the conference (6). This work was also presented at the Centre National d'Etudes Spatiales (CNRS) Summer School held in Toulouse, France in July 1984 and was published as part of the lecture notes of the summer school (5). Aspects of this work were presented at several meetings (15, 16, & 17). This work also formed a substantial part of an invited paper given at the 1986 National Meeting of the Society of Industrial and Applied Mathematicians (SIAM) held in Boston, Massachusetts, July 21-25, 1986 (20).

In order to better understand the distribution of seismicity on the San Andreas Fault system a fractal analog was developed. The analog consisted of a third order parallel and series network of elements with a fractal distribution of sizes; each element was given a random strength. The system effectively modelled the occurrence of foreshocks and aftershocks. The distribution of failures of elements of various sizes was effectively modelled by the empirical Richter frequency-magnitude relation and a reasonable b-value was obtained. This work was presented at the 1986 Spring Annual Meeting of the American Geophysical Union (18).

The fractal concept also provides a means of testing whether clustering in time or space is a scale-invarient process. We have analyzed a catalog of earthquakes from the New Hebrides for the occurrence of temporal clusters that exhibited fractal behavior. In all cases significant deviations from random or Poisson behavior were found. This method introduces a new method for quantifying the clustering of earthquakes. This work was presented at the Spring Annual Meeting of the American Geophysical Union, Baltimore, Maryland, May 19-22, 1986 (19).

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