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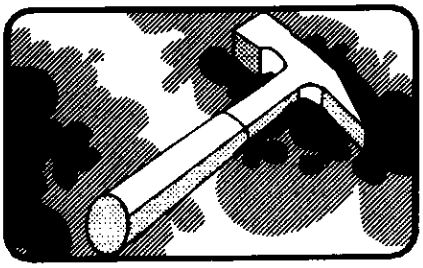

Fractals and Chaos

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The Spring Meeting of the American Geophysical Union (AGU), held in Baltimore, MD, May 28-June 1, 1990, featured AGU's first Short Course (on any topic). The title was "Nonlinear Dynamics, Fractals and Chaos in Geophysics", and the course was followed by two Technical Sessions on similar themes: one, a Union session devoted to Dynamical Systems in Geoscience, and the other devoted to Chaos in Space Plasmas.

The one-day Short Course was delivered by Donald Turcotte (Cornell U), whose topic was Fractals, and by Anastosios Tsonis (U of Wisconsin, Milwaukee) who talked about Nonlinear Dynamics and Chaos. It was attended by about 170 registrants, each of whom received a book of notes, with 97 pages devoted to fractals (draft sections of a book on the subject which Turcotte has in preparation), and 66 pages consisting of reprints of papers published by Tsonis (introductory reviews of nonlinear dynamics, and applications in meteorology). A "guest appearence" was also made by Christopher Essex (U of Western Ontario (UWO), Applied Math). There seem to be no plans to issue the book of notes as a separate AGU publication.

The Union session on the following day continued the analysis of many of the topics touched on in the Short Course. In the discussion that follows, I concentrate on three main topics: the new time series analysis methods opened up by chaos theory, the search for low-dimensional attractors in nature, and the use of fractals to describe and analyse geologic phenomena.

As described briefly by Middleton (1990), chaos theory has suggested new techniques to analyse time series that seem to display a substantial random component (*e.g.*, using conventional spectral analysis). There are two components to the new methods: one attempts to reconstruct low-dimensional attractors (generally in three-dimensional space) by plotting points separated in the series by time lags (t, 2t, 3t...) as though they were points in space. This is a technique first applied to the analysis of the irregular time intervals between drops falling from a dripping faucet, a homely phenomenon well known to insomniacs, which proved to be accurately described by a three-dimensional system of differential equations that gives rise to a chaotic attractor known as the Rössler attractor. Though it seems at first as though the technique attempts the impossible (to get information about three or more variables from a time series of a single variable), it has a sound theoretical base, and it is not surprising that it has been tried on a variety of geophysical phenomena. A notable example, presented by Michael Nicholl (U of Nevada) and described by him as "an inverted dripping faucet", is the Old Faithful geyser in Yellowstone Park. Though Nicholl presented an interesting analysis of the data, he has not yet been able to demonstrate convincing evidence that Old Faithful is indeed a strange attractor.

The second component of time series analysis using chaos theory concepts is a numerical technique pioneered by Grassberger and Procaccia (for references see Middleton, 1990). This is a numerical technique to detect the presence of an attractor, and determine its dimension, if one exists. It, and a variety of similar techniques, have been widely used. A controversy has developed about the results, centred around two main questions: how long a time series is required to detect an attractor of (fractal) dimension D? and what is the effect of ("genuine random") noise, and/or smoothing techniques designed to eliminate noise, on the results. Many mathematicians, *e.g.*, Ruelle (1990: Royal Society of London, Proceedings, v. A427, p. 241-248), have been profoundly sceptical about applications that have claimed to detect relatively high-dimensional attractors (say DØ6). Some have claimed that estimates of dimension must be based on time series of as many as 42^D data. Even the more modest estimate suggested by Ruelle ($D<2\log N$) indicates, for example, that to detect an attractor of dimension 6, one needs a times series of at least 10,000 points. Very few geological time series (*e.g.*, periods between magnetic reversals, large earthquakes, or volcanic eruptions, or estimates of paleoclimate based on paleontological or isotopic data) have more than a few hundred data, so the need for long time series and high precision severely limits the potential applications in the earth sciences. At the meeting, Christopher Essex (UWO, Applied Math) presented the results of a new theoretical analysis that shows that many authors have greatly overestimated the number of data needed, though 1000 points or so are still needed for low-dimension attractors such as the Rössler attractor. A paper on sunspots by M.D. Mundt and W.B. Maguire II (U of Colorado, Centre for Astrodynamic Research) claimed to have detected a strange attractor of dimension between 2 and 3. The analysis was based on a strongly smoothed subset of the full sunspot record, however, and was received with some scepticism by some members of the audience (an unpublished study at McMaster U also suggested an attractor in some parts of the sunspot data, but with a dimension of about 4).

A more fundamental question was raised by several participants. Among them were Shaun Lovejoy (McGill University, Physics) who was one of the pioneers in demonstrating the fractal nature of clouds and rain: he seemed to doubt that in any large system (such as the atmosphere) displaying turbulence, any substantial part of the dynamics can be explained by low-dimensional systems. Another objector was Per Bak (Brookhaven National Laboratory, Upton, NY), who has deduced from the apparently power law (fractal) relationship between earthquake magnitudes and frequencies, that earthquakes indicate that the crust is in a "self-organized critical state" similar to that of a sand pile near the angle of repose. On this theory, earthquakes (as slumps of sand) take place at unpredictable intervals because this is a phenomenon "at the border of chaos", not because it is a system determined by a small number of nonlinear equations with a strange attractor. Other speakers, however, presented models of earthquakes that would lead to just such low-dimensional chaos, and which, it is claimed, predict types of behaviour similar to those observed in some fault zones. Franklin Horowitz (Northwestern U, Civil Engineering) presented an analysis of earthquake data suggesting that the "power law" displayed by earthquakes was more an artifact of the method of averaging than a real feature of the data. Unfortunately, just as the discussion on these matters started to become most interesting, time ran out and the session ended.

On the evidence of this meeting, the use of fractal concepts to analyse geophysical data is now a thriving subdiscipline. Beyond their application to describe coastlines, landscapes (and oceanscapes), clouds, rainstorms, floods, pore space, and fault surfaces, fractal theorists have now gone a long way to answer the query recently posed by Leo Kadanoff: "Fractals: where's the physics" (*Physics Today*, February 1986, p. 6-7). An interesting example, discussed in the course by Turcotte, and in papers presented by Charles Sammis (U of California, Los Angeles (UCLA)) and Sandra Steacy (UCLA) and Sammis, is that of rock fragmentation. The fact that crushed rock displays a power law relationship between the size and number (or weight) of rock fragments of a given size class has been known since the work of J.G. Bennett (1936, Journal of the Institute of Fuel, v. 10, p. 22-39) who also developed a stochastic model to explain these observations (this is the relationship known to sedimentologists as the Rosin-Rammler law).

The same type of relationship has been observed in fragments produced by nuclear explosions, and by Sammis in fault gouge (or breccia). Turcotte cited evidence in his lectures that it can be extended to metre-size fractures, and indeed to entire systems of faults and fault blocks, such as those displayed by the crust of the state of California. A physical model that displays much the same fractal dimension as observed in these examples can be developed using the reasonable premise that blocks fragment only when two blocks of nearly equal size come into contact with each other in a zone of compression or shear.

My personal reaction to these two days at AGU was first that these are exciting and controversial times during which the practical application of the main concepts and techniques of nonlinear dynamics are being extensively tested for the first time on a wide range of geological phenomena, and second that I must immediately learn a lot more about fractals — there is a great deal more there than pretty pictures! A short bibliography of references not in my recent review article on nonlinear dynamics follows. The emphasis is on practical applications rather than on mathematical theory.

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Reminder: GAC is sponsoring a two-day Short Course on Nonlinear Dynamics, Chaos and Fractals (with Applications to Geological Systems) at the 1991 Annual Meeting in Toronto, 27-29 May 1991.

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CANQUA

Rapid Change in the Quaternary AMQUA/CANQUA 1990

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On 4-6 June 1990, more than 250 participants from across Canada and the US attended the first joint meeting of AMQUA (American Quaternary Association) and CANQUA (Canadian Quaternary Association) at the University of Waterloo. Although this was the second CANQUA meeting in as many years, it did not seem to affect attendance by Canadians, underlining the need for an annual regular scientific CANQUA meeting. This conference was extremely well organized, with a wealth of excellent presentations on a variety of Quaternary interests. Each province and territory was represented by participants, in addition to most US states. Participants were split among industry, government, and university research personnel.

Before the conference, three field trips showed participants the numerous Quaternary features in the region of Southern Ontario and northern New York state. I personally found the Waterloo regional glacial geomorphology trip to be excellent. In addition to seeing five different local moraines, we examined Wittlesea shorelines, visited a major drumlin field, a series of kames *sensu stricto*, a kettle lake, and karst features that may have been carved during melting of the local ice. Also evident on the trip were several examples of poor regional planning that did not consider local Quaternary geology:

1. Continued unrestrained urban expansion has so taxed the local water supply that a major project to draw water from the Grand River and pump it through the local aquifer has become necessary.
2. A housing development had to be abandonned because methane leaching from a land fill could not dissipate through the clay-rich till.
3. More than 25 years of corn-based agriculture have so reduced the quality of the soil, that wind erosion has deflated the *entire* A and B horizons in many fields, leaving exposed C horizons. In the 60 km+ winds, on the day of our trip, we watched incredible amounts of soil blow away.

Other participants on the Eastern Lake Erie basin and Lake Ontario north shore trips reported that they had seen some fascinating glacial and archeological sites as well.

The conference kicked off with a mixer on Sunday night at which many old friends had an opportunity to catch up on recent events. Early Monday morning, the scientific sessions started with welcomes from conference Chairman Alan Morgan, Barry Warner, and Dr. D.V. Wright, President, University of Waterloo.

The theme for the conference was rapid change in the Quaternary. In the keynote address, Bill Fyfe repeatedly asked the question "What will the world be like in 2050?" With vivid pictures and eloquent phrases, he then described to us what it will be like if we do not start to clean up our act as a race. He cited a variety of evidence to convince us that global change is upon us whether we like it or not:

1. Canadians use more energy per capita than any other nation, with the US only slightly behind us.
2. If world population continues adding 90,000,000 per year, then by 2050, there will be 10 billion. Population will increase to 14 billion before leveling off.
3. 40,000 children a day die of starvation and/or disease.
4. If the efficiency of the earth's thermal blanket increases by 1%, the ice caps will melt in 60 years!
5. Iowa has lost *one-half* of its top soil.
6. As much as 30 cm of top soil can be lost from land cleared of jungle in Thailand in *one* rain.
7. Several towns in Poland have had *no live* births in decades due to pollution.
8. In the Amazon basin, the major dam project will silt up in less than 10 years, but is only producing 5% of its capacity. Plus, it has covered millions of hectares of jungle in a lake averaging 1 m deep, the ideal breeding ground for malaria.
9. One edition of the Sunday New York Times requires 77,000 Canadian trees.
10. More than half the elephants alive in 1981 are now dead due to poaching.
11. Primary productivity in the Mediterranean has almost ceased now due to pollution.

This gloomy litany of symptoms indicates a sick planet. Dr. Fyfe emphasized that the solution must include education for all, especially women, everywhere, but an education that ensures people are literate, "numerate", and "sciencate" (scientifically literate). Our governments must stop considering scientists to be plumbers who get called in only when there's a leak. Technological innovation must include a readily available cheap power supply, such as GaAs and GaSb power cells, in which one hour of solar energy stored will provide for a fridge, TV, fan, and