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A mathematica toolbox of nonlinear systems for mineral exploration

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Mineral Dynamics

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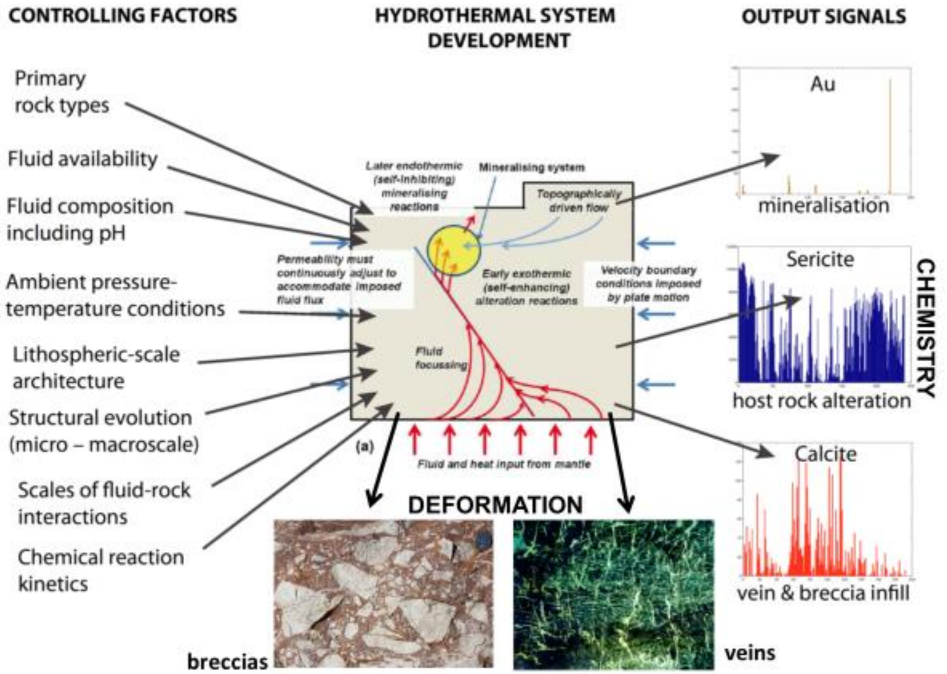
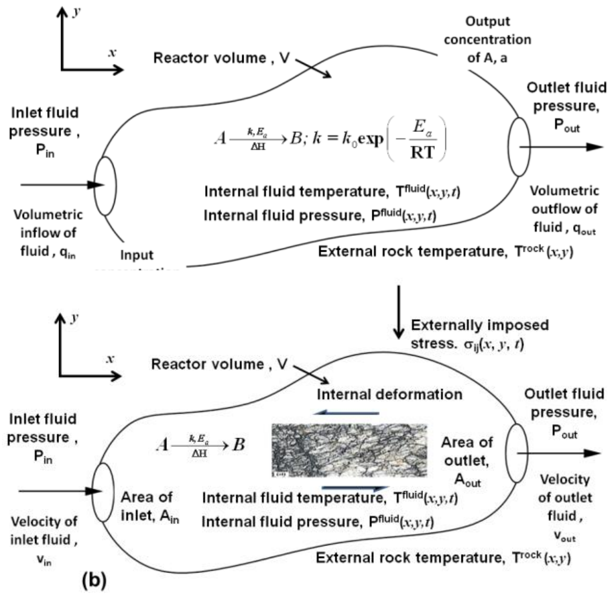
Hydrothermal Mineralising Systems as Nonlinear Chemical Reactors.





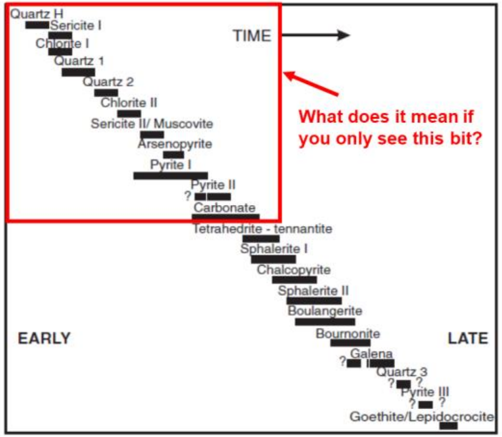
Combustion

Hydrothermal mineralising systems as open flow chemical reactors held far from equilibrium by the inflow of energy and mass. These reactors continue to operate far from equilibrium whilst the inputs of energy and mass are maintained and suitable reactants exist in the system.

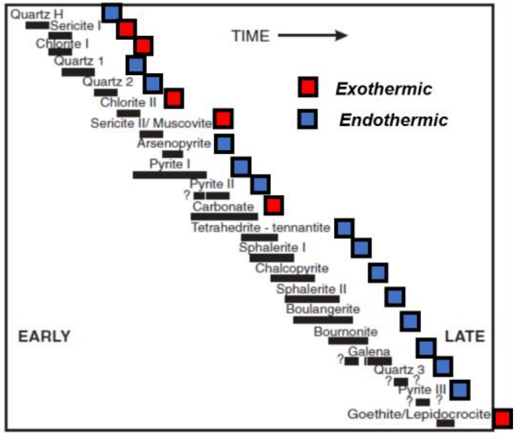
Alison Ord

The University of Western Australia, CSIRO, Australia

Bruce Hobbs



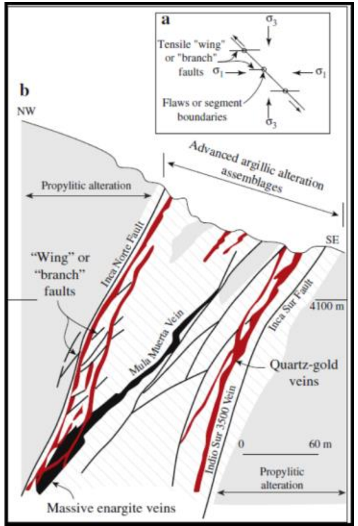
Paragenetic sequence of Feitais stockwork vein minerals. S Portugal
Inverno et al., 2008



Paragenetic sequence of Feitais stockwork vein minerals. S Portugal
Inverno et al., 2008

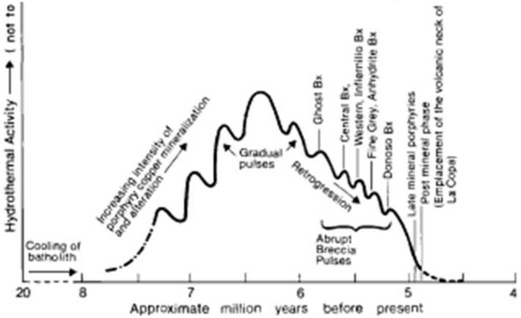
The competition between *endothermic* (metal and sulfide deposition, formation of anhydrous mineral assemblages) & *exothermic* (formation of hydrous and carbonate alteration assemblages, deformation including brecciation) processes with the supply of heat and mass generates systems that behave in an irregular or chaotic manner.

Mineralisation imposed on **fracturing** imposed on **alteration**



El Indio mine, Chile
Berger & Henley 2011

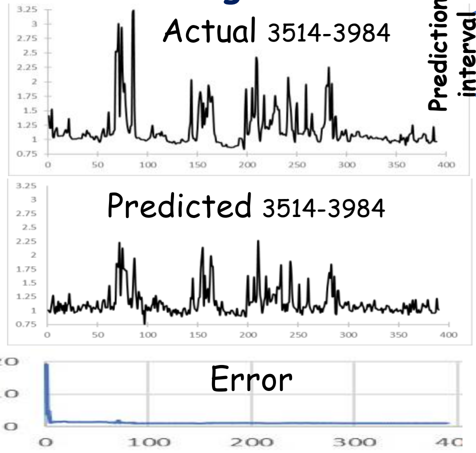
Continuing sequences of alteration/fracturing/ mineralisation result in the largest deposits

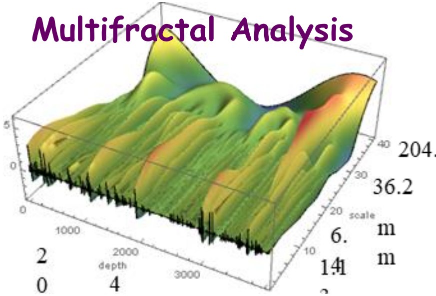


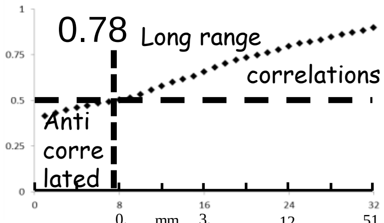
Schematic representation of the sequence of hydro-thermal events during the formation of the Los Bronces-Rio Blanco porphyry copper and breccias.
Warnaars et al., 1985

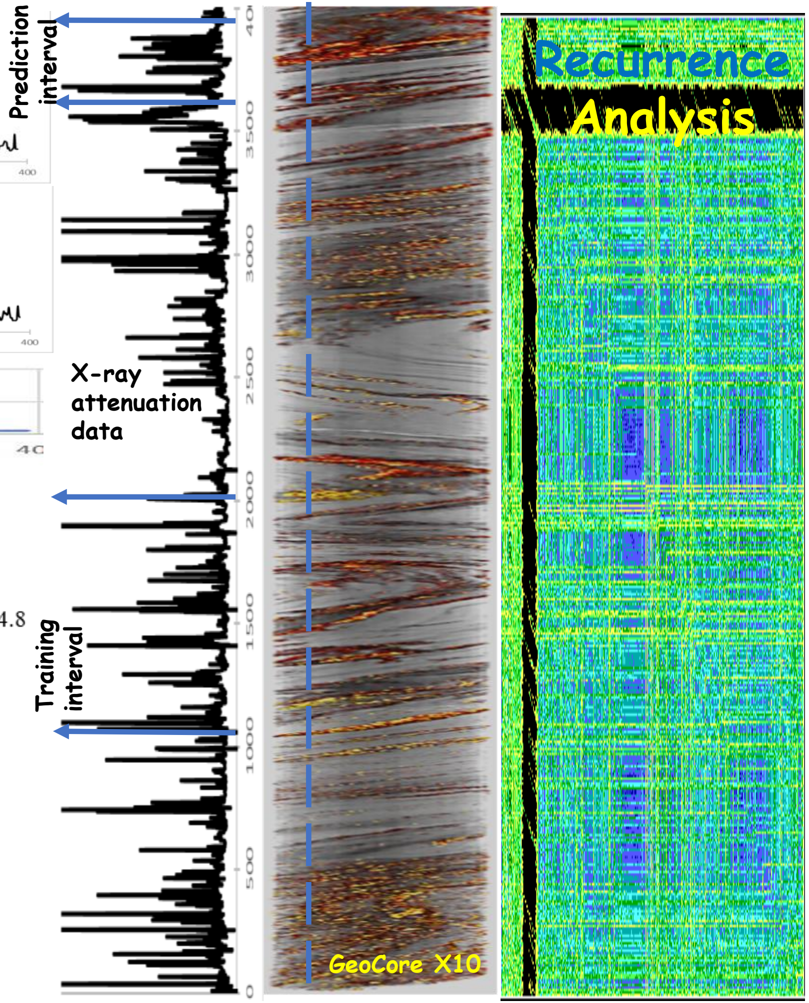
Nonlinear data driven analysis

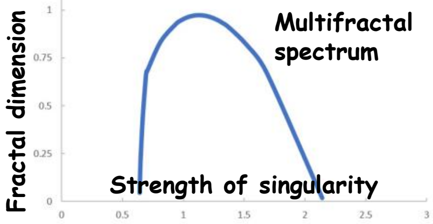
Nonlinear prediction of signal

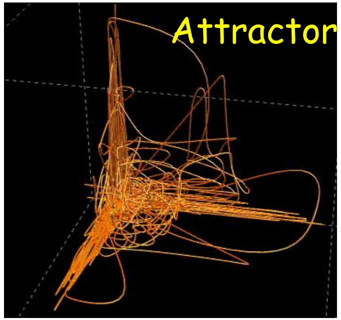










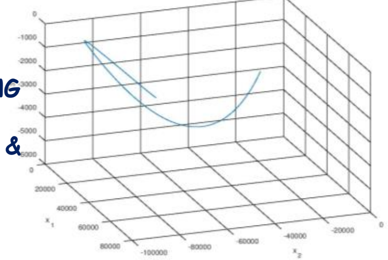


OBJECTIVES OF NONLINEAR DATA DRIVEN ANALYSIS

- CHARACTERISATION & FINGERPRINTING
- PREDICTION & RESOURCE ESTIMATION
- CONTROL & OPTIMISATION OF PROCESSING
- OPTIMISATION OF DRILLING & SAMPLING
- PHYSICAL/CHEMICAL & GEOLOGICAL UNDERSTANDING

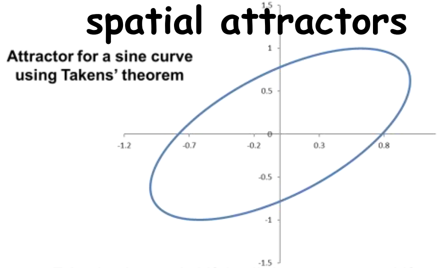
Sparsely identified nonlinear dynamical system

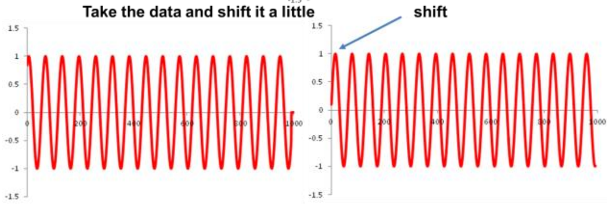
$$\dot{x}=2.0-0.51x+0y-0.15z+0.04xz$$
$$\dot{y}=1.0+0.04x-0.3y+0.06z$$
$$\dot{z}=1.2+0x+0.05y-0.3z$$



The tools of nonlinear dynamics

spatial attractors



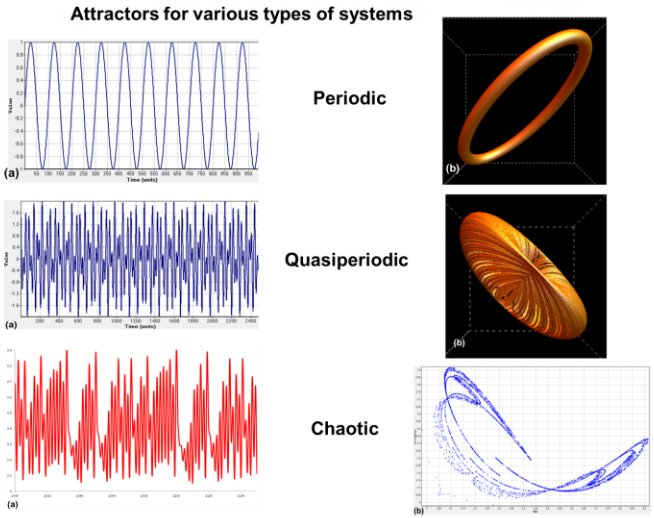


In a coupled nonlinear system all of the behaviour of the system is contained in the behaviour of one component of that system (Takens 1981). A component might be the abundance of sericite.

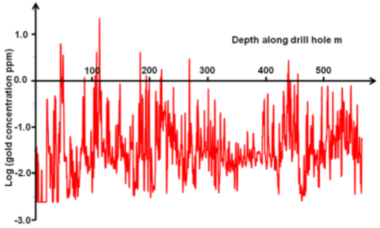
The complete dynamical behaviour of that system can be obtained from one set of data from that system.

The dynamical behaviour is expressed as an ***attractor*** for that system, a footprint.

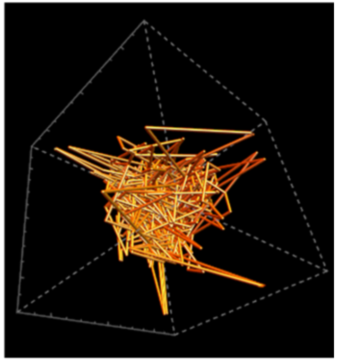
The attractor represents all possible states that the system can occupy.



PREDICTION OF NATURAL GOLD CONCENTRATION



Log (gold concentration ppm) from Yilgarn gold deposit

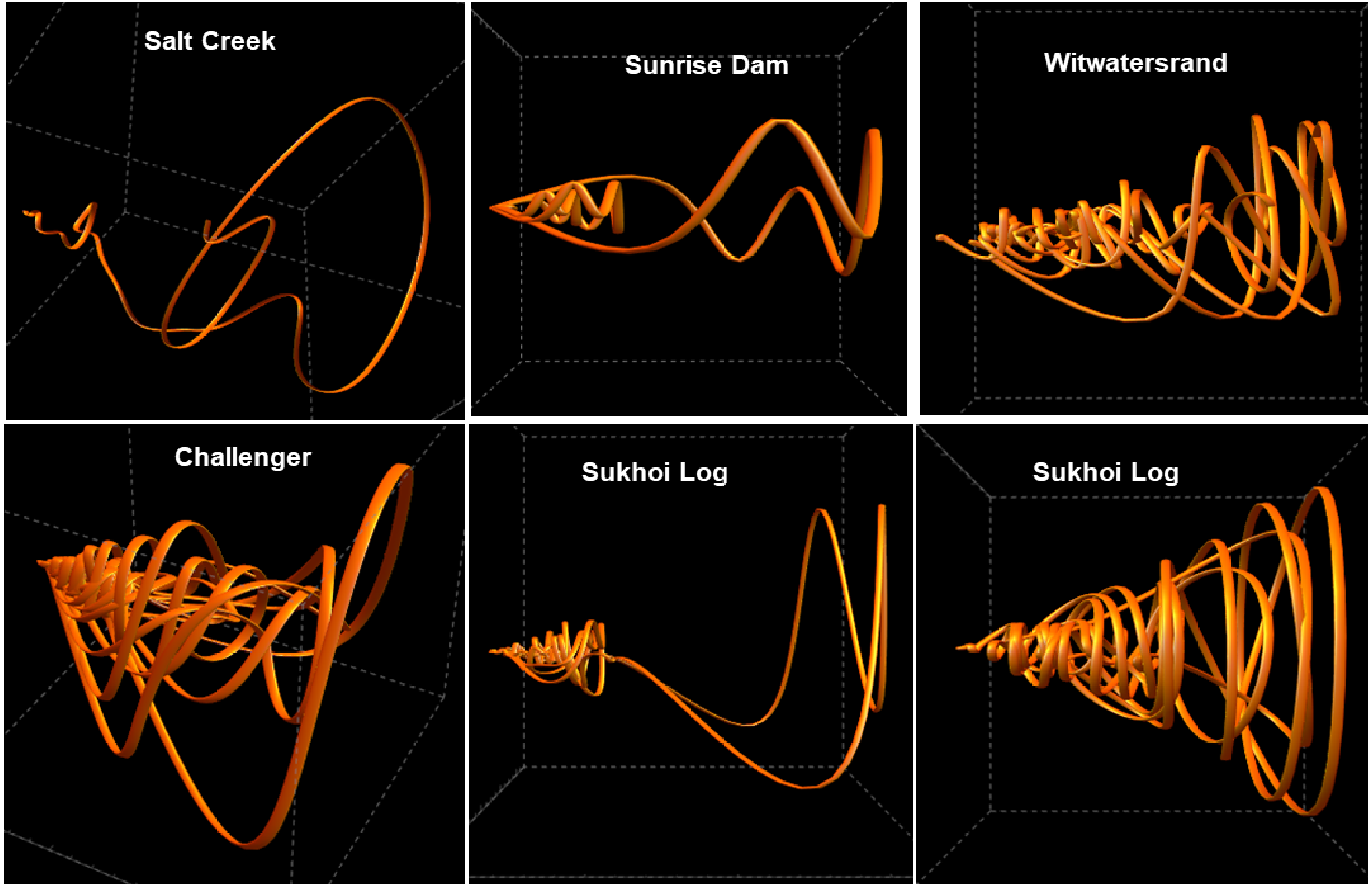


3D attractor projected from ≈10 dimensions

The input data are not constrained to any type of statistical distribution and the data are not required to be stationary.

There is no need to know the mathematical rules (if any) governing the system under study.

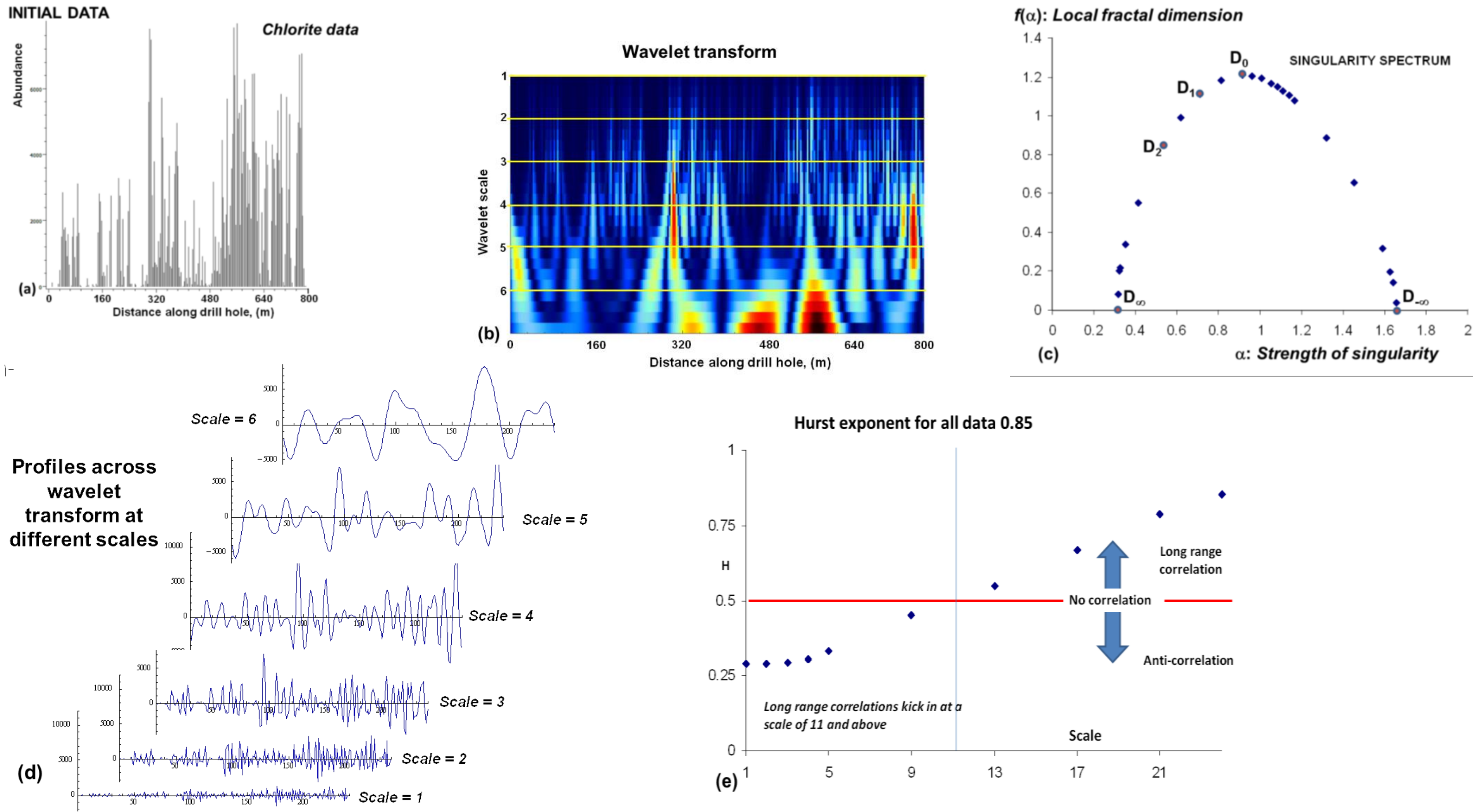
spatial attractors derived through singular value decomposition.



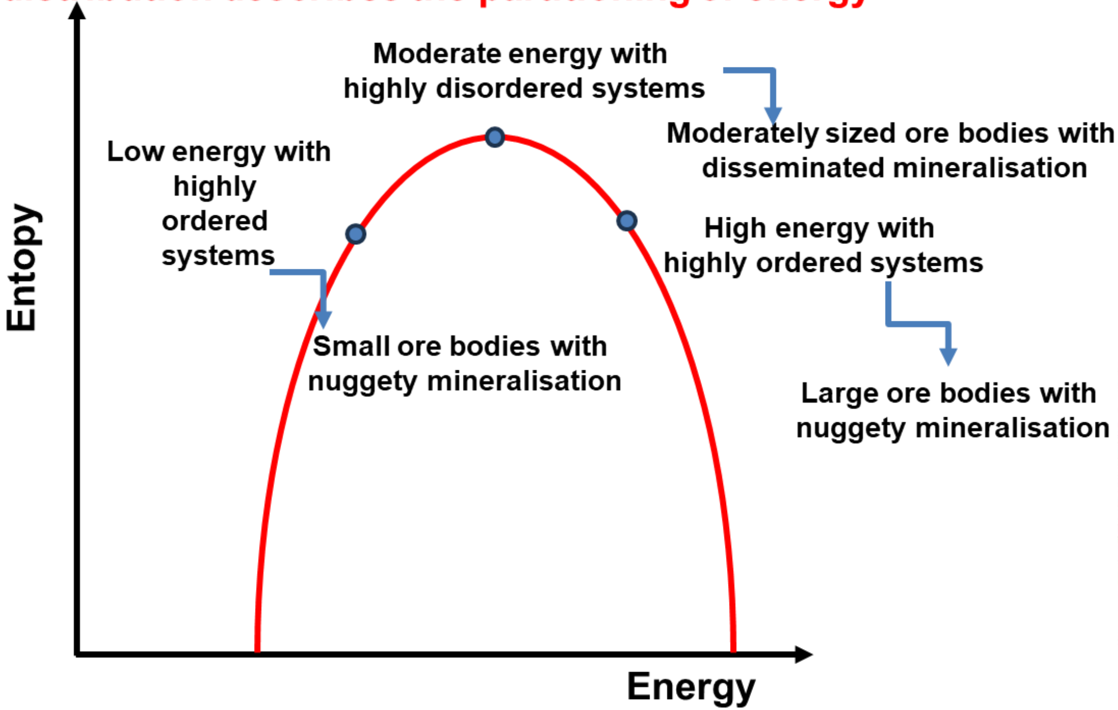
The similarity of the attractors for various ore bodies highlights

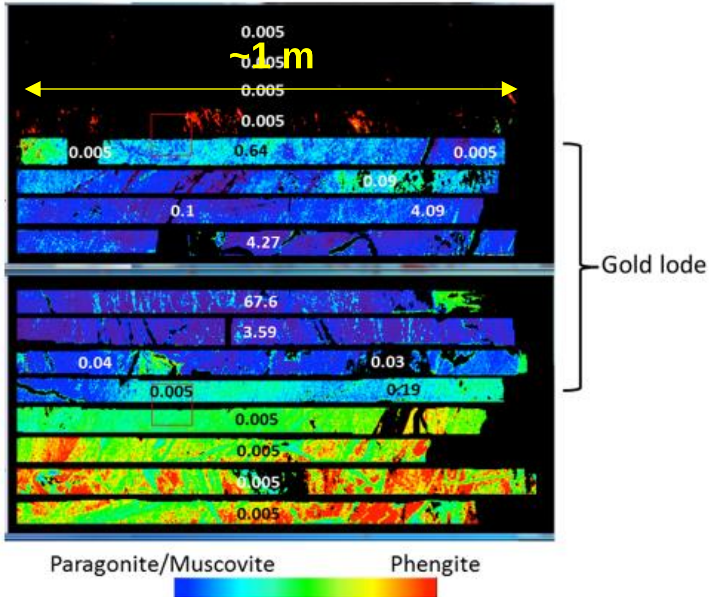
- that similar physical and chemical processes operate in all ore bodies and
- reinforces the suggestion that ore bodies differ in the details of the energy/fluid supply processes together with those of the dissipative mechanisms.

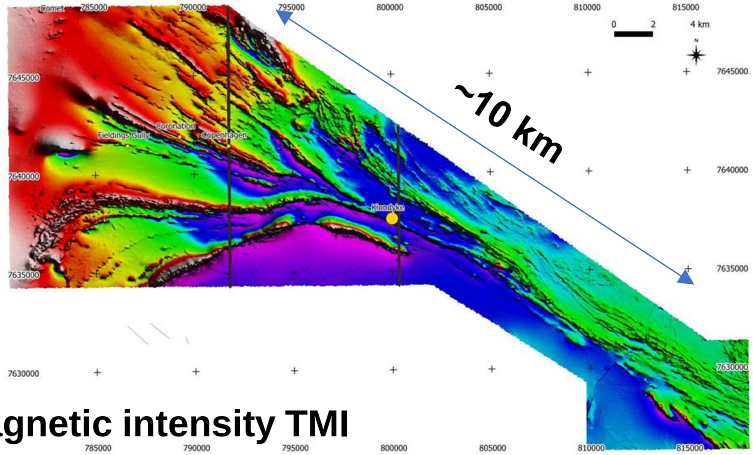
Workflow in establishing long range correlations



From a thermodynamic point of view the multifractal distribution describes the partitioning of energy



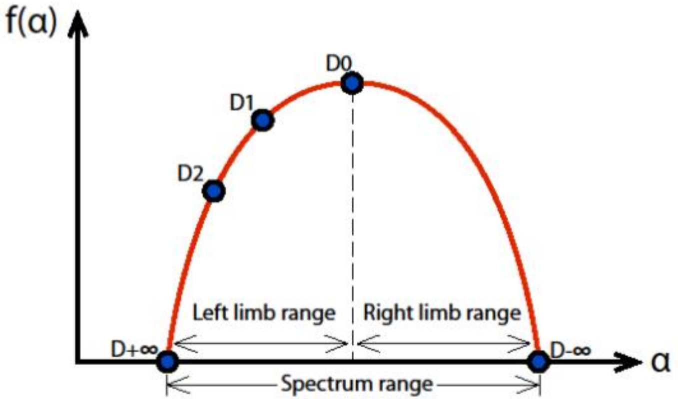




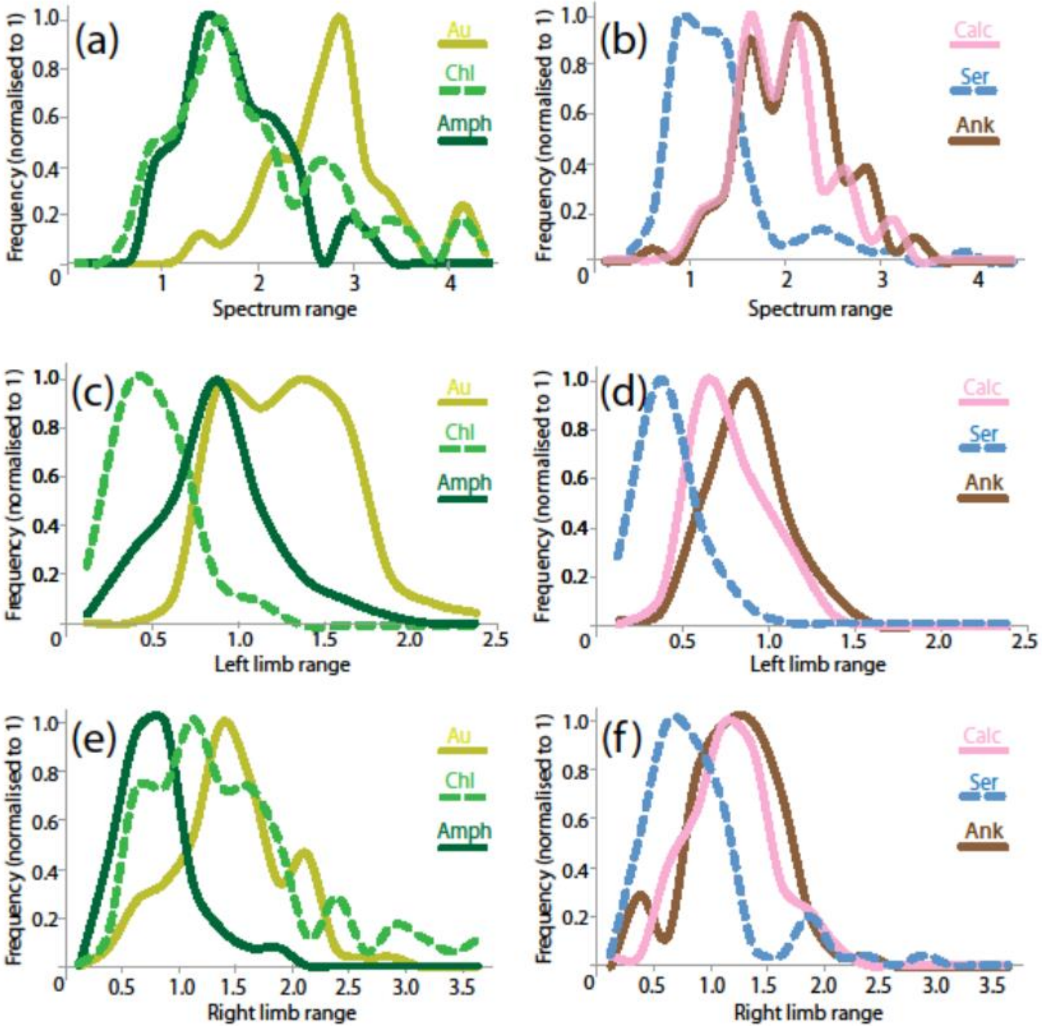
total magnetic intensity TMI

The tools of nonlinear dynamics

Drill core



The width of the spectrum increases as the fluctuations increase



Wavelet-based analysis of routinely acquired hyperspectral reflectance signals is demonstrated to be effective for quantifying the dynamical organization of down-hole primary mineralization, host rock alteration, and vein and breccia infill mineralogy.

Munro et al. 2017 Geol. Soc. Lond. Spec. Pub.

Geophysical data for metamorphosed areas

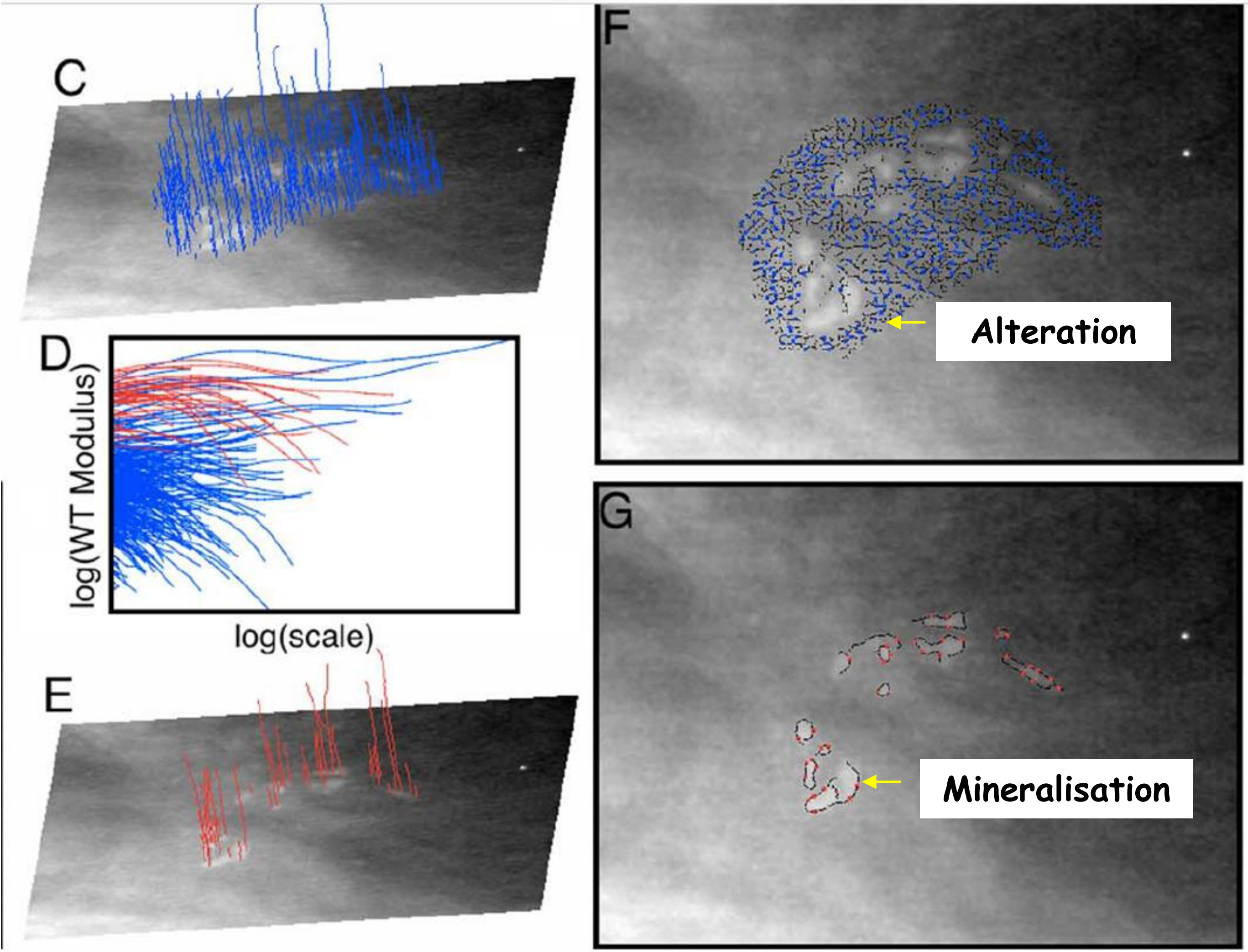
The microstructural arrangement of the minerals responsible for the magnetism of the rock arises from the physical processes and chemical reactions that occurred during metamorphism.

Hence the microstructure at each point reflects the processes that operated.

The magnetic properties constitute part of a nonlinear dynamical system.

Thus Takens' theorem and all the other properties of nonlinear systems apply.

This is the same as saying that the microstructure of a deformed metal that has undergone phase transitions reflects the nonlinear coupled deformation/chemical reactions that produce the elastic and plastic properties of the metal.

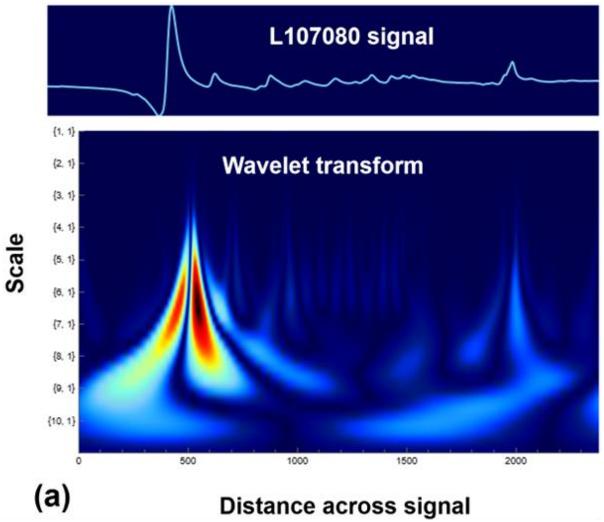


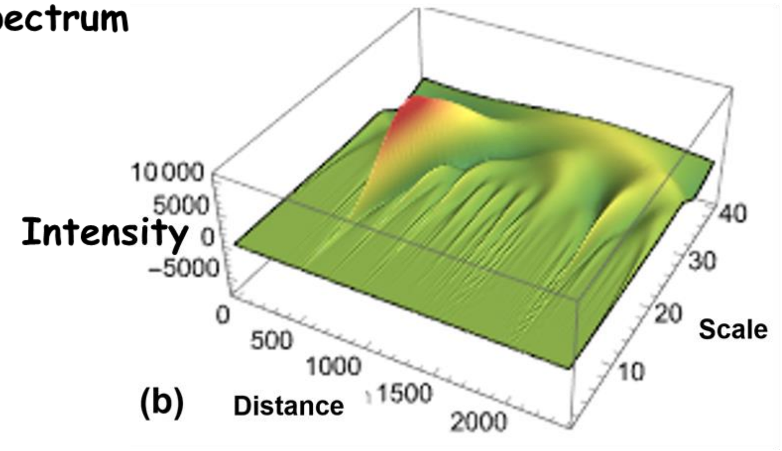
Delineation of regions with different multifractal characteristics using wavelet transforms

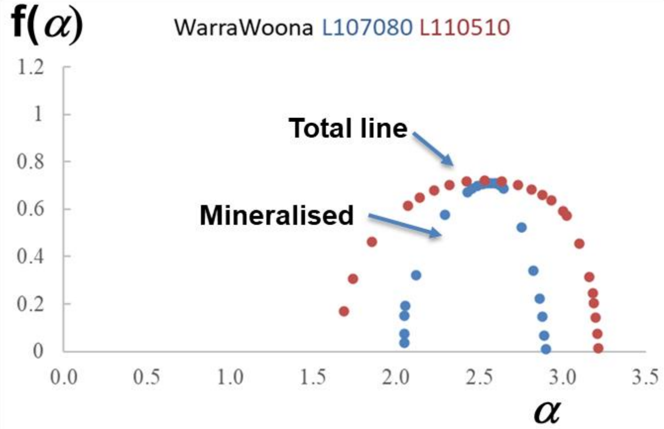
Aeromagnetics

3D image of wavelet transform of L107080 flight line

Wavelet analysis of multifractal spectrum





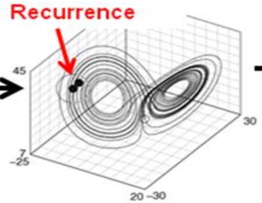


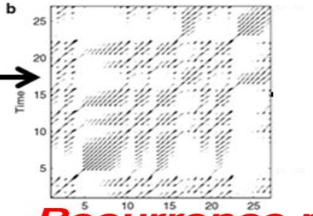
Recurrence is a fundamental characteristic of many dynamical systems and was introduced by Poincaré in 1890.

An important concept in nonlinear analysis is the recurrence plot; this contains all the information that defines the underlying dynamics of a system.

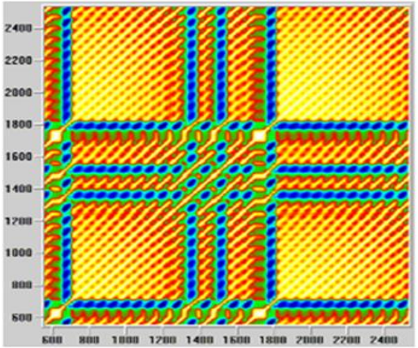
Coupled sets of nonlinear processes leads to chaotic behaviour in space and time

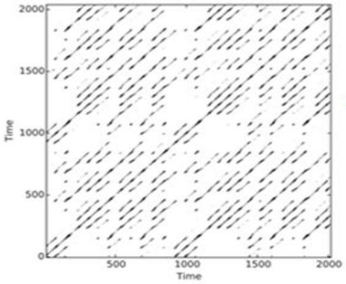
The behaviour of such systems can be represented by an attractor that is a plot of all possible states of the system



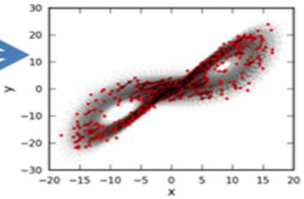


Recurrence plot





Lengths of diagonal lines is a measure of predictability



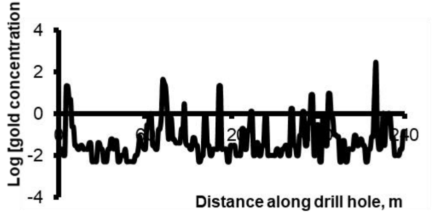
The recurrence plot can be converted to a recurrence network that mimics the attractor for the system

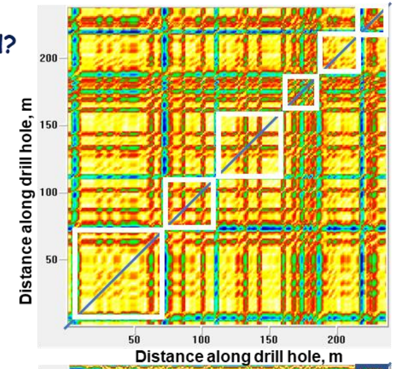
A recurrence plot determines the times (or locations for a spatially patterned signal) at which a trajectory in phase space visits roughly the same area in that phase space.

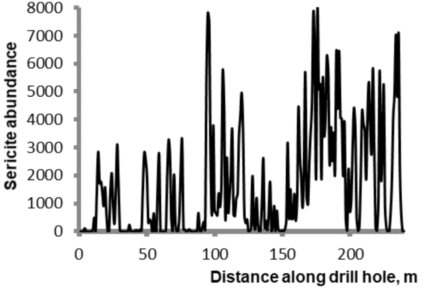
Gold & alteration distribution from an orogenic gold deposit in the Yilgarn of Western Australia

What about correlations with gold?

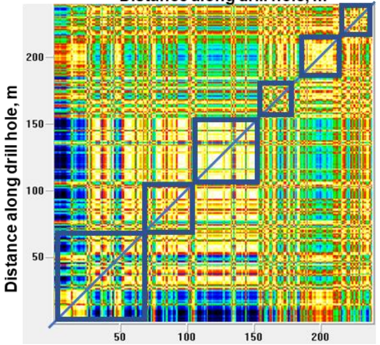
Gold concentration along a drill hole





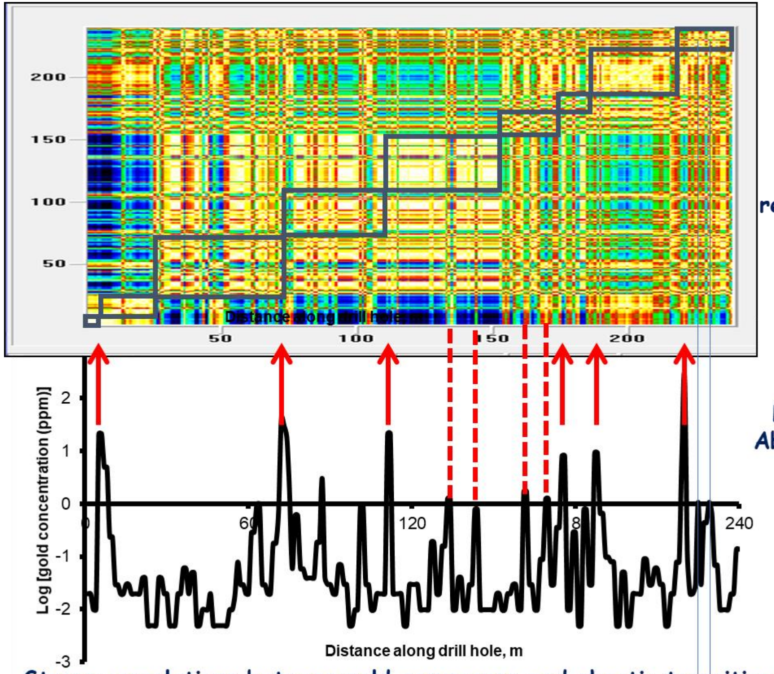


Sericite abundance along a drill hole



Quantitative measures reveal otherwise undetected correlations between mineralisation and alteration.

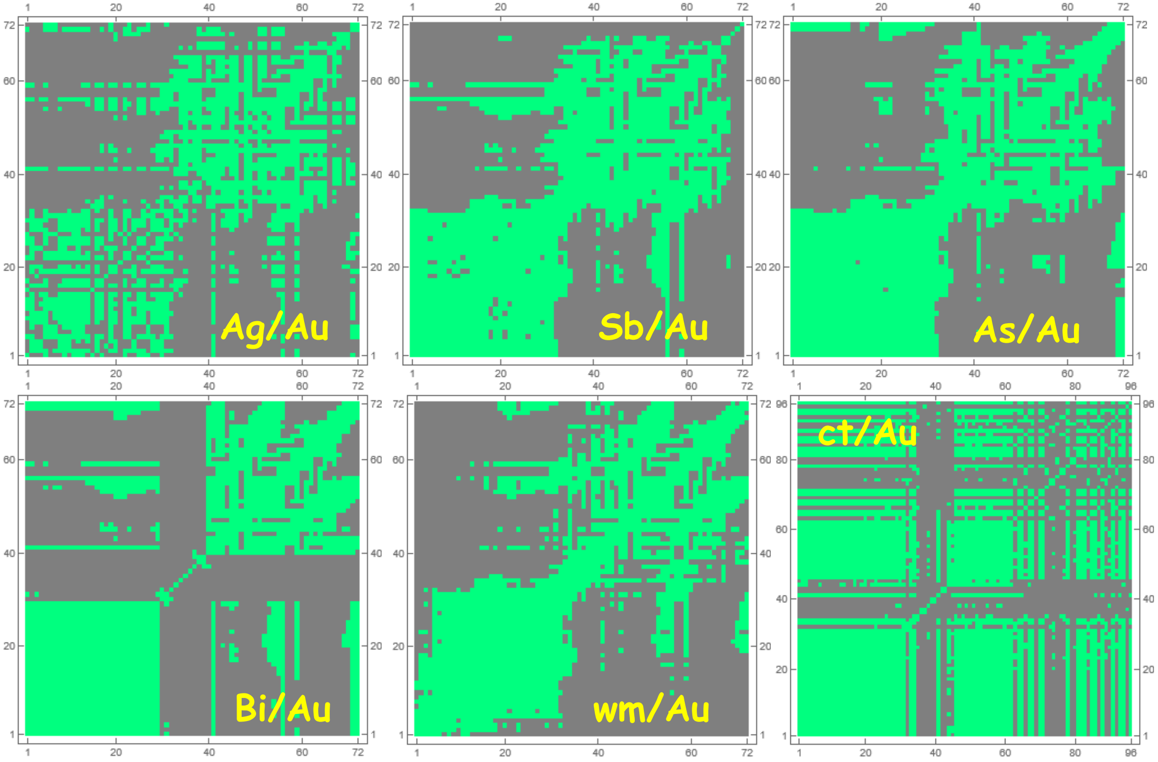
Results enable the mineral reactions and processes responsible for mineralisation to be constrained together with nonlinear prediction of gold grade.



Sericite recurrence plot

Log(gold Abundance) plot

Strong correlations between gold occurrence and chaotic transitions in sericite



Joint recurrence plots

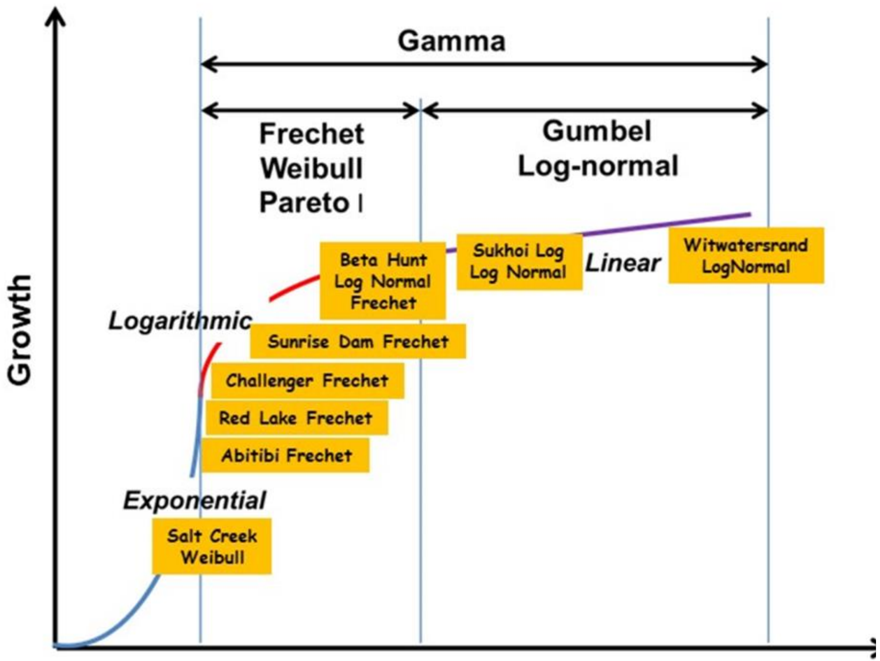
(a) Ag/Au
(b) Sb/Au
(c) As/Au
(d) Bi/Au
(e) White mica/Au
(f) ct/Au

Joint recurrence analysis reveals that all parts of the system are part of the same dynamical attractor and hence parts of the same physical-chemical system.

This is true even though classical statistics says there is no correlation between these parts.

The tools of nonlinear dynamics

Growth and probability distributions



- **Log Normal Distribution:** Typically associated with very large mineral deposits with an extensive potential range of mineralisation.
  - Implies minimal heat loss and a prolonged mineralisation process, with flow rates beginning slowly and continuing to accelerate.

Dateline provided drill hole data from four holes. Ord & Hobbs had no role in selecting the drill holes. Two of the drill holes (CM23 -06 & CM23-08) were from the South breccia pipe and were completed by Dateline Resources Limited and two were historic drill holes from the north breccia pipe that were drilled by BP in the 1980's (CP-59 and CP-89). All four drill holes were analysed as fitting a Log Normal distribution.

Alison Ord commented *"The data for all four drill holes are consistent with a Log Normal distribution"*

ASX Release
13 February 2024

DATELINE RESOURCES LIMITED

(ACN 149 105 653)
ASX Code: DTR

CAPITAL STRUCTURE
Share Price (12/02/24) $0.011
Shares on issue 1.3 billion
Market Cap $14 million

MAJOR SHAREHOLDERS

DATELINE RESOURCES

WIDE HIGH-GRADE GOLD AT COLOSSEUM
70.1 metres at 6.53g/t Au

Highlights

- **70.1m @ 6.53g/t Au** in drill hole CM23-14 Inc. **25.9m @ 15.31g/t Au.**
- Consistency of assay results for drill hole CM23-14 suggests stability in the geologic structure.
- Multi-element geochemistry analysis of drill hole CM23-14 is underway.
- **New hole,** CM24-15, is almost complete and will test the southern extension of the sedimentary unit. **Results are expected in March 2024.**
- Mineral Dynamics researchers confirm Colosseum drill hole data fits a Log Normal Energy distribution.

Mineral Dynamics – Ord & Hobbs Research

Ground-breaking research out of Western Australia, spearheaded by Mineral Dynamics, Dr Alison Ord and Dr Bruce Hobbs, can **assist mineral exploration by focusing on the thermodynamics of hydrothermal mineral systems**, particularly gold deposits.

Their work challenges traditional chemical-centric approaches, emphasising the significance of oscillating heat flow patterns as crucial indicators for predicting gold deposit size.

Using data from established mining operations, they provide tools for explorers to better understand mineral systems by using established cumulative probability distribution functions to indicate the size of the system that created the gold deposit.

Described below are the primary differences between the three main probability distributions that are most common for gold deposit analysis, Weibull, Fréchet and Log Normal:

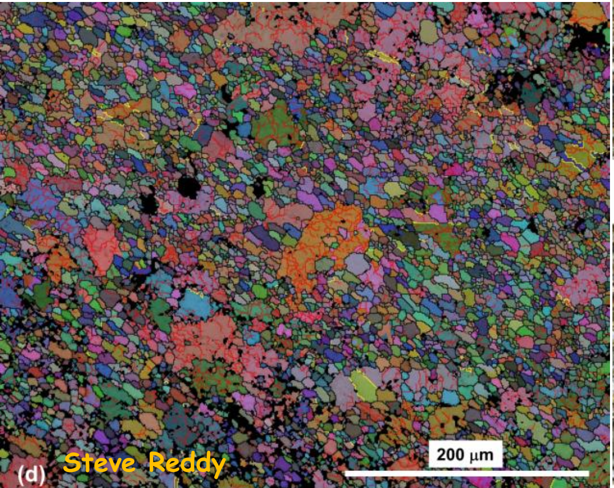
- **Weibull Distribution:** Typically associated with smaller mineral deposits with limited potential range of mineralisation.
  - Indicates rapid heat loss during mineralisation, characterized by a slow birth, quick growth, and quick death of mineralisation flow rates.
- **Fréchet Distribution:** Associated with larger mineral deposits with a broader potential range of mineralisation.
  - Suggests minimal heat loss during mineralisation, showing a stronger beginning and an extended continuation of the flow-mineralising process.

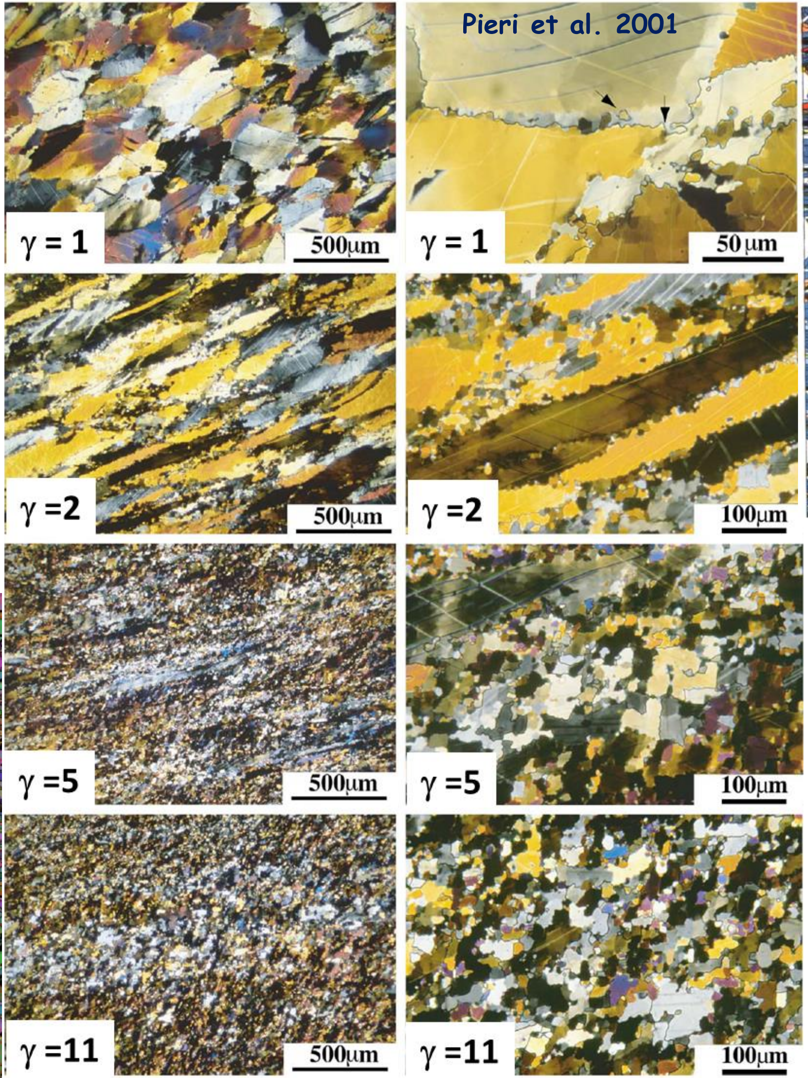
The tools of nonlinear dynamics

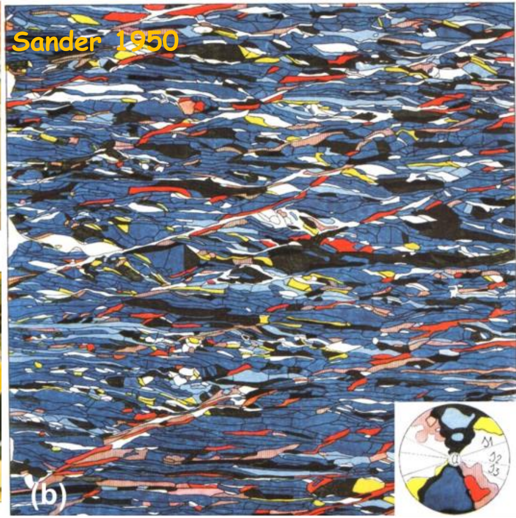
n-point correlation functions

Quantitative measures of & characterisation of microstructure.

1-point correlation functions: volumetric proportions of grains, subgrains, CPO-domains.
2-point correlation functions: grain- and domain-size distributions.



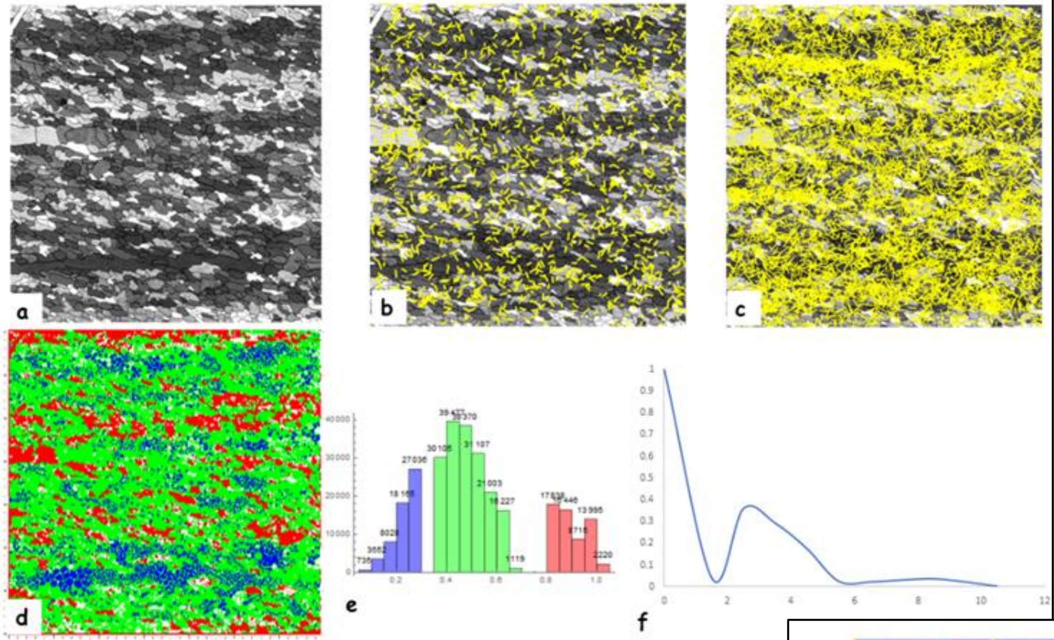




3-point correlation functions: grain and domain shape distributions; anisotropy
4-point correlation functions:
n-point correlation functions

Application to photo-micrographs, EBSD-images & X-ray tomography.

Reconstruction of microstructure.



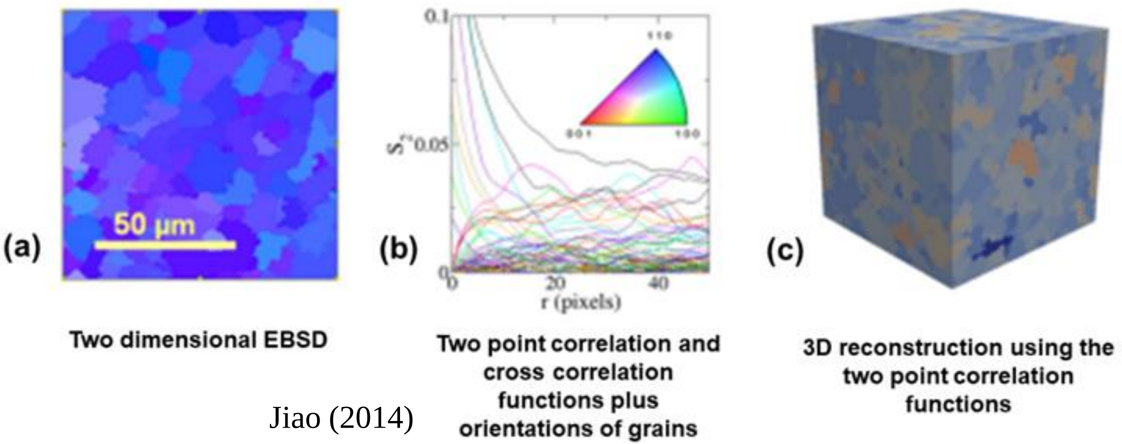
2-point correlation analysis of a deformed quartzite.

(a) Map of c-axis orientations in quartz. (b, c) End-points (heads and tails) of each line are on pixels of similar gray scales/crystal orientations.

(b) Length of line is less than 10 pixels.

(c) Length of line is less than 20 pixels.

(d) Orientations colour-coded according to the histogram in (e). The histogram represents on the x axis, the image value for any point, where black is 0 and white is 1; and on the y axis, the number of points with that particular shade of grey. (e) The two-point correlation function for (c) versus the segment length. The 2-point correlation is the joint volume or probability density for the lines represented by heads and tails randomly placed on similar gray scales/crystal orientations.



Jiao (2014)

The tools of nonlinear dynamics

n-point correlation functions

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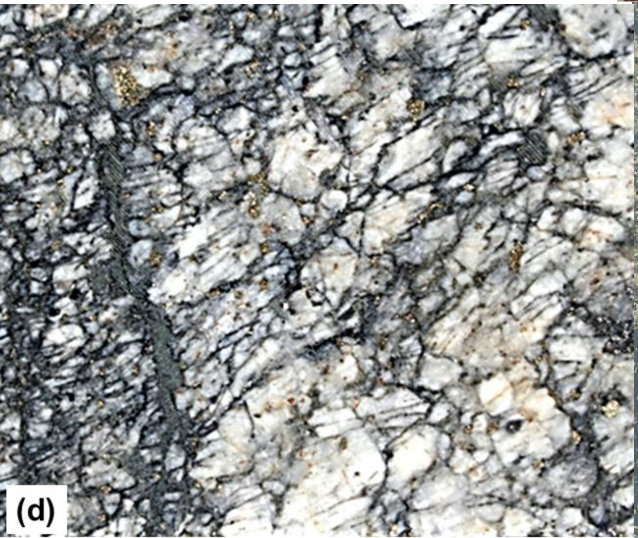
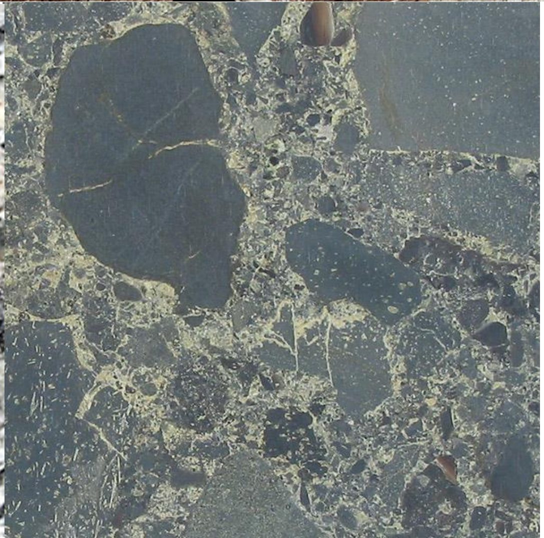
2-point correlation functions: grain- and domain-size distributions.





3-point correlation functions: grain and domain shape distributions; anisotropy
4-point correlation functions: *n*-point correlation functions

Application to photo-micrographs, EBSD-images & X-ray tomography.

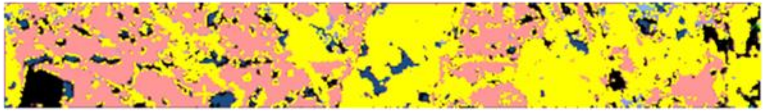
Reconstruction of microstructure.

n-point correlation functions

Analysis for gypsum (deep pink regions)

1 point correlation

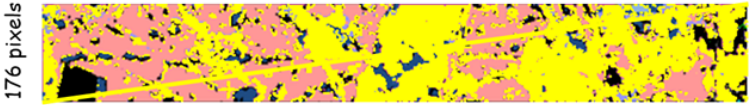
(a) 1254 pixels



(b) 100 000 throws 36 863 Deep pink
Points on deep pink shown in yellow

(cropped) original image in (a), and the one point correlation for deep pink in (b). 36 863 points landed on deep pink out of 100 000 throws. They are shown in yellow in (b).

2 point correlation



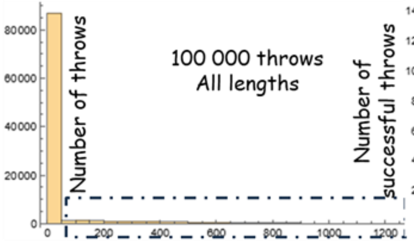
(a) 1254 pixels Diagonal is ~1270 units, used to normalize lengths.

1270

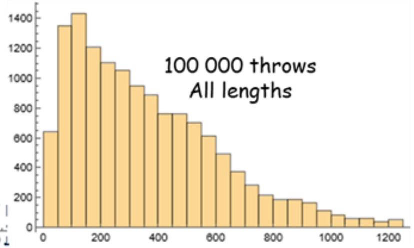
635

159

318



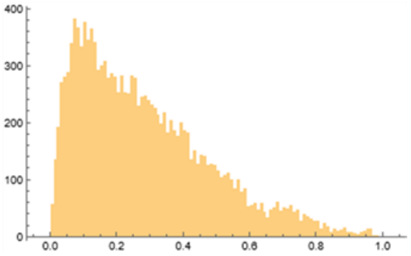
(b) Length of each line



(c) Length of each line

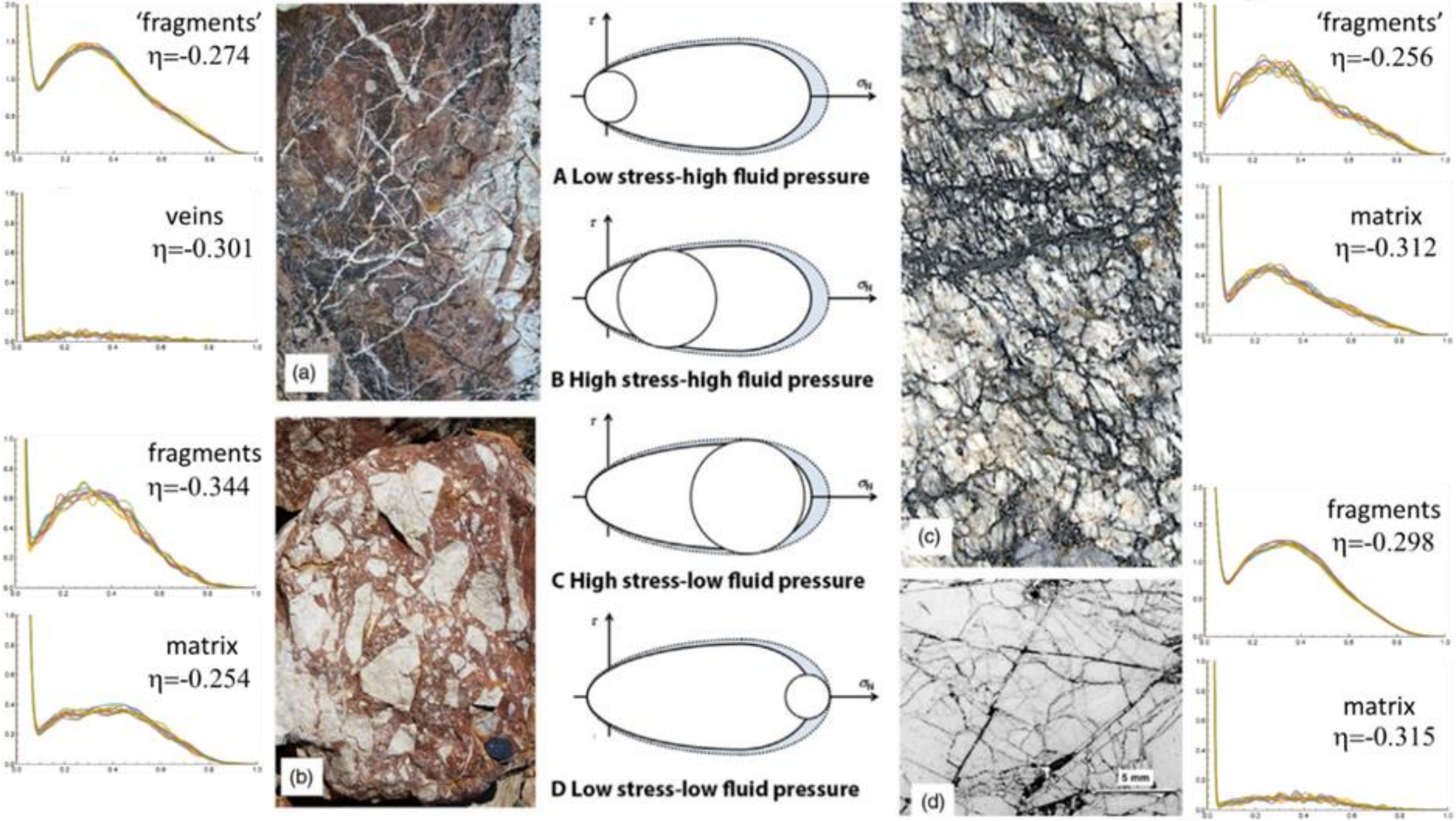
This histogram shows the results of all throws. The two ends of each line are required to lie on deep pink.
The box extending almost to ~90 000 represents the number of times that 2 ends of each line do not fall on the same phase. Note that the maximum distance allowed is ~1270.

This histogram shows only the number of times on the y axis that the 2 ends of each line fall on deep pink. Note that the maximum distance allowed is ~1270.



(d) 100 000 throws All lengths
13 962 lines

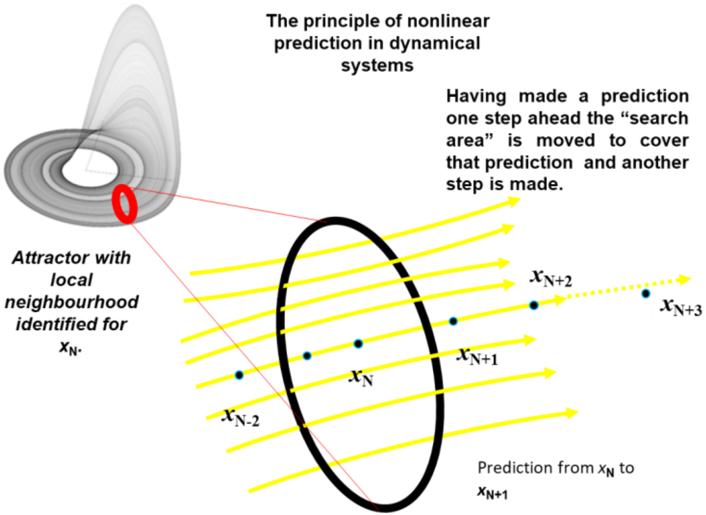
Results for when the two ends of each line are required to lie on deep pink. In this case, the number of lines falls fairly regularly from a peak at about 100 lines (0.1), with the trace of a broad peak centred at about 900 lines (0.7). Unit lengths are shown in black beneath the image in (a).

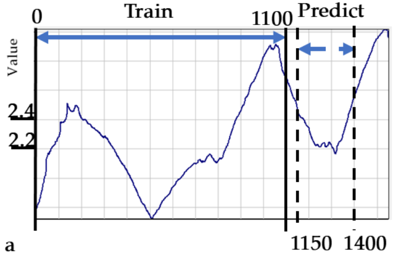


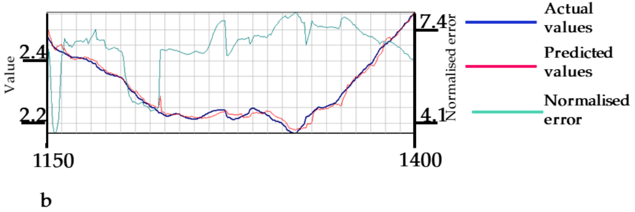
The outer columns of the figure show the probability distribution functions for all lengths for 10 runs of a two point correlation analysis. η is the differential entropy derived from a Gamma2 probability distribution function fitted to the output of such a correlation analysis.

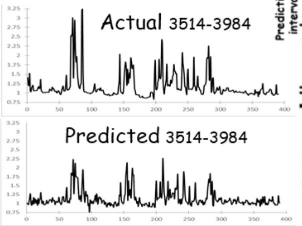
Prediction

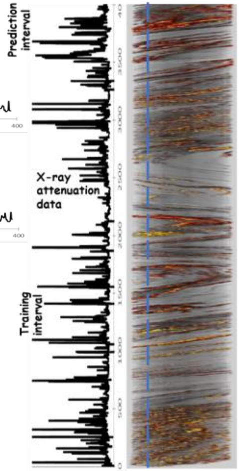
The principle of nonlinear prediction in dynamical systems







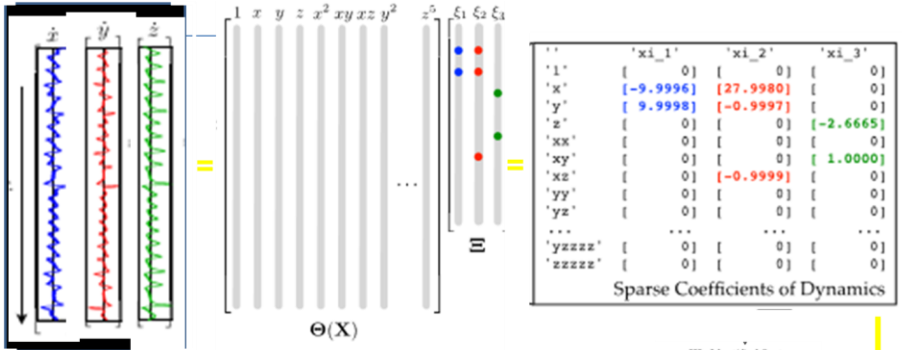




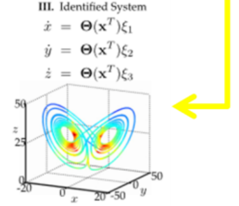
Discovery of physics from data

How purely data driven methods can be used to unravel the dynamic processes involved in the mineralising process.

Parsimonious systems & deriving the underlying equations that describe the processes that produced the data derived directly from the data



''	'xi_1'	'xi_2'	'xi_3'
'1'	[0]	[0]	[0]
'x'	[-9.9996]	[27.9980]	[0]
'y'	[9.9998]	[-0.9997]	[0]
'z'	[0]	[0]	[-2.6665]
'xx'	[0]	[0]	[0]
'xy'	[0]	[0]	[1.0000]
'xz'	[0]	[-0.9999]	[0]
'yy'	[0]	[0]	[0]
'yz'	[0]	[0]	[0]
...	...	...	...
'yzzzz'	[0]	[0]	[0]
'zzzzz'	[0]	[0]	[0]



IDENTIFICATION OF SYSTEM DYNAMICS FROM DATA USING SPARSE REGRESSION

After Brunton et al., 2016

Discovery of physics from data

Still waiting

CONCLUSIONS

What do we learn from all this that we did not know before?

These nonparametric approaches, driven solely by the data, represent entirely new ways of prediction, analysing, interpreting and thinking about geoscientific data.

They offer ways of predicting and inverting structural, geophysical and geochemical data sets with no ambiguity.

They even offer ways of detecting unknown components of a system given only the data with no underlying statistical or model assumptions.

The message is:

Understanding is in the data

NOT in the statistics (kriging, potential field inversion)
which are always ambiguous

Knowledge is in the dynamics

which are derived from nonlinear analysis

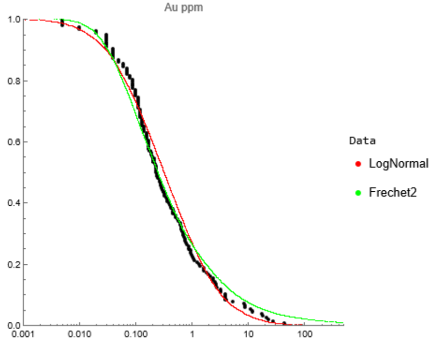
The results of which are sparse, parsimonious and unique.

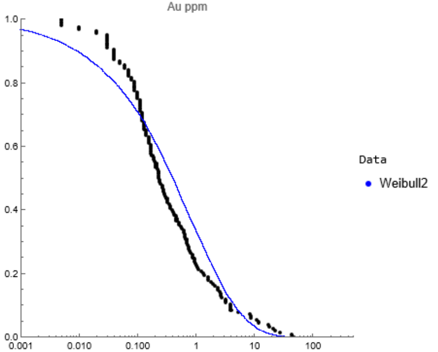
These non-parametric, nonlinear approaches and their rapidly developing generalisations represent the future of data analytics in the geosciences.

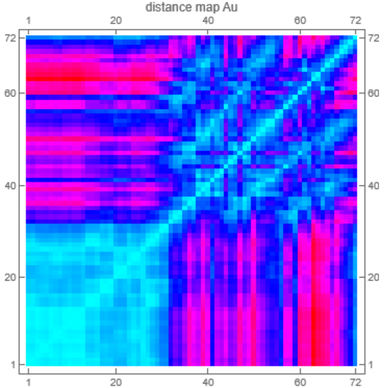
I acknowledge that:

I have an (almost) complete set of software, in the Wolfram Language, Mathematica, designed to apply these tools to questions critical for minerals exploration.

Mathematica provides access to an highly intelligent, creative, and physically and mathematically rigorous team. Using Mathematica provides daily education and learning, bumping into great things such as the The Ultimate Univariate Probability Distribution Explorer blog. The golden attractors visualised are a great success.







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