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Title: Analysis of Regional Deformation and Strain Accumulation Data Adjacent to the San Andreas Fault

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A new approach to the understanding of crustal deformation was developed under this grant. This approach combined aspects of fractals, chaos, and self-organized criticality to provide a comprehensive theory for deformation on distributed faults. It is hypothesized that crustal deformation is an example of comminution: Deformation takes place on a fractal distribution of faults resulting in a fractal distribution of seismicity. This research culminated in the book "Fractals and Chaos in Geology and Geophysics" by the Principal Investigator published by Cambridge University Press [21]. Much of the research under this grant was done by Jie Huang as a graduate student (Ph.D. Cornell 1990) and as a postdoctral associate.

Our primary effort under this grant was devoted to developing an understanding of distributed deformation in the continental crust. An initial effort was carried out on the fractal clustering of earthquakes in time. It was shown that earthquakes do not obey random Poisson statistics, but can be approximated in many cases by coupled, scale-invariant fractal statistics. We applied our approach to the statistics of earthquakes in the New Hebrides region of the southwest Pacific because of the very high level of seismicity there. This work was written up and published in the Bulletin of the Seismological Society of America [1]. This approach was also applied to the statistics of the seismicity on the San Andreas fault system.

We also developed a fractal analog for the San Andreas fault system. This used a series-parallel system of elements with a fractal distribution of sizes and a statistical distribution of strengths. An element failure represented an earthquake. When an element broke, stress was transferred to adjacent elements and many of these broke representing aftershocks. In about 25% of the cases the failure of an element acted as a foreshock triggering a failure of a larger element. These statistics are similar to those for the San Andreas fault system. This simple system produced a frequency-size distribution of failures with a b-value appropriate to the San Andreas system. This work was presented at the Symposium on Crustal Dynamics held at Uppsala University, Sweden in April, 1987 and was published in the proceedings of that conference [3].

From January to June, 1987 the Principal Investigator was on Sabbatic Leave at the

Institut de Physique du Globe de Paris. During this time, he actively collaborated with Professor Paul Topponier of the University of Paris on problems of the tectonics of the Western United States. Arrangements were made for Dr. Yves Gaudemer, a member of Professor Topponier's group, to visit Cornell for a year from March, 1987 with the support of the C.N.R.S. to work on these problems. The P.I. gave an invited review paper on fractal tectonics at the Fall Annual Meeting of the American Geophysical Union held in San Francisco, December 8-12, 1986 [A1]. This review was subsequently published in an issue of Pure and Applied Geophysics devoted to fractals in the earth sciences [7].

Our work emphasized the distribution of earthquakes on the San Andreas System, particularly the relationship between b-value and the fractal distribution of faults. A paper on the fractal approach to seismic hazard assessment on the San Andreas Fault System was given at the Symposium on Seismic Hazard Assessment held during the XIX General Assembly of the International Union of Geodesy and Geophysics in Vancouver, Canada, August 9-22, 1987 [A3]. This work was subsequently written up and published in the Proceedings of the Symposium [8].

Another effort was to study whether fractal mapping could provide a better understanding of tectonics in the Western United States. Digitized topography was divided into subunits and the fractal dimension and roughness amplitudes were obtained. The original work was done for Arizona because of its diverse tectonics and the availability of digitized topography for the whole state. As expected, the variations in fractal dimensions were relatively small, but the variations in roughness amplitude correlated well with geological provinces. This is a technique of texture analysis with a wide variety of applications. This work was presented at the Fall Meeting of the American Geophysical Union, San Francisco, December 7-11, 1987 [A6]. Subsequently, this work was written up and published in the Journal of Geophysical Research [5].

Our continuing work on crustal deformation emphasized a fractal distribution of stress and strength in a tectonic zone. This work was presented at the 1988 Spring Meeting of the

American Geophysical Union, Baltimore, Maryland, May 16-20, 1988 [A5]. This work was also written up and published in Earth and Planetary Science Letters [2].

We presented several invited papers on our work on fractal deformation. An invited paper was presented at the XVII International Congress of Theoretical and Applied Mechanics, Grenoble, France, August 21-27, 1988 [A8]. This review was written up and published in the proceedings of this Congress [4]. An invited paper was presented in a special fractal session at the 1988 Annual Meeting of the Geological Society of America, Denver, Colorado, October 31 - November 3, 1988 [A9]. A presentation was also made at poster session [A10]. The review paper will be published in a Special Volume of the Geological Society of America [19]. Our approach was presented at the NAS-ASUSSR Bilateral Workshop on Earthquake Prediction, Leningrad, USSR, October 10-14, 1988. It was also presented the next week at the C.D.P. Principal Investigators Meeting in Munich.

Y. Gaudemer, on leave at Cornell from the Institut du Physik du Globe, University de Paris, was partially supported by this grant to work on the use of river offsets in California to determine whether secondary faults of the San Andreas system are active. LANDSAT images were used for the study and were successful in estimating rates of displacement on the Big Pine, San Gabriel, and Elsinore faults. This work was presented at the 1988 Fall Meeting of the American Geophysical Union, San Francisco, California, December 6-11, 1988 [A25] and at the 5th Meeting of the European Union of Geosciences, Strasbourg, France, March 20-23, 1989 [A13]. This work was written up and published in Ann. Tectonicae [9].

Joint research on the evolution of land surfaces was carried out with Bill Newman who was on sabbatic leave from UCLA at Cornell. A cascade model was developed to explain the fractal character of landscapes. The basis is that major storms rejuvinate topography by creating new gullies at all scales. An implication is that the erosion associated with major floods is also fractal. This work was given at the CDP Principal Investigator Meeting at the Jet Propulsion Laboratory, Pasadena, California, April 11-14, 1989. This work was written up and has been published in the Geophysical Journal International [22].

Our continuing work on fractal topography was presented at the 1988 Fall Meeting of the American Geophysical Union, San Francisco, California, December 6-11, 1988 (J. Huang and D.L. Turcotte, Correlations of fractal measures on topography, Trans. Am. Geophys. Un. 69, 1207, 1988). A review paper on our studies was presented at the International Alfred Wegener Conference on the Contributions of Solid Earth Sciences to the International Geosphere - Biosphere Program, Hamburg, Germany, December 13-16, 1988 [A12]. This work was written up and was published in the Proceedings of the meeting [13]. We continued our work on fractal analysis of digitized topography. We completed an analysis of the state of Oregon and this work was published in the Journal of the Optical Society of America [11].

The next phase of our work emphasized the use of slider block models as an analog for distributed seismicity. We were able to demonstrate that a pair of slider blocks exhibited classical deterministic chaos as long as some asymmetry was present. The period doubling route to chaos was found which obeys the Feigenbaum scaling rules. Similar results were obtained for static-dynamic and velocity weakening friction laws. This work was presented at the 1989 Fall Meeting of the American Geophysical Union, San Francisco, California [A15]. This work was also written up and published [10]. This work was also presented at the US-Japan Conference on Fractals, Form, and Fracture held at Lake Arrowhead, California, September 24-27, 1989 and at the GDP Principal Investigators Meeting at NASA Goddard, Greenbelt, Maryland, October 24-25, 1989. This work has been written up and submitted for publication [18].

We were able to relate the behavior of our two-block analog system to two observed systems. The first application was to the relationship between the Parkfield section of the San Andreas fault and the locked system to the south. A weak block modeled the Parkfield section and a strong block modeled the southern locked section. The system demonstrated excellent analog behavior. The weak block exhibited several "Parkfield earthquakes" between "great Southern California Earthquakes" on the strong block. Chaotic behavior was obtained. Two sequences of coupling were observed. In some cases a Parkfield earthquake directly triggered (was a precursor to) the great earthquake; in other cases, however, the Parkfield earthquake stressed the locked section so that it subsequently failed without a Parkfield earthquake as a precursor. We also successfully modeled the sequencing of earthquakes in the Nankai Trough, Japan. Using two blocks nearly equal in strength we observed both blocks to slide on some occasions, and the blocks to slide sequentially on other occasions, the behavior was chaotic. This is very similar to the observed sequencing of great earthquakes in the Nankai Trough. This work was presented at the SIAM Conference on Dynamical Systems, Orlando, Florida, May 7-11, 1990 and was written up and published in Nature [12].

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