Mineral Systems as Chemical Reactors with no Mathematics

Alison Ord and Bruce Hobbs

Mineral Dynamics
Fremantle

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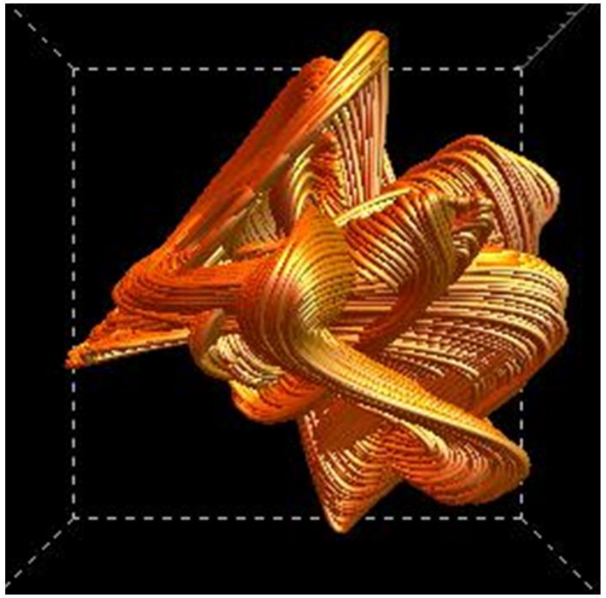
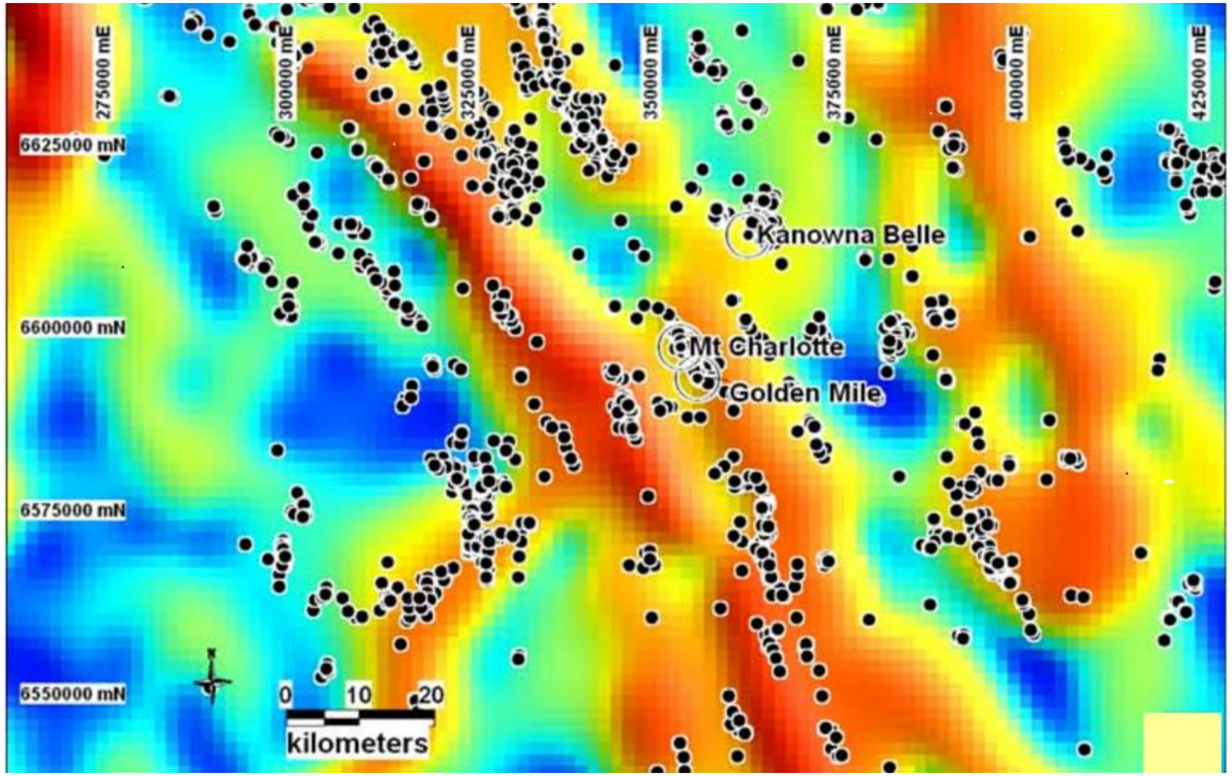
Session 7. 15.30 – 17.00

Application to regional exploration

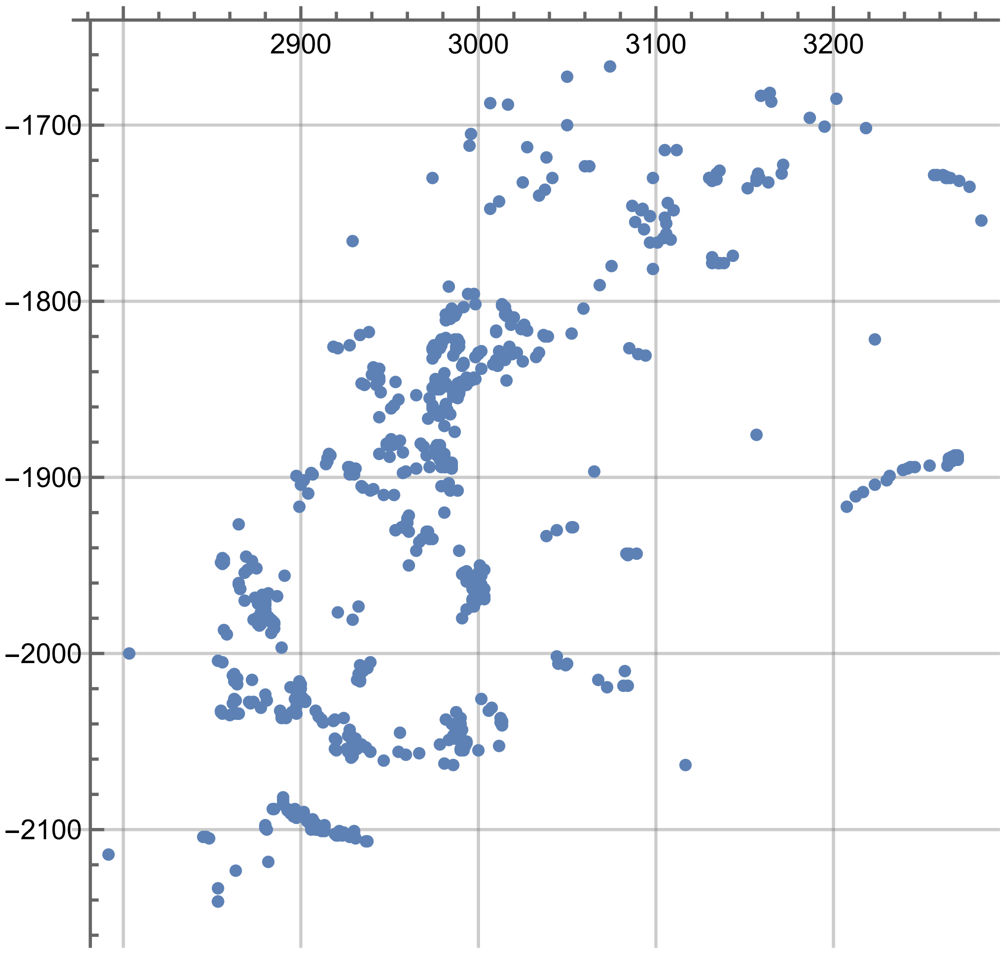


- Spatial distributions of mineralisation
- Regional endowments
- Networks
- Communication over mineralising networks
- Detection of hidden nodes
- Future developments

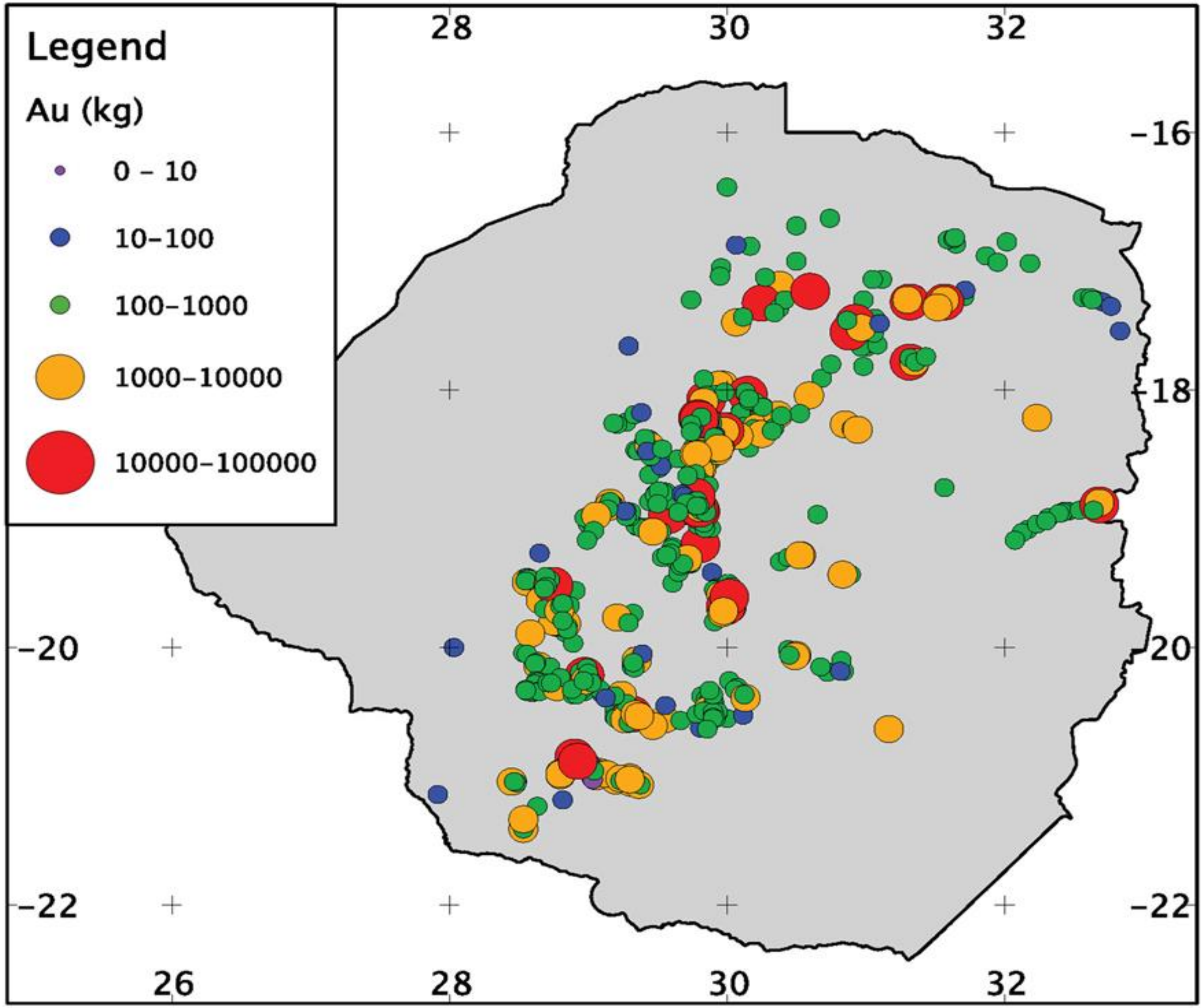
Spatial distribution of orogenic gold deposits



**The question we want to answer is:
How can we tell if there is
a hidden deposit?**



Zimbabwe Gold Deposits



If the network is a nonlinear system we expect every node in the network to be correlated with every other node.

The issue is: What is the form of this correlation?

If I add a new node, does it change the form of this correlation?

The correlation is measured by n-point correlation functions and network metrics

The questions to be explored are:

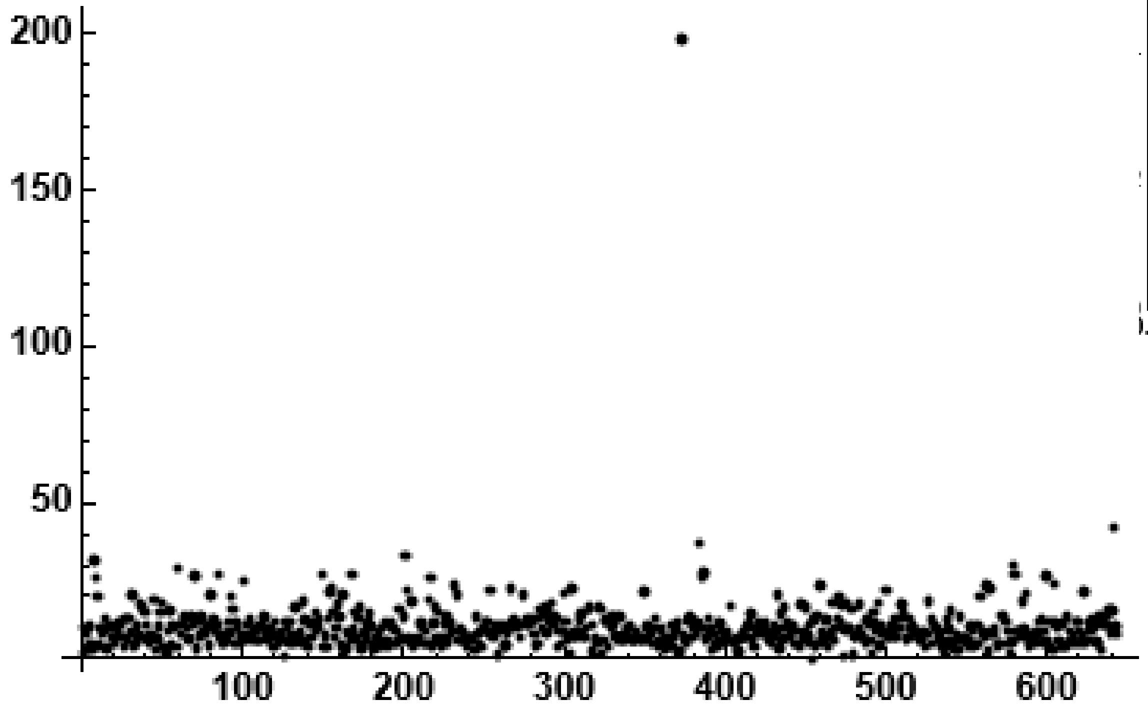
Does the probability distribution for the network change if I add a new node?

Do the metrics of the network change if I add a new node?

Are there hidden nodes?

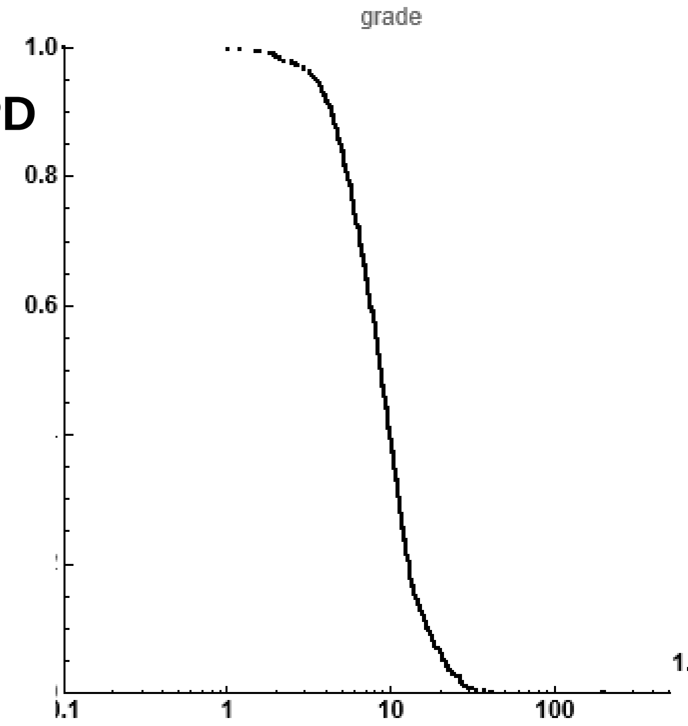
Zimbabwe gold deposits

Grade



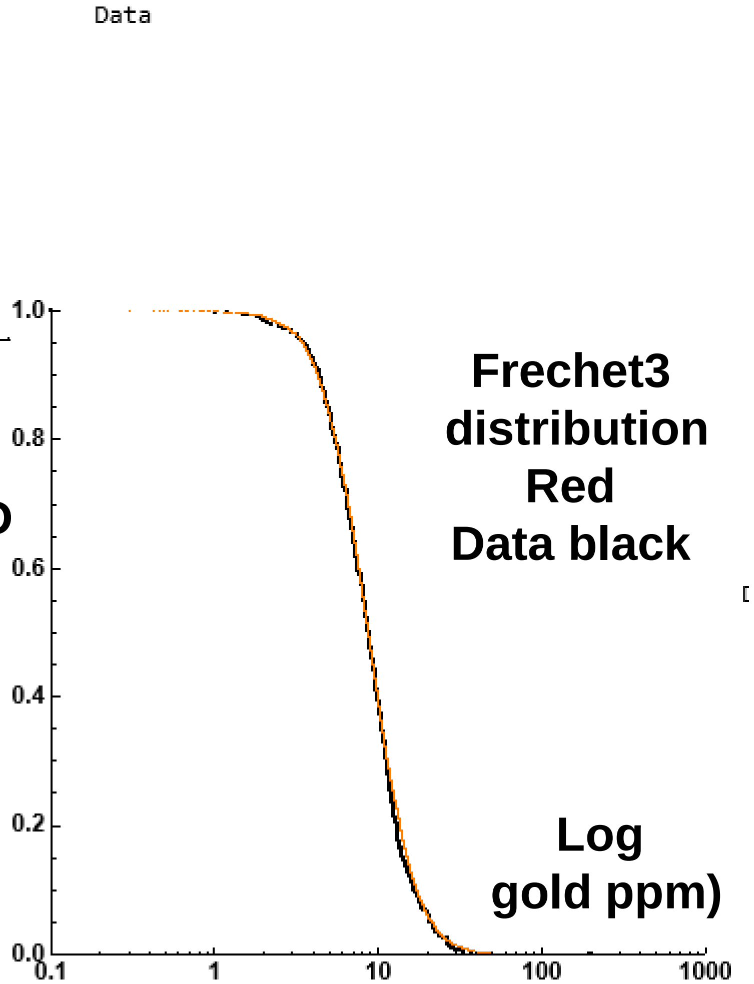
Deposit

1-CPD



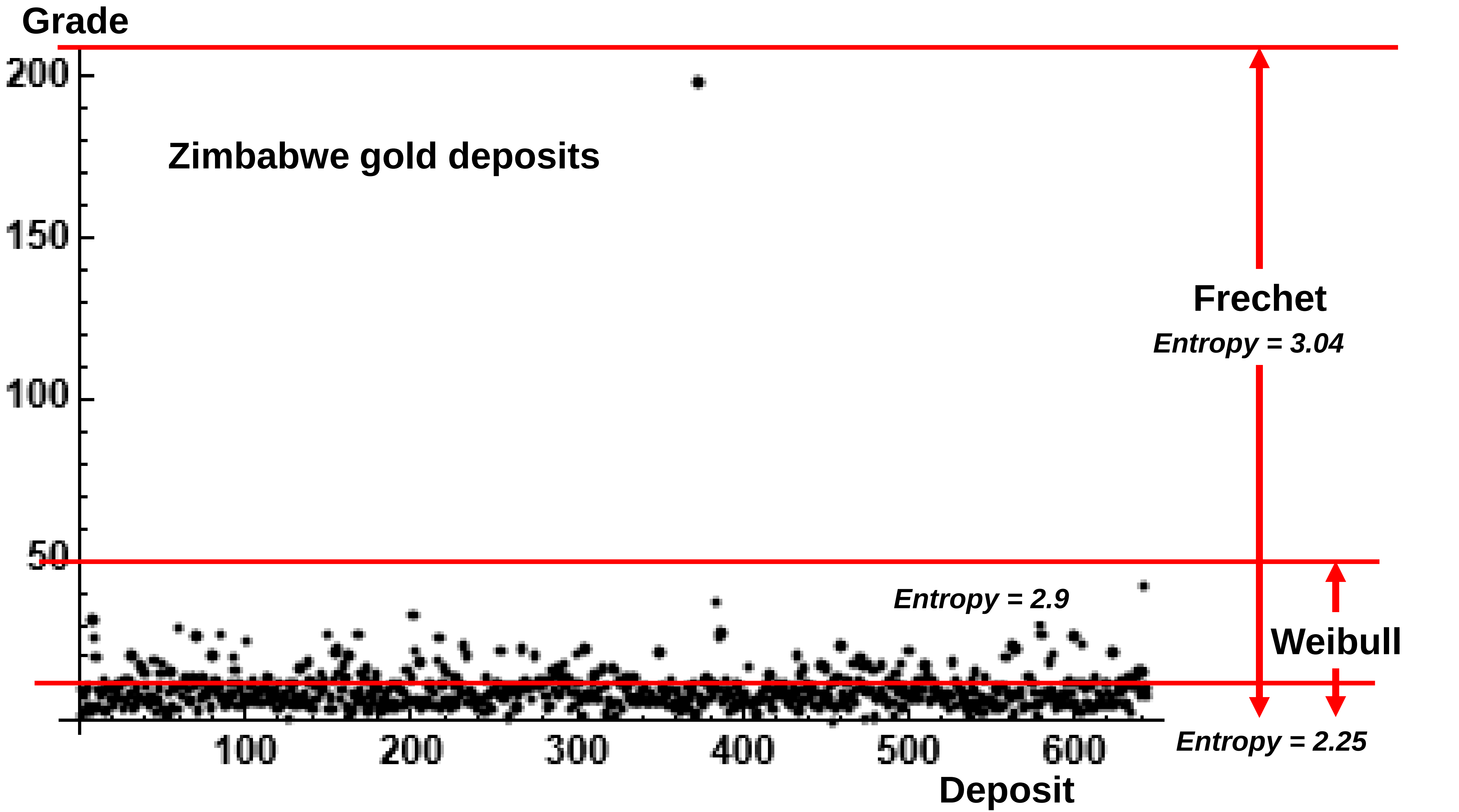
Log (gold ppm)

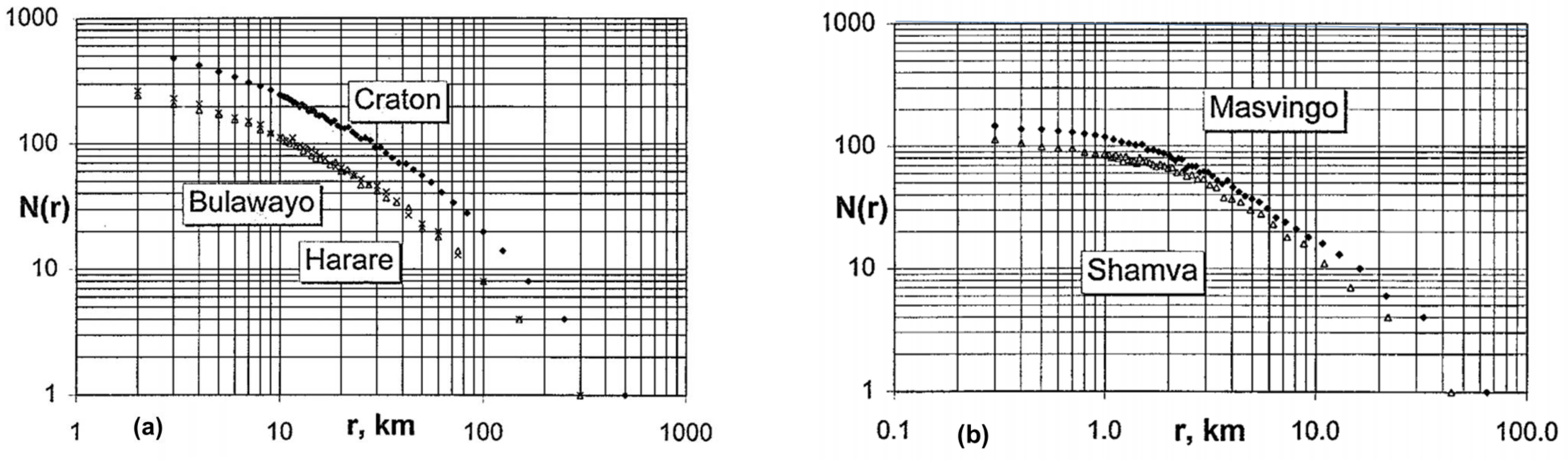
1-CPD



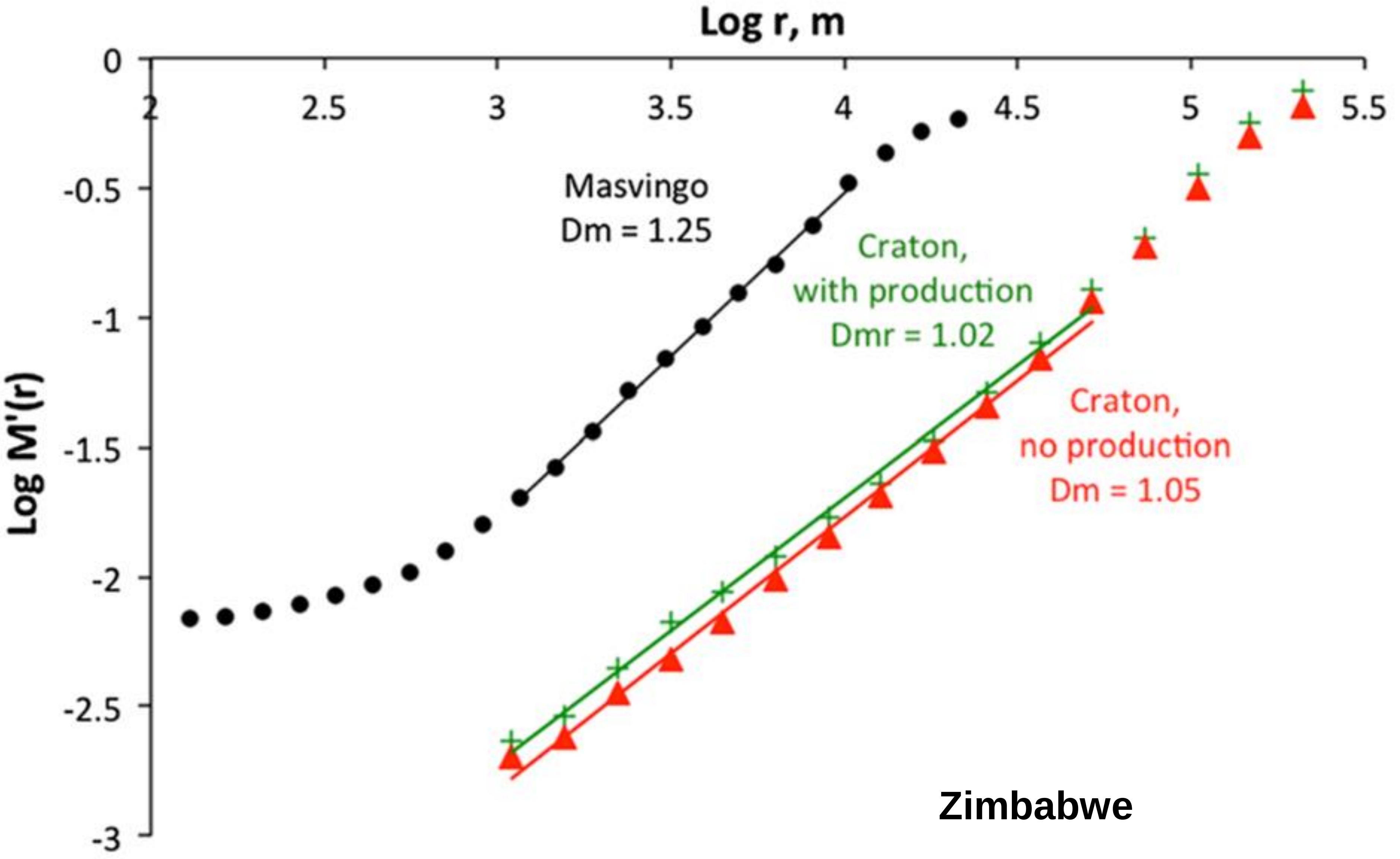
Frechet3 distribution Red
Data black

Log
gold ppm)


Grade
200
150
100
50
Zimbabwe gold deposits
Frechet
Entropy = 3.04
Entropy = 2.9
Weibull
Entropy = 2.25
100
200
300
400
500
600
Deposit



So called "fractal" distributions Zimbabwe. Obtained by box counting.


Log r, m
0
2
2.5
3
3.5
4
4.5
5
5.5
-0.5
-1
-1.5
-2
-2.5
-3
Log M'(r)
Masvingo
Dm = 1.25
Craton,
with production
Dmr = 1.02
Craton,
no production
Dm = 1.05

Zimbabwe

In fact, the box counting procedure is a way of conducting a nearest neighbour distribution

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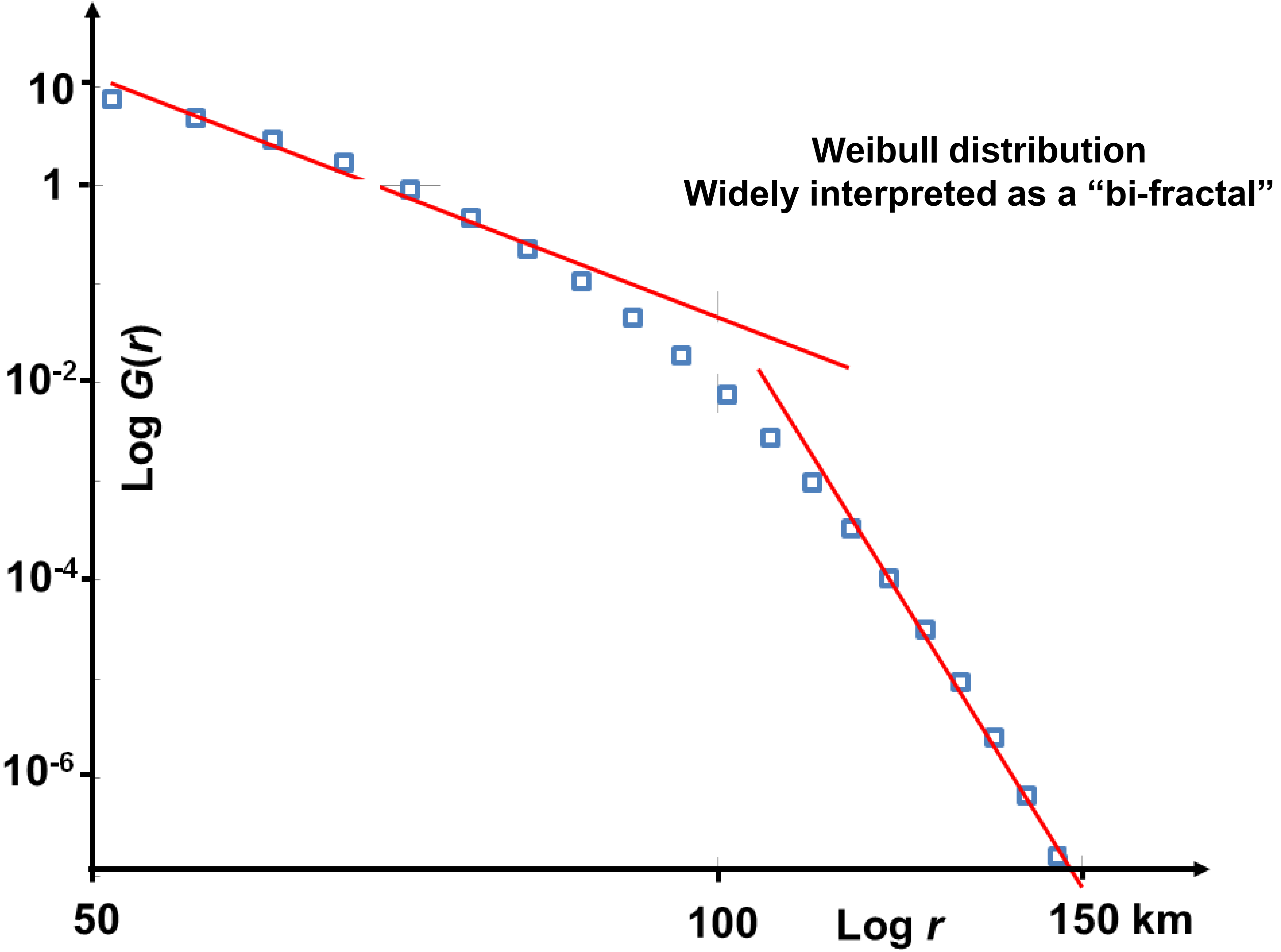
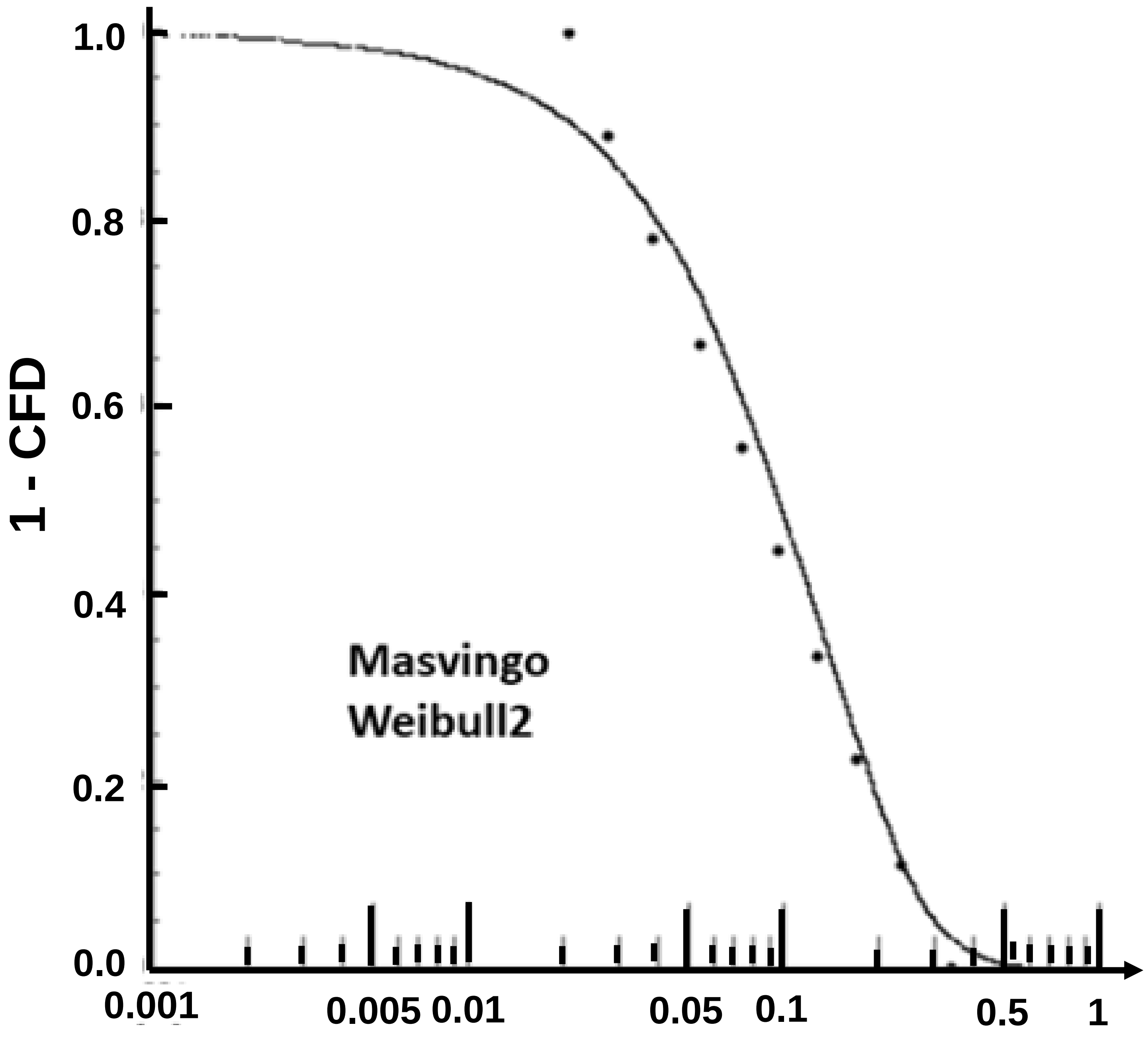
The spatial distributions of mineralisation

Bruce E. Hobbs [a,b], Alison Ord [a,*], Thomas Blenkinsop [c]

This is always a Weibull distribution independently of the underlying spatial distribution

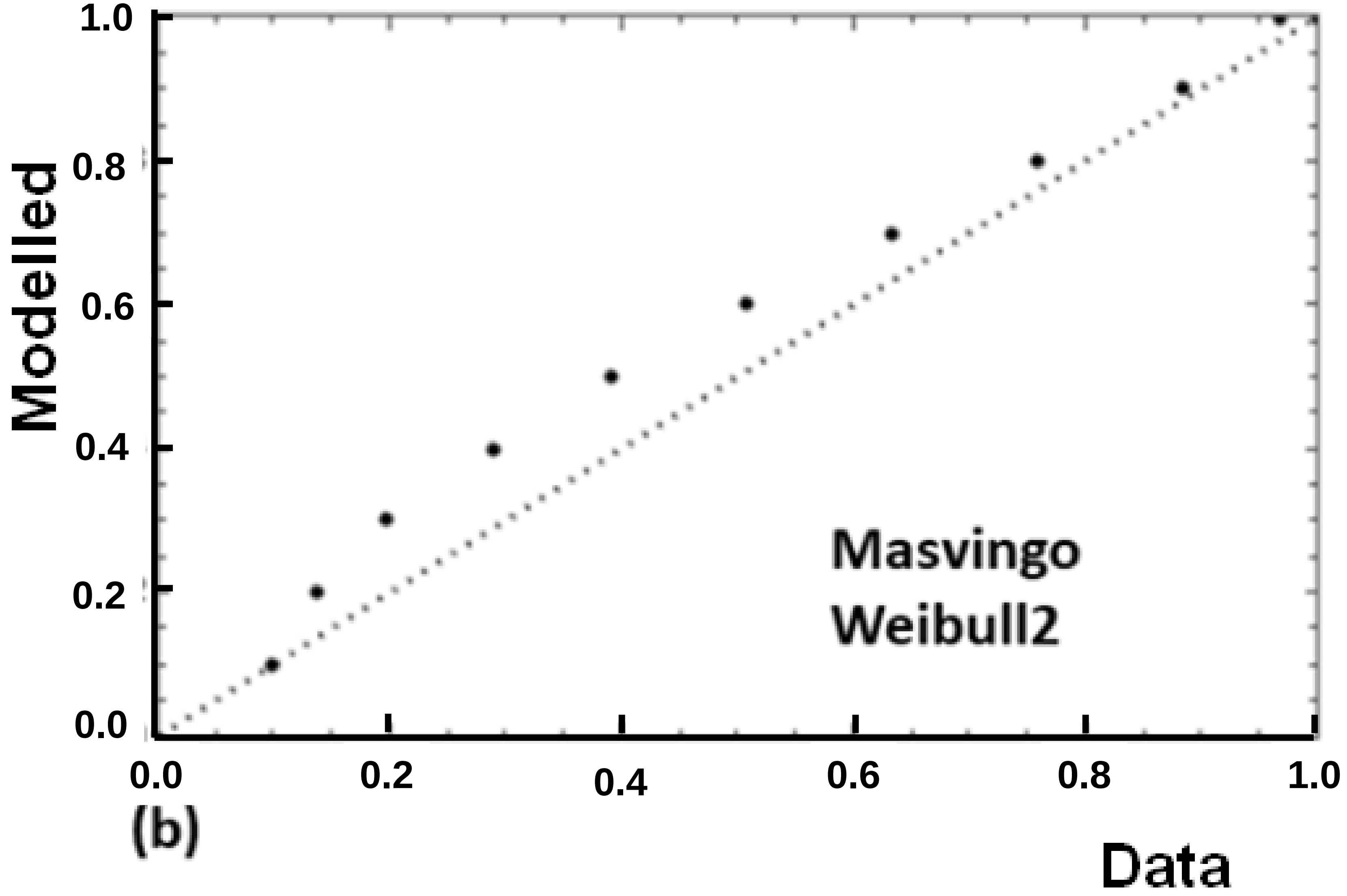


Weibull distribution
Widely interpreted as a “bi-fractal”
10
1
10-2
10-4
10-6
Log G(r)
50
100
Log r
150 km

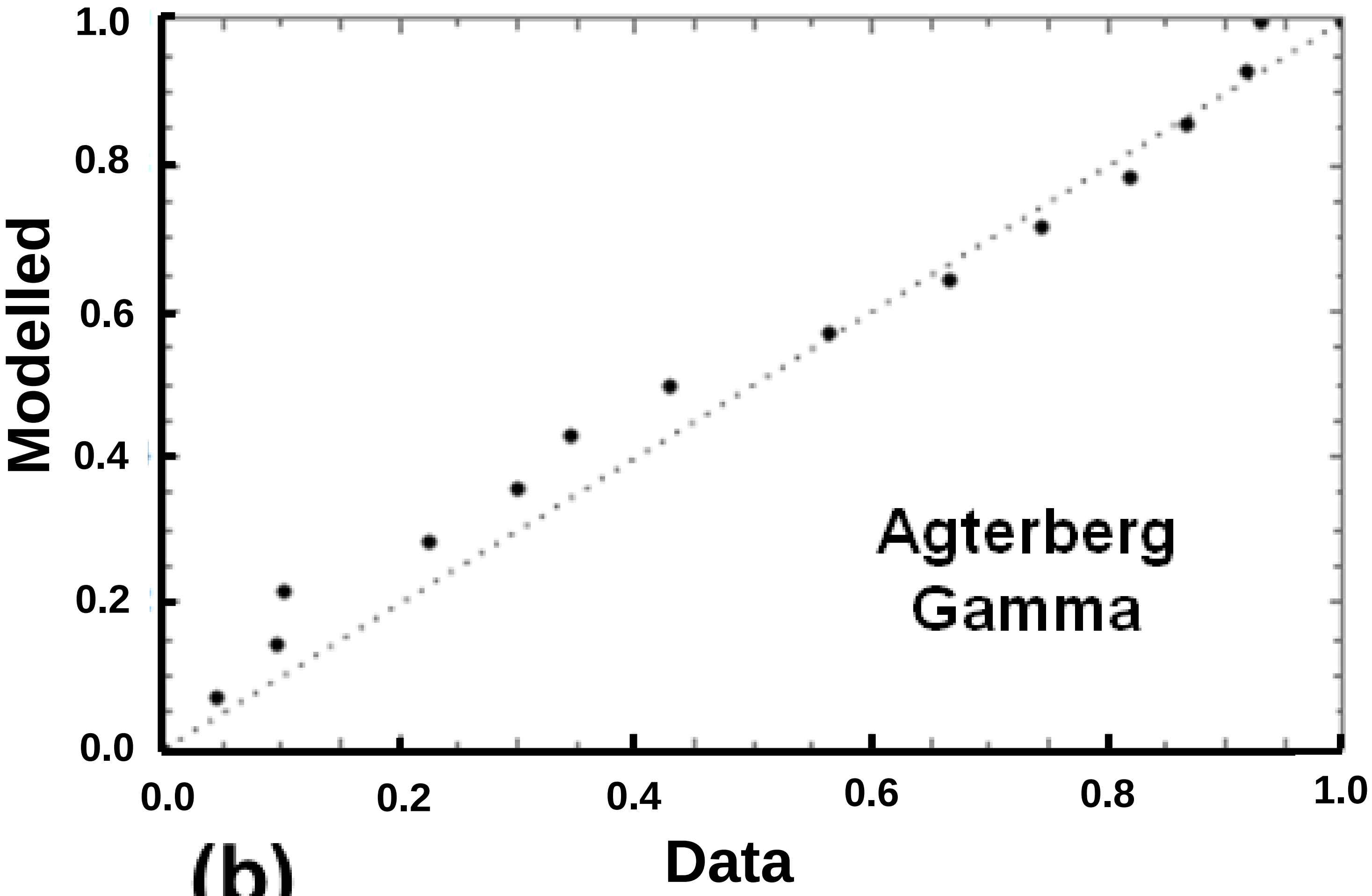


1 - CFD
1.0
0.8
0.6
0.4
0.2
0.0
Masvingo
Weibull2
0.001
0.005
0.01
0.05
0.1
0.5
1

(a)

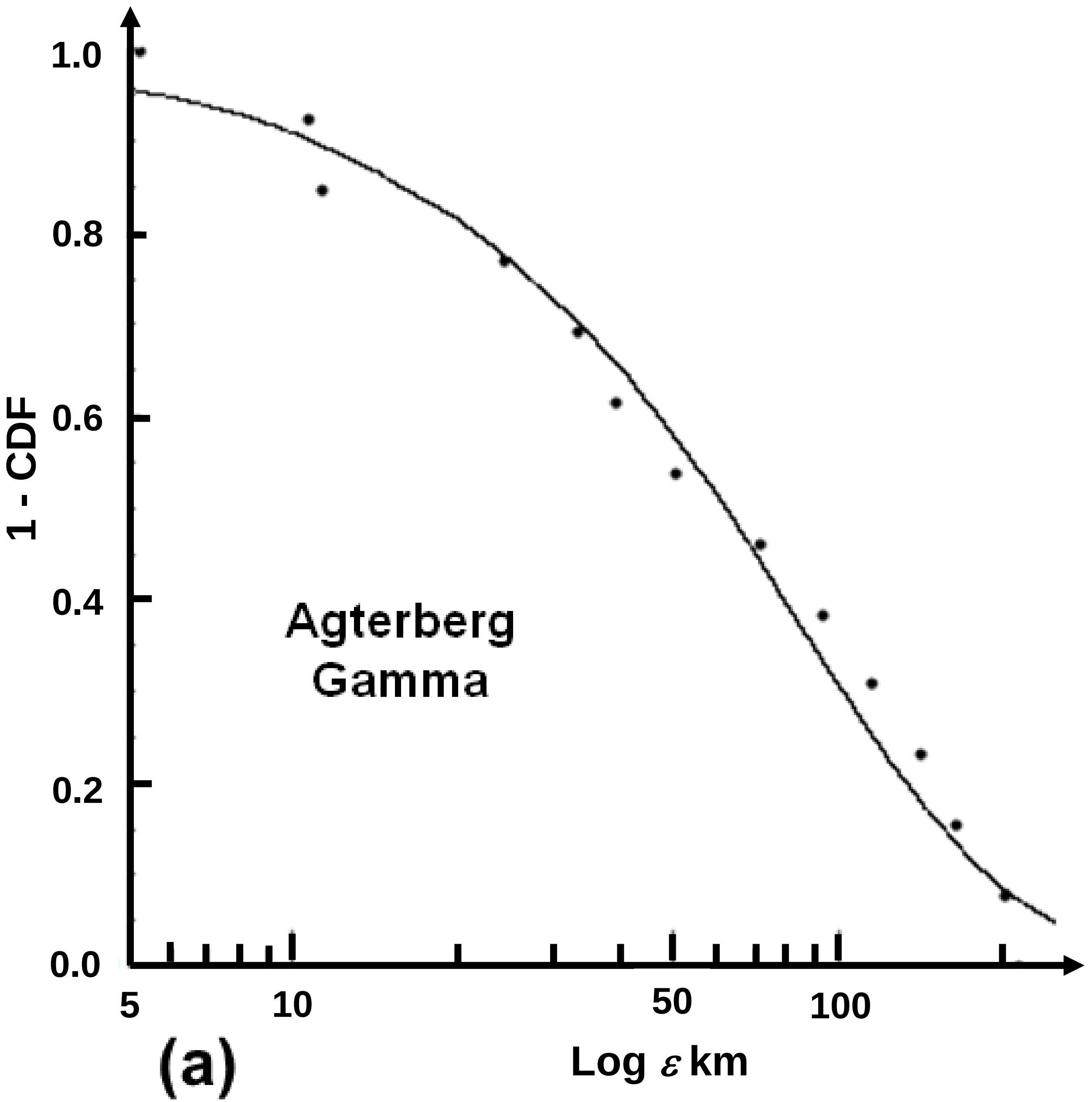


Modelled
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Masvingo
Weibull2
(b)
Data



1.0
0.8
0.6
0.4
0.2
0.0
Modelled
Agterberg
Gamma
0.0
0.2
0.4
0.6
0.8
1.0
Data

(b)



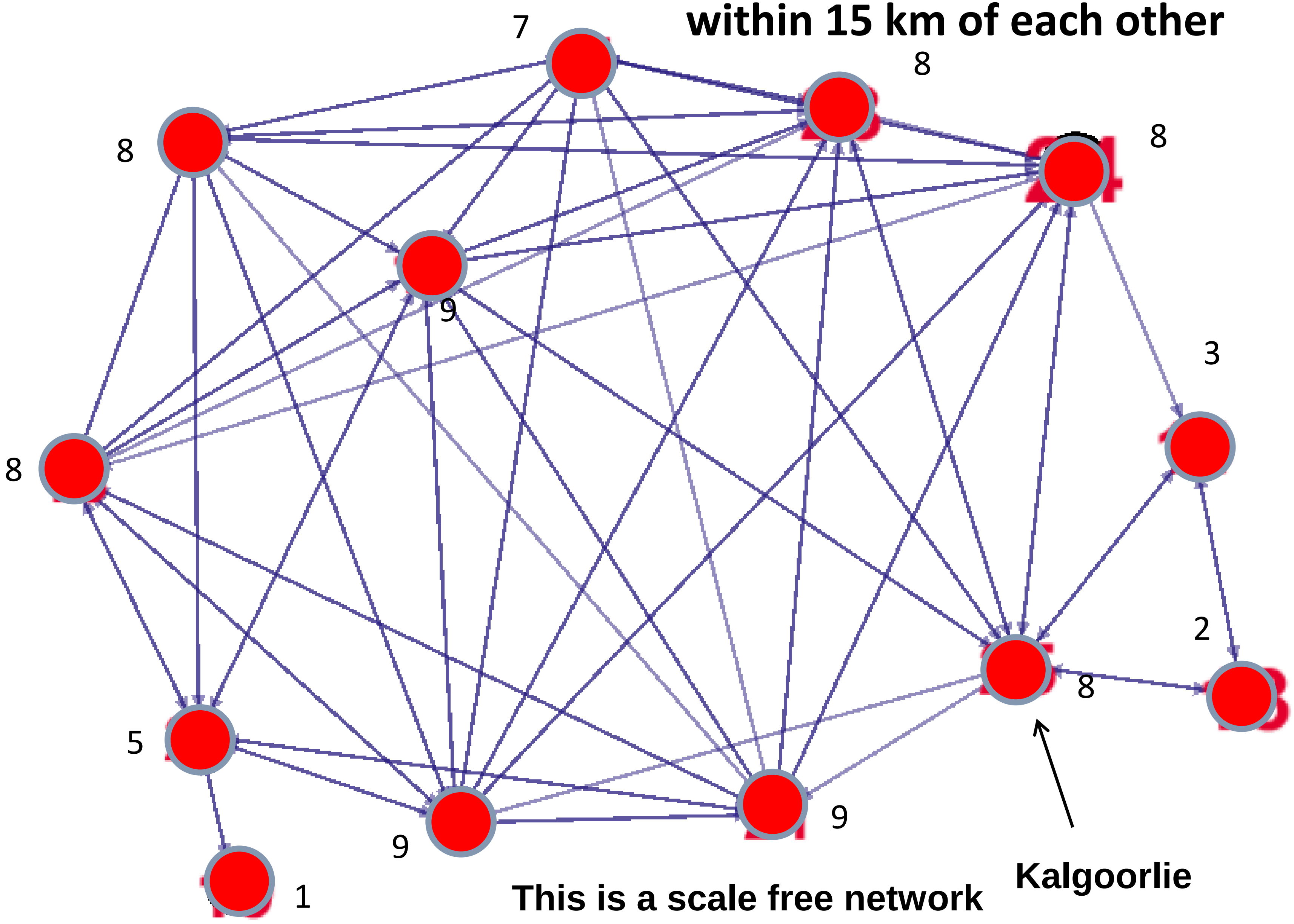
1.0
0.8
0.6
0.4
0.2
0.0
1 - CDF
Agterberg
Gamma
5
10
50
100
Log ε km
(a)

The issue is that since a box count always produces a Weibull distribution,
We have no understanding of what kind of distribution defines
the regional distribution of mineralisation anywhere.

We need to turn to other methods of defining regional distributions.

Network science offers a way forward.

Kalgoorlie sub-network. Ore bodies within 15 km of each other

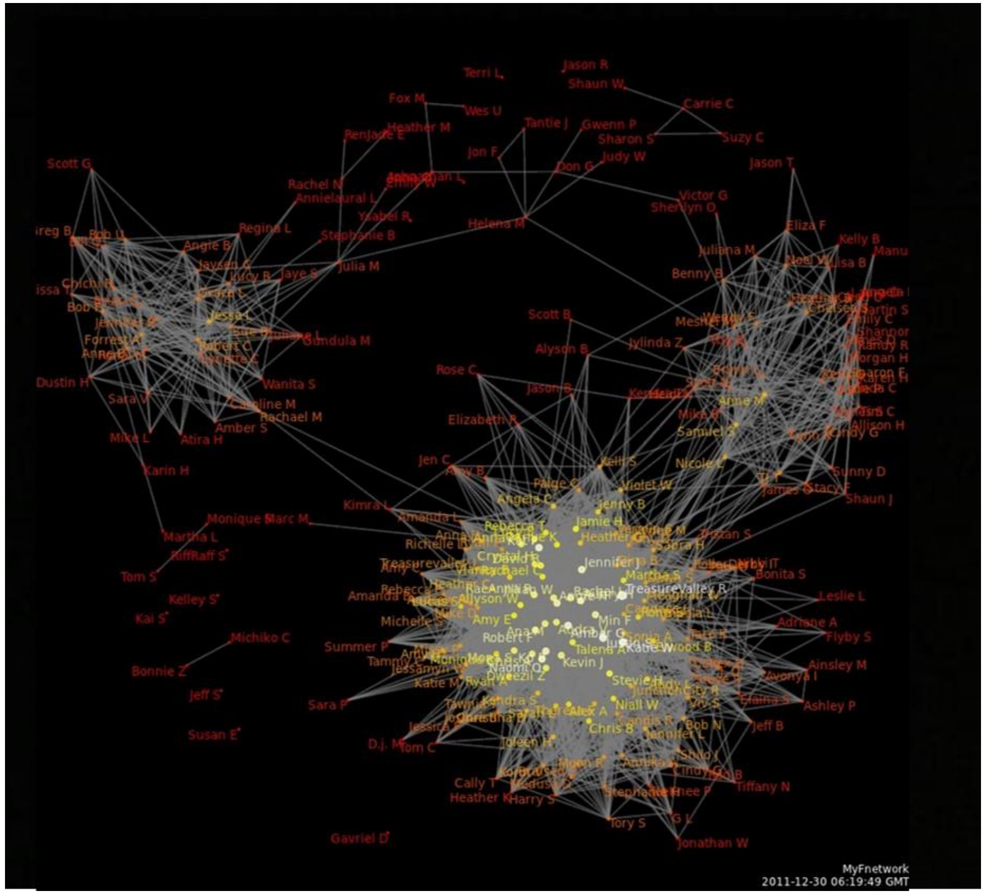


This is a scale free network

Networks

Networks associated with complex systems presumably display some form of organisational principles which should at some level be encoded in in the network topology.

One of the most important characteristics of complex networks is their internal structure, i.e., how the components and connections between components are arranged or organized.

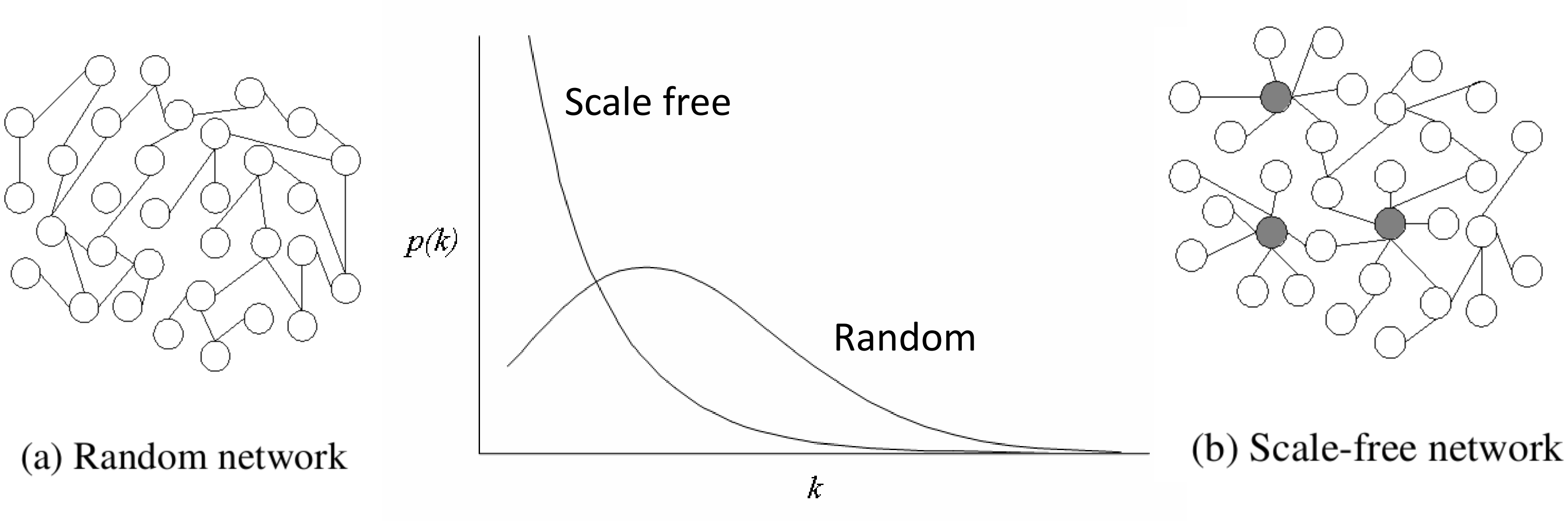


The reason for this is that the structure of complex networks has a significant influence on their function and performance.

A scale-free network is a network whose degree distribution follows a power law, at least asymptotically. That is, the fraction *P*(*k*) of nodes in the network having *k* connections to other nodes goes for large values of *k* as

$$P(k) \sim k^{-\gamma}$$

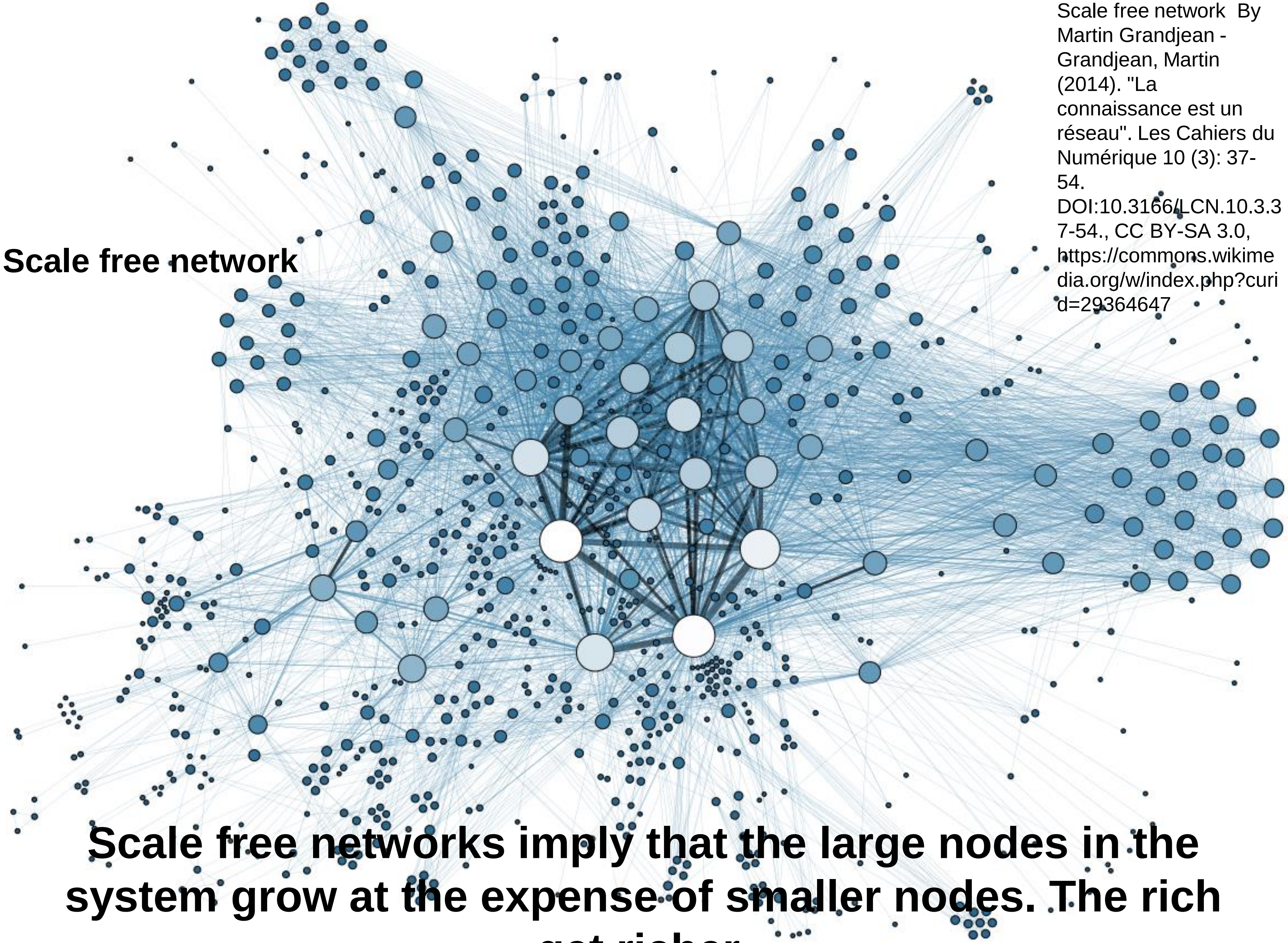
where γ is a parameter whose value is typically in the range $2 < \gamma < 3$, although occasionally it may lie outside these bounds.



(a) Random network

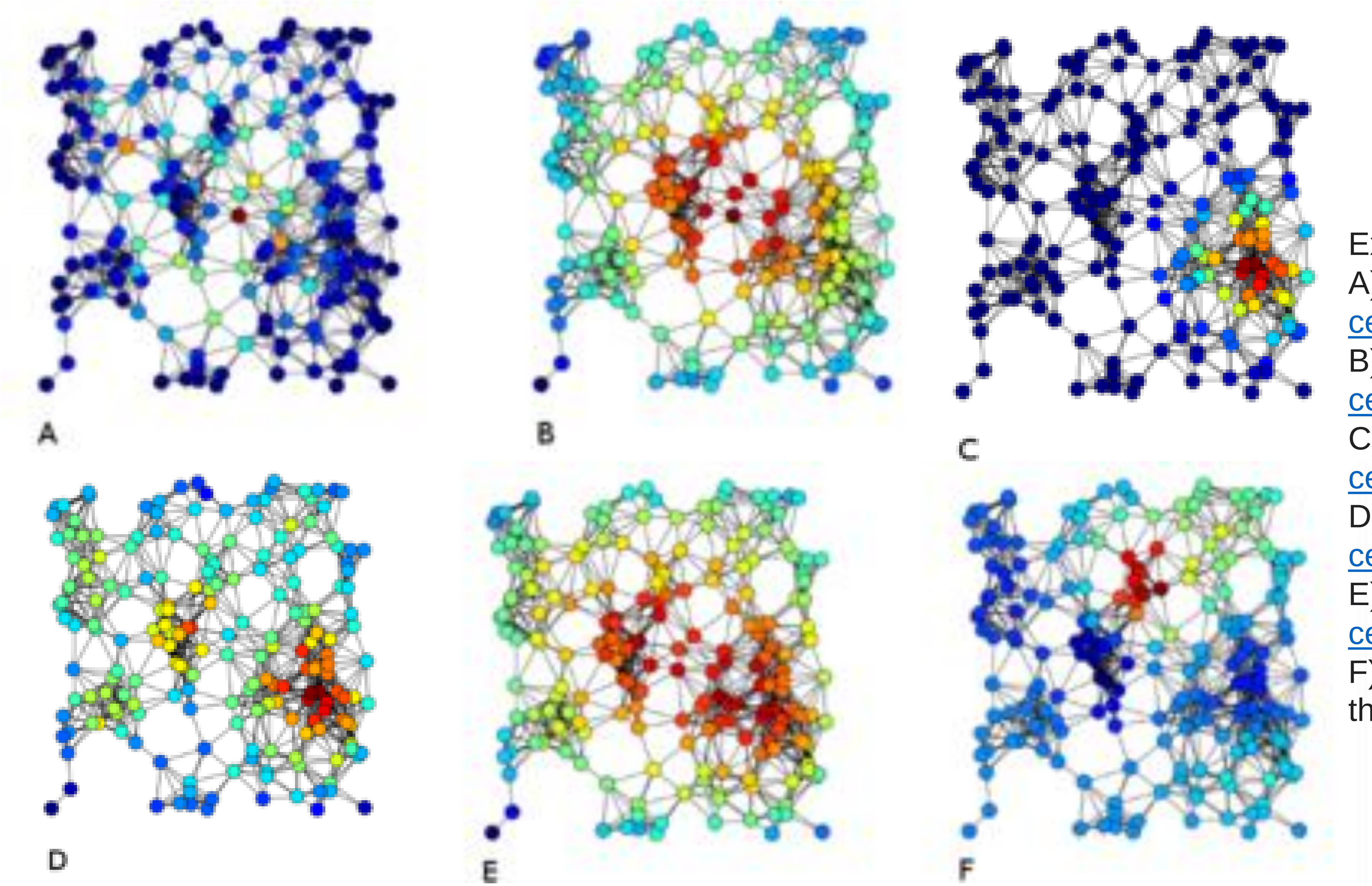
(b) Scale-free network

Scale free network

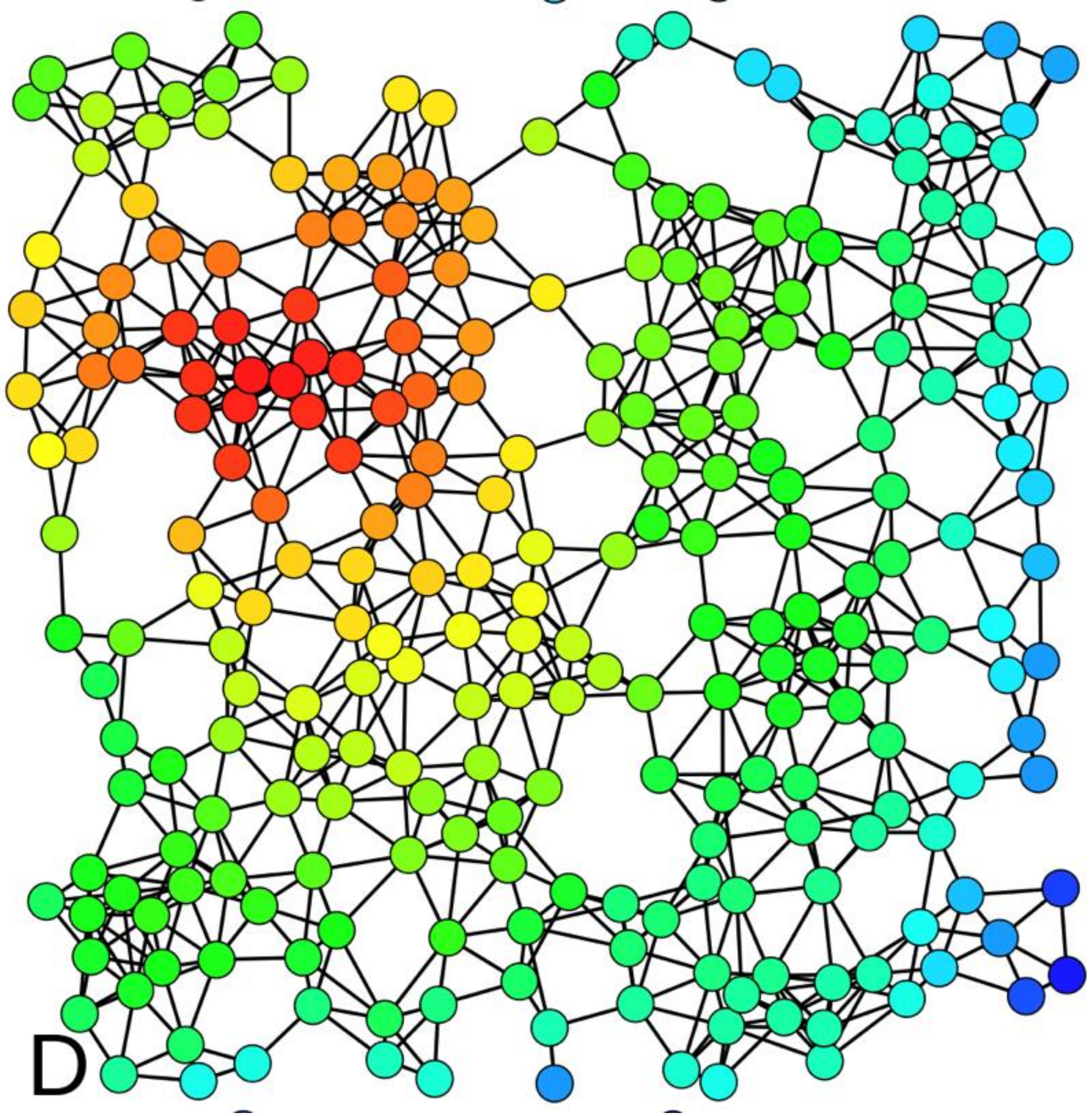


Scale free network By Martin Grandjean - Grandjean, Martin (2014). "La connaissance est un réseau". Les Cahiers du Numérique 10 (3): 37-54. DOI:10.3166/LCN.10.3.37-54., CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=29364647

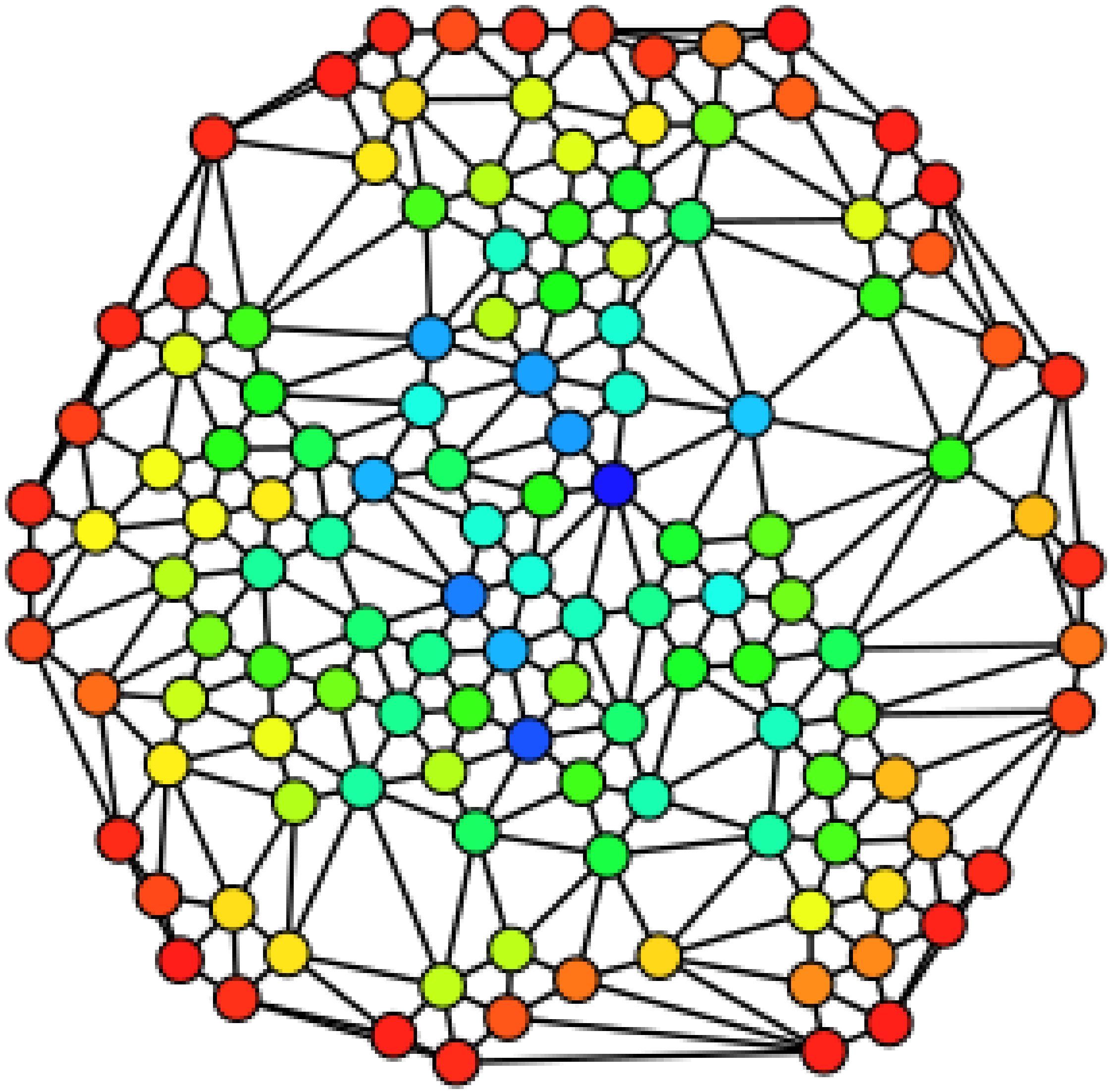
Scale free networks imply that the large nodes in the system grow at the expense of smaller nodes. The rich get richer.



Examples of
A) Betweenness centrality,
B) Closeness centrality,
C) Eigenvector centrality,
D) Degree centrality,
E) Harmonic centrality and
F) Katz centrality of the same graph.



An undirected graph colored based on the eigenvalue centrality of each vertex from least (red) to greatest (blue).



An undirected graph colored based on the betweenness centrality of each vertex from least (red) to greatest (blue).

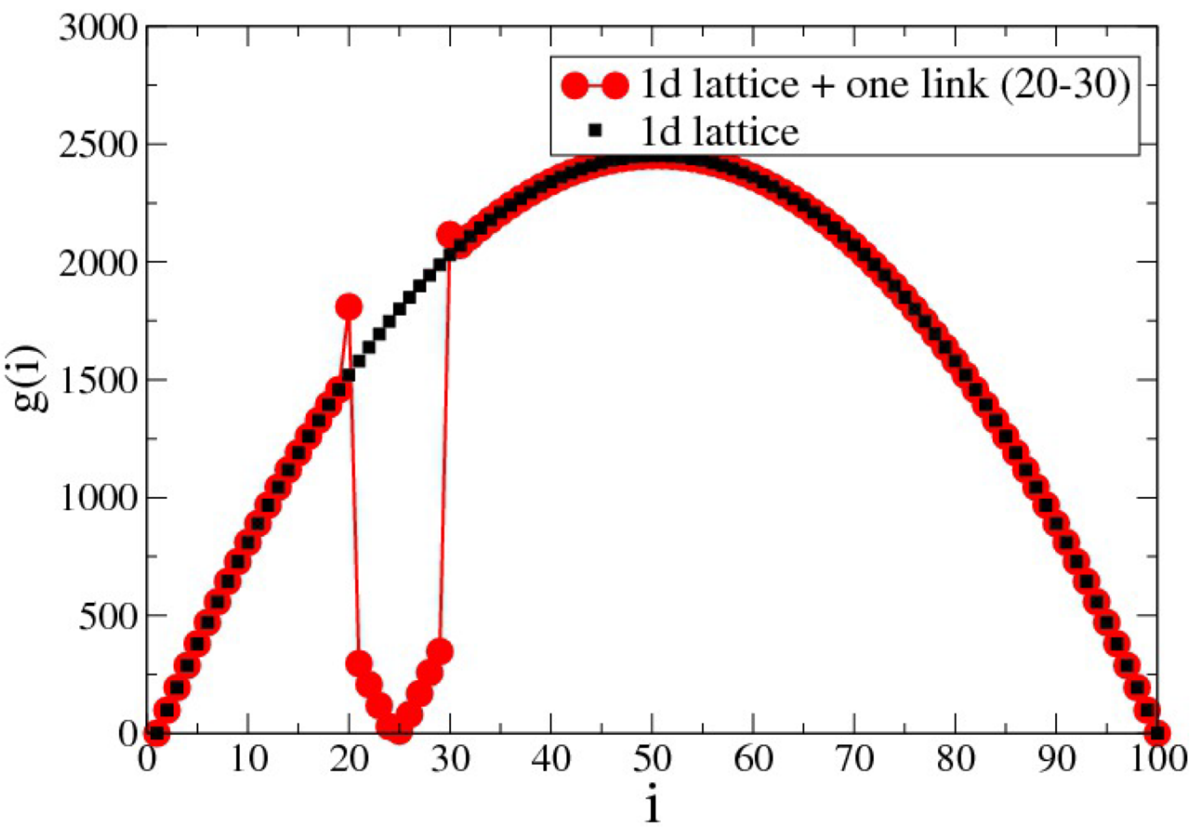
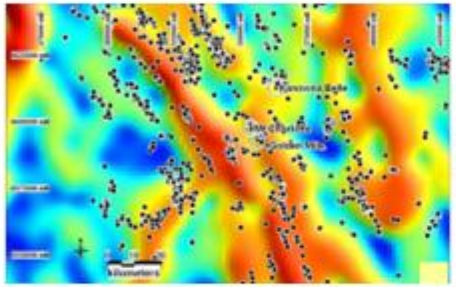
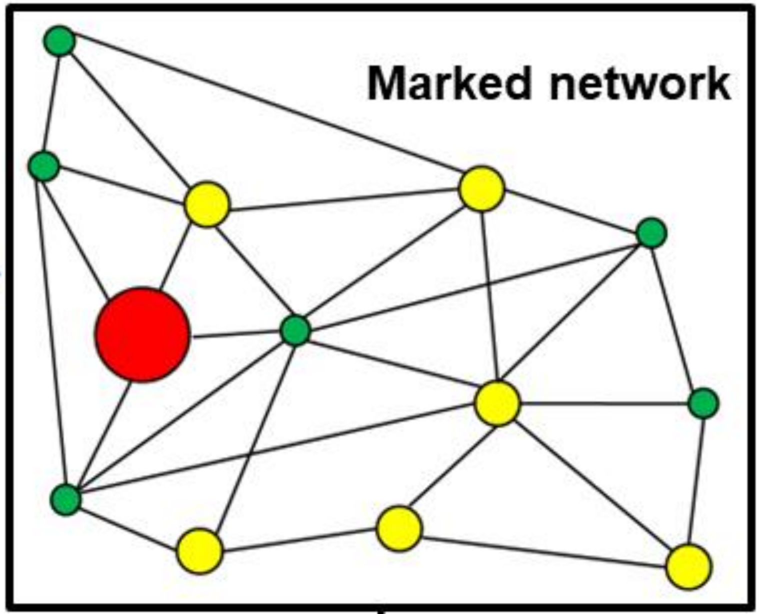
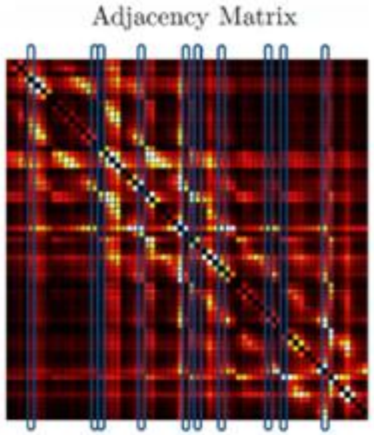


FIG. 4 Example of how the addition of a link perturbs the centrality. In black, the betweenness centrality for the 1d lattice (of size ($N = 100$) has a maximum at the barycenter $N/2 = 50$. The addition of a link between $a = 20$ and $b = 30$ decreases the betweenness centrality between a and b and increases the betweenness centrality of nodes a and b.





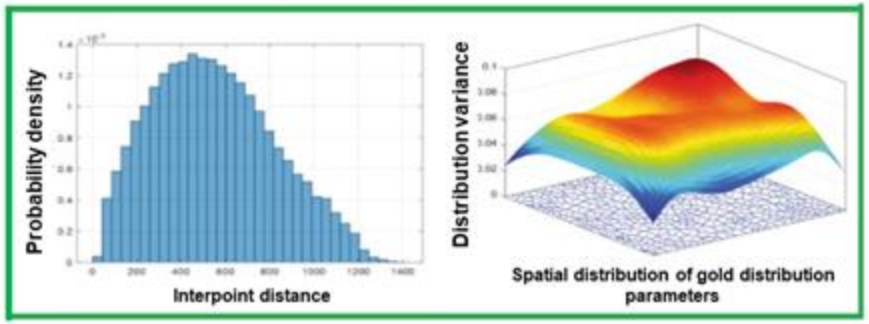
CHARACTERISATION OF NETWORK



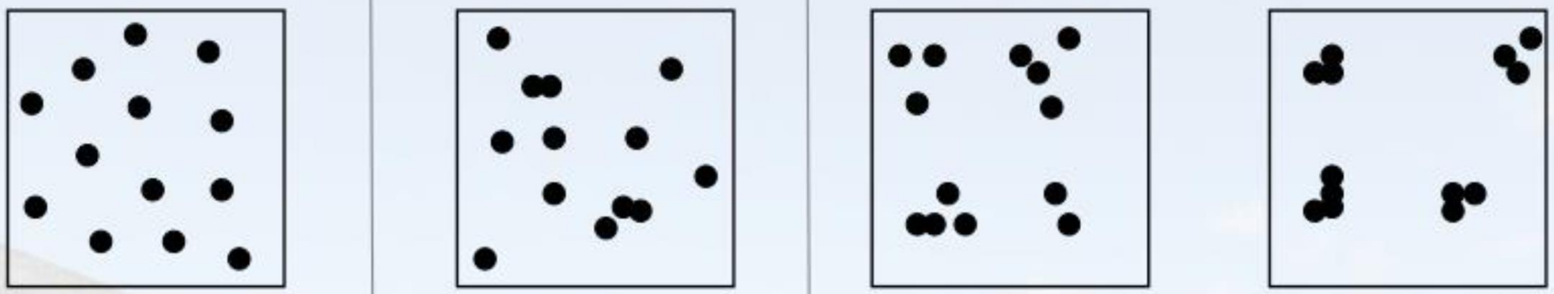
NETWORK METRICS
Degree
Centrality
Closeness
Betweenness centrality
Clustering

NETWORK CLASSIFICATION
Small world
Heavy tailed
Poisson
Heterogeneous Poisson
Cox
Gibbs
Max stable

NETWORK STATISTICS
Nearest neighbours
Node measure probability
Global connectiveness
N-point correlations
Adjacency matrix



Each point process has different statistics



uniform | random | clustered | clustered

<u>Inhibitory/over dispersed</u>

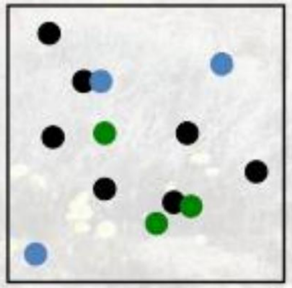
Scale of inhibition?

No interaction

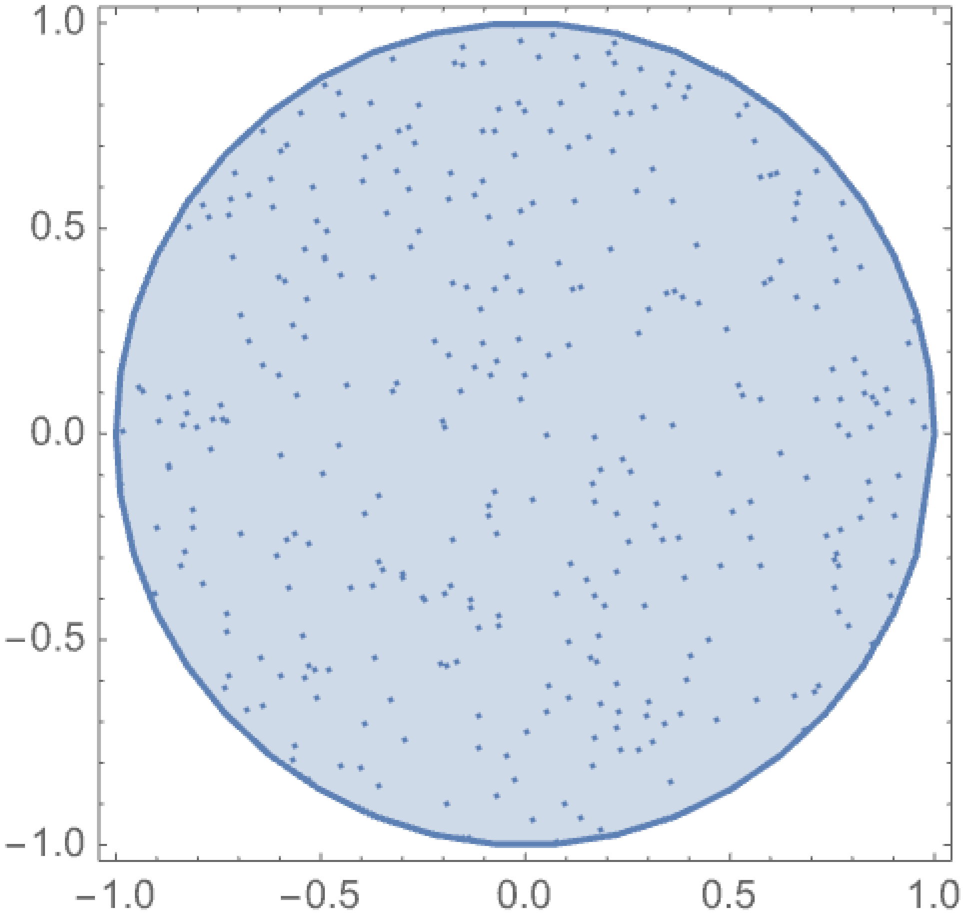
Attractive or repulsive Gibbs processes

Size of a cluster?

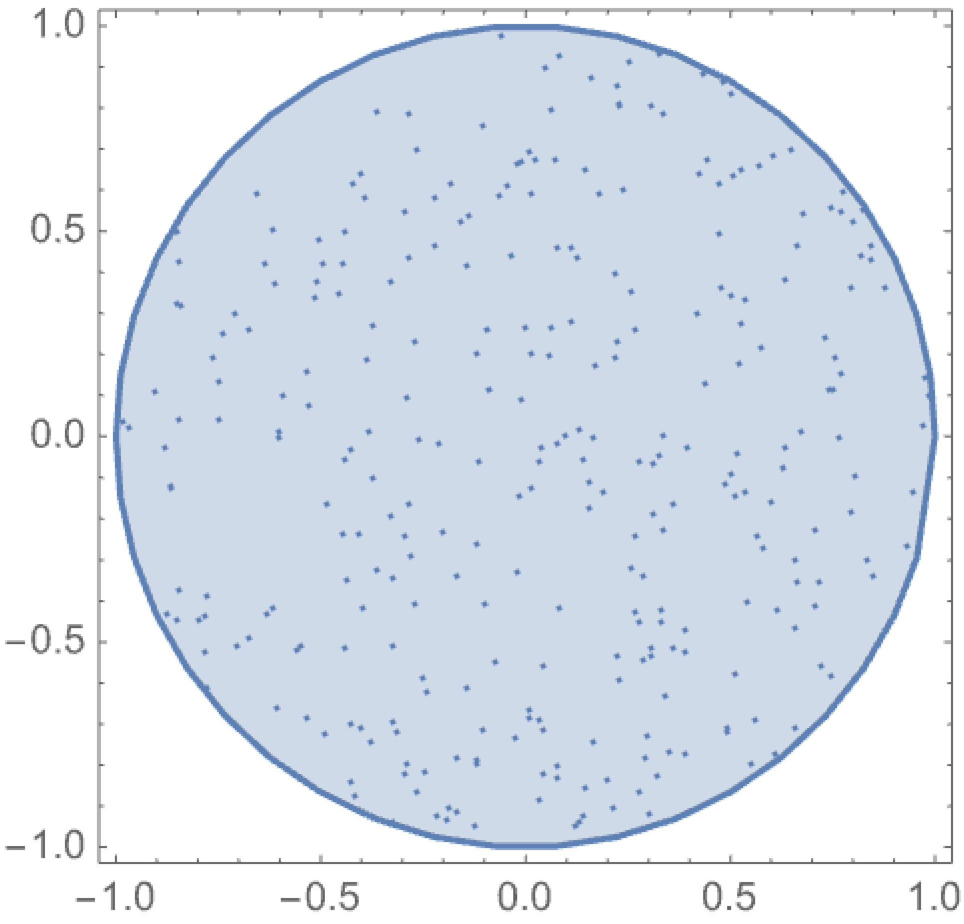
Multi-type point pattern



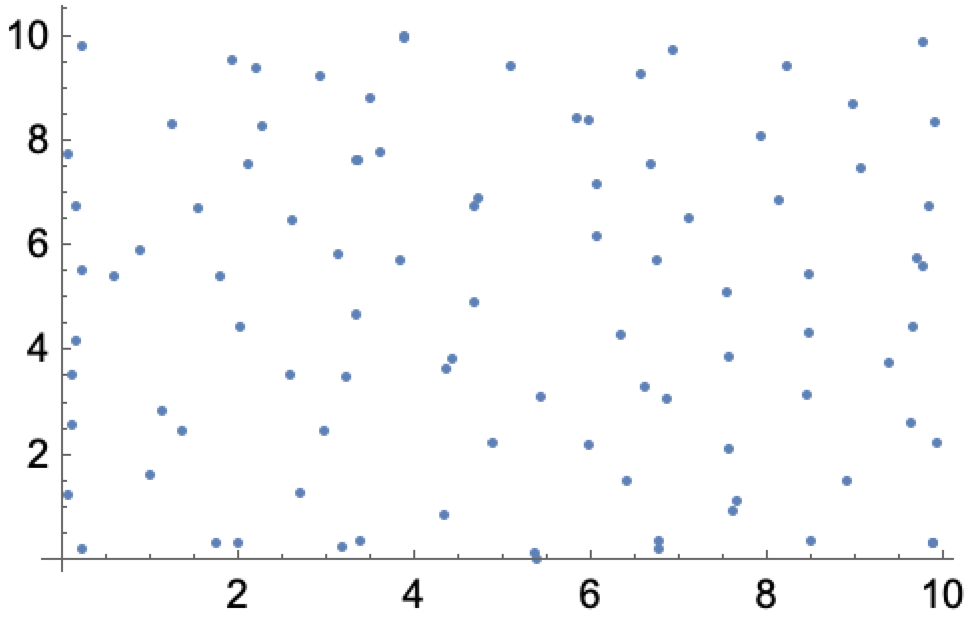
Marked point pattern



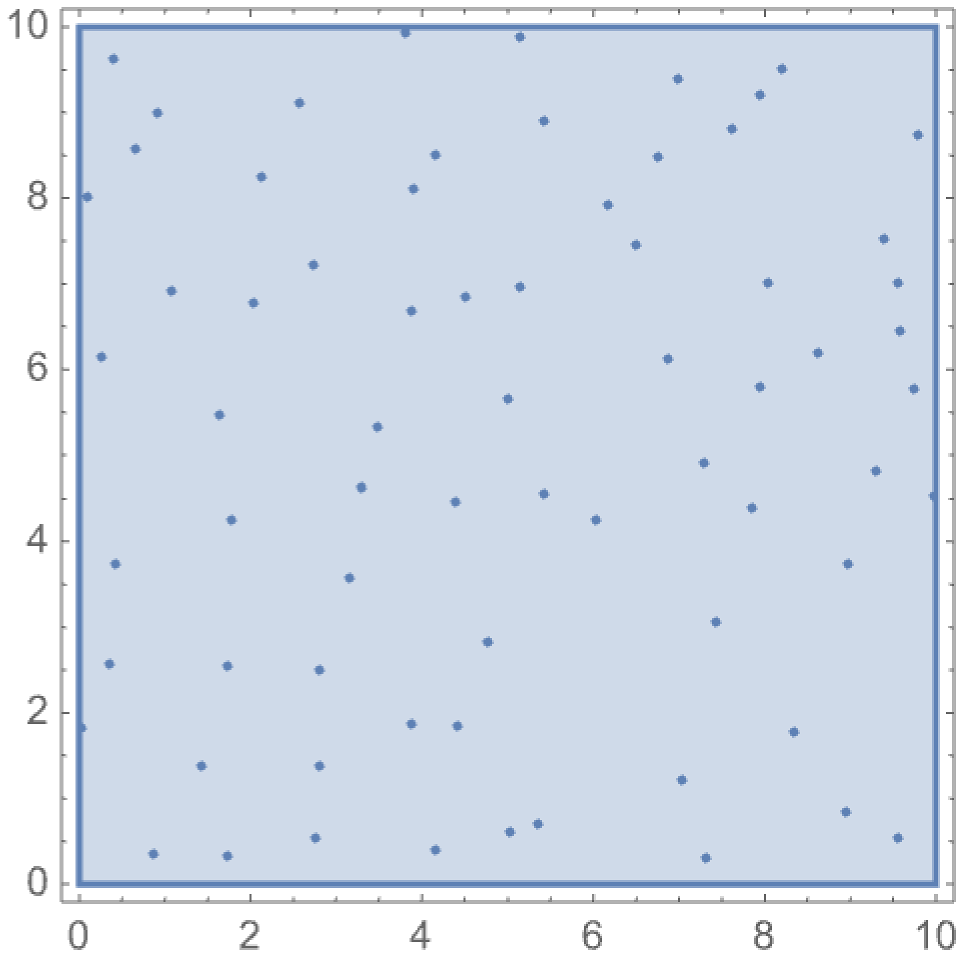
Poisson



Gibbs

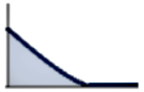
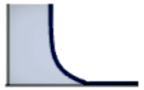
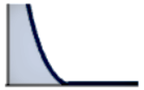


Strauss



Diggle Gates

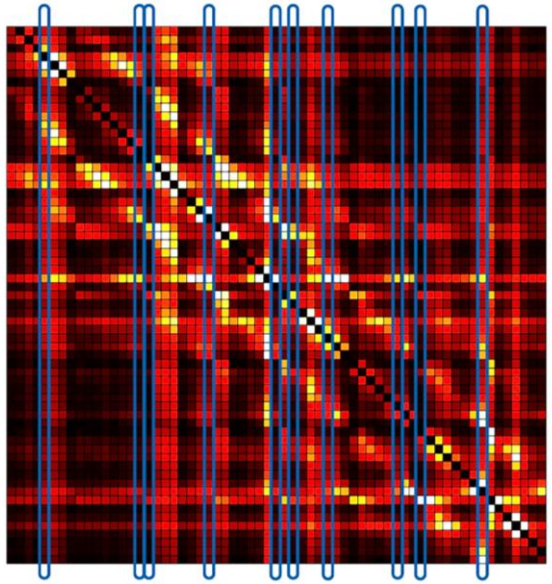
Gibbs Point Processes

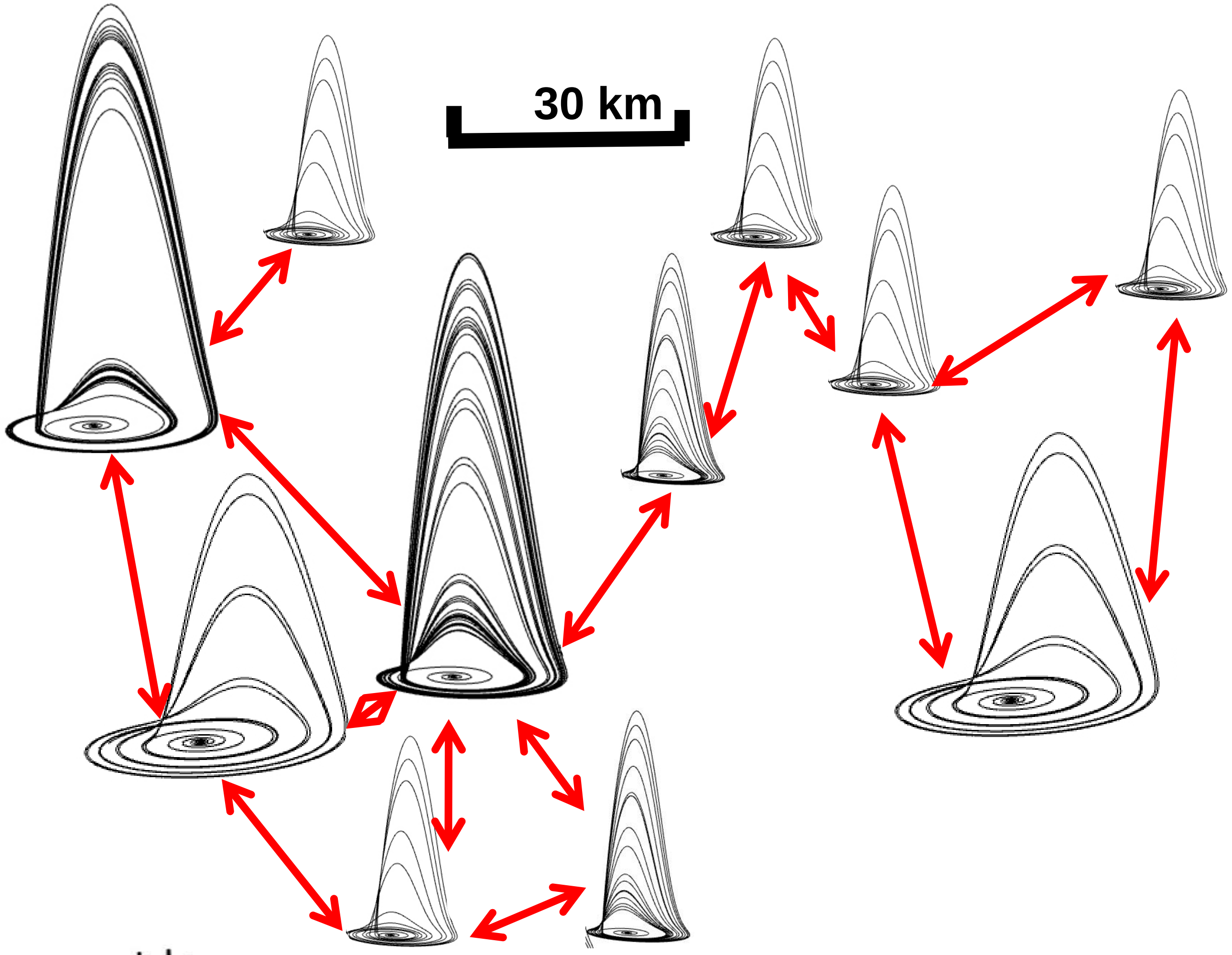
process	pair potential $\phi(r)$	characteristic
HardcorePointProcess		hardcore interaction
StraussPointProcess		constant strength softcore interaction
StraussHardcorePointProcess		inner hardcore with an outer softcore
PenttinenPointProcess		interaction based on overlapping area
DiggleGrattonPointProcess		inner hardcore with decreasing softcore
DiggleGatesPointProcess		smooth transition from point hardcore

The questions are:

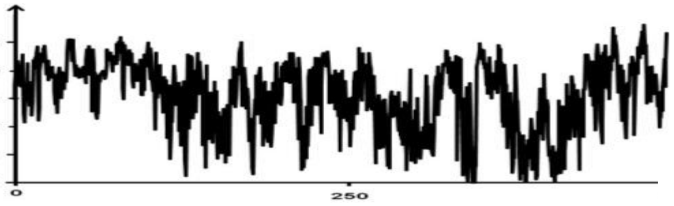
- **What are the metrics of the network formed by the mineralised sites?**
- **Is the point distribution a Gibbs process? If not what is it?**
- **Is there evidence of a depleted region around big deposits?**
- **What happens to the metrics of the network and of the point distribution if I remove a deposit?**
- **What happens to the metrics of the network and of the point distribution if I insert a deposit?**
- **Is there any evidence of a hidden node?**
- **Does the Zimbabwe network differ topologically from the Yilgarn network?**

Communication processes between mineralising sites





Each chemical reactors has its own operating signal

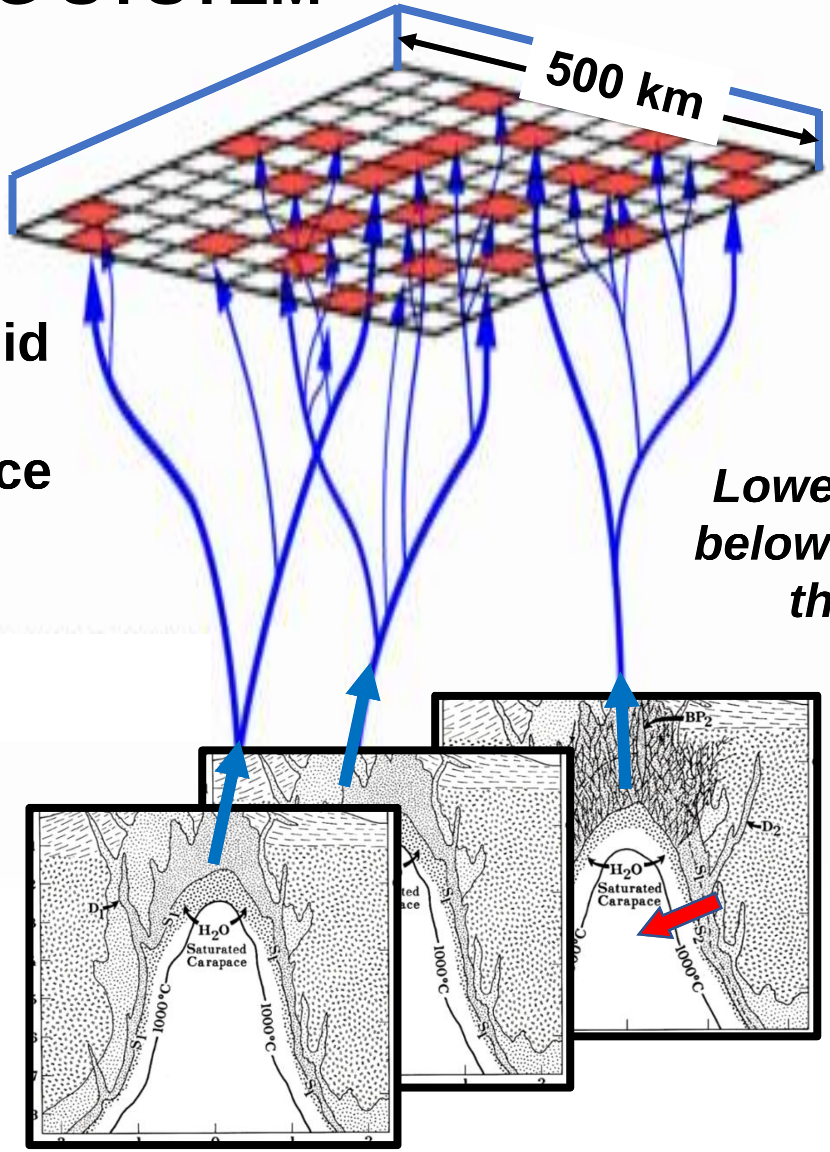


A regional array of chemical reactors each representing an ore body

Do they talk to each other?

Over what length scale? Do they synchronise?

MINERALISING SYSTEM



Mid crust just below percolation threshold

Fluctuations in fluid pressure at the collapsing carapace are transmitted throughout the system

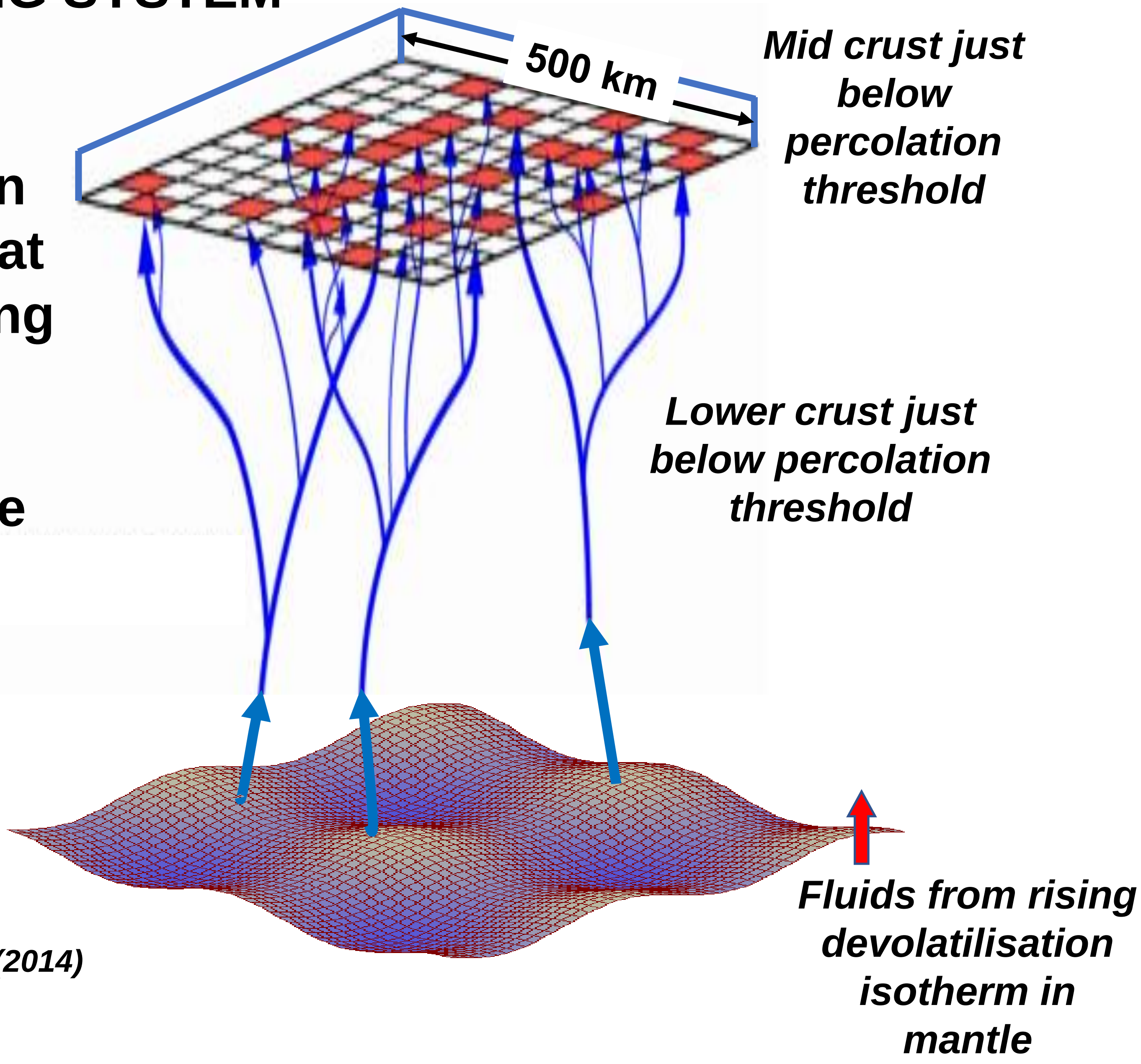
Lower crust just below percolation threshold

Fluids from collapsing carapace in crystallising plutons low in crust

From Blenkinsop (2014) and Burnham (1979)

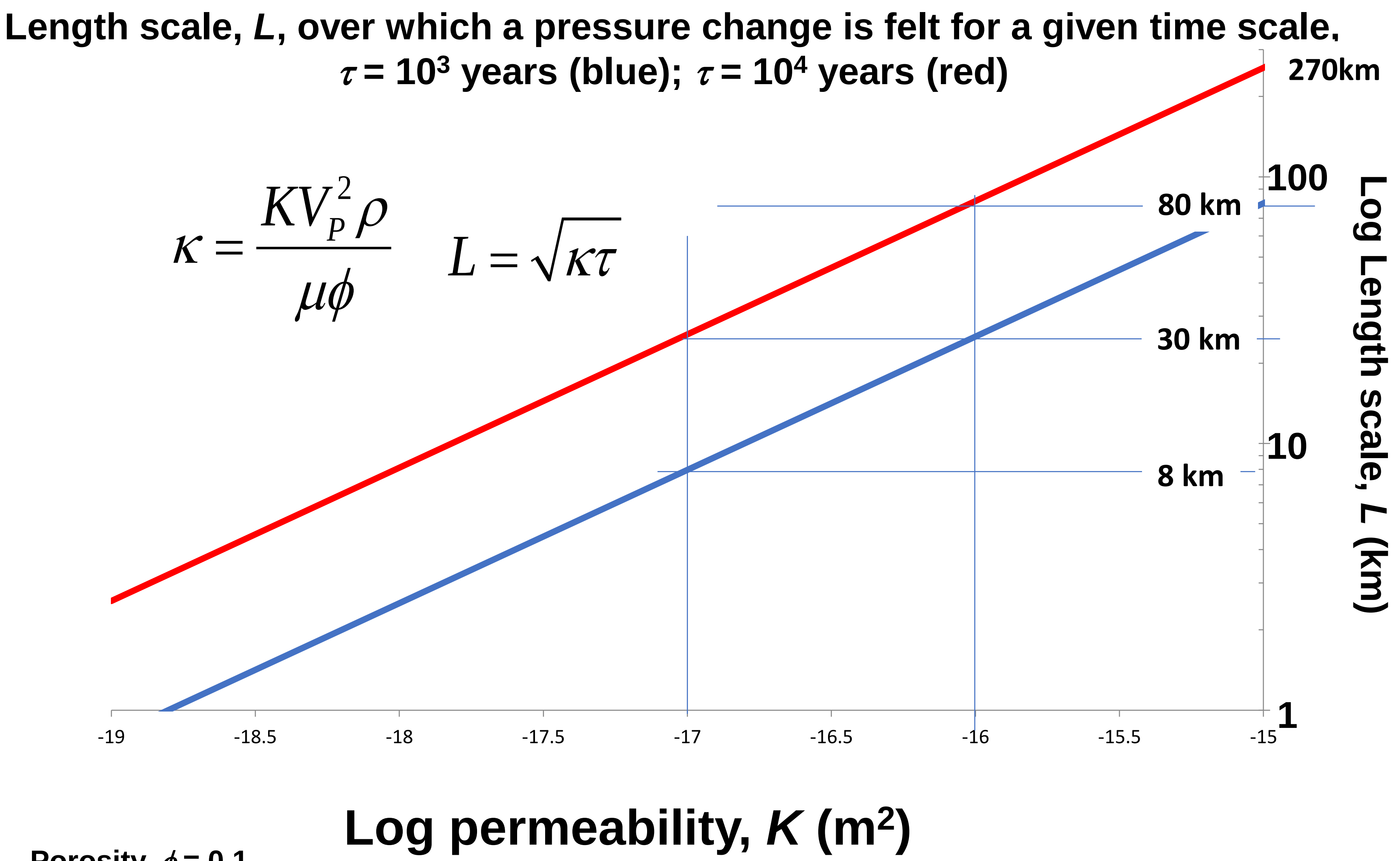
MINERALISING SYSTEM

Fluctuations in fluid pressure at the devolatilising front are transmitted throughout the system



From Blenkinsop (2014)

Distances over which plumbing systems can communicate



$$\kappa = \frac{KV_P^2\rho}{\mu\phi} \qquad L = \sqrt{\kappa\tau}$$

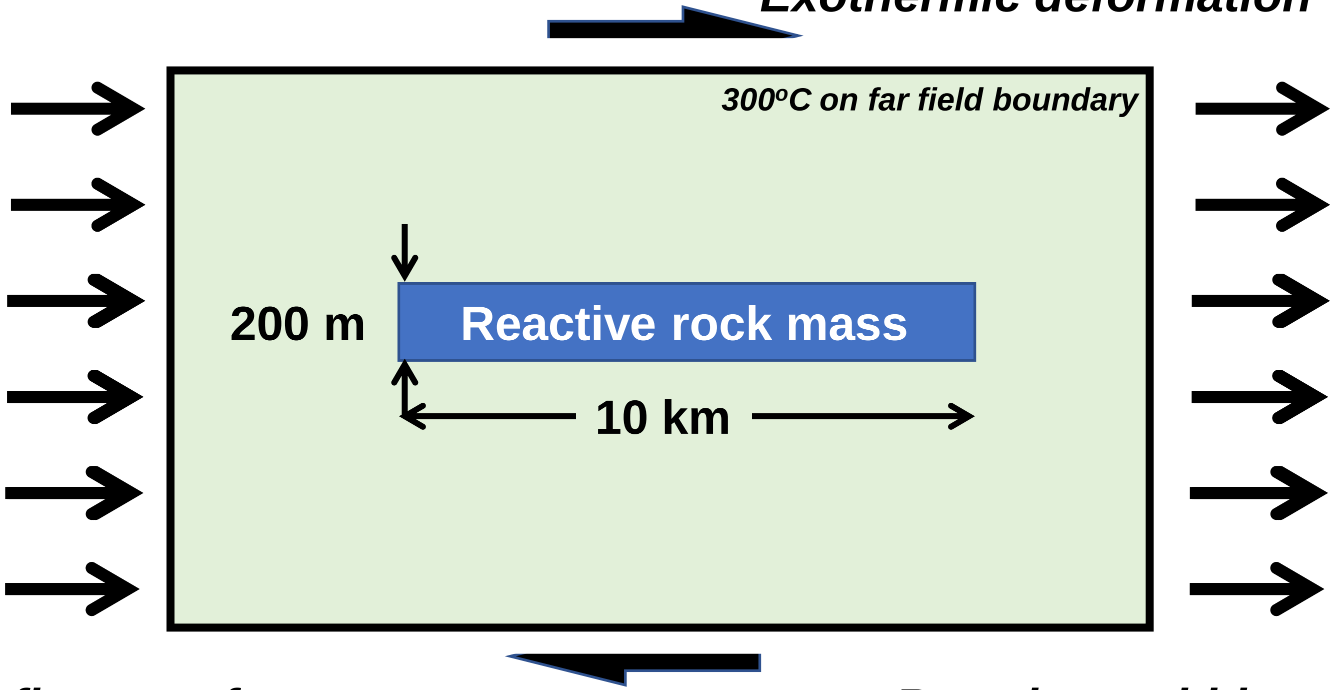
Porosity, $\phi = 0.1$
$V_P = 1400$ m s^{-1}
Viscosity, $\mu = 10^{-4}$ Pa s
Density, $\rho = 10^3$ kg m^{-3}

κ is hydraulic diffusivity

Input gold concentration 10 ppb by weight of fluid

An example

Exothermic deformation



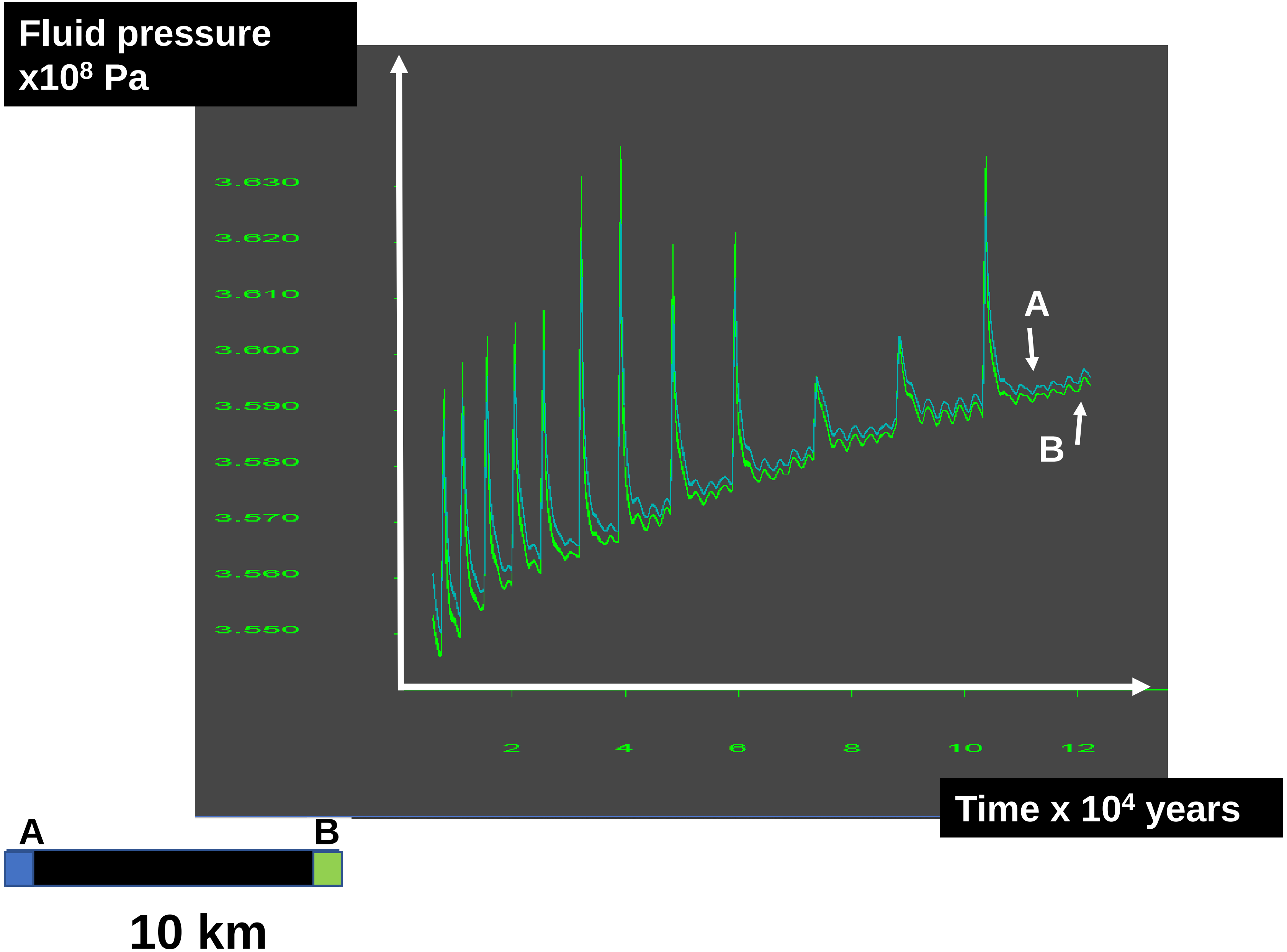
Imposed flow rate for lithostatic fluid pressure gradient

Reactions within reactive region endothermic with fluid release

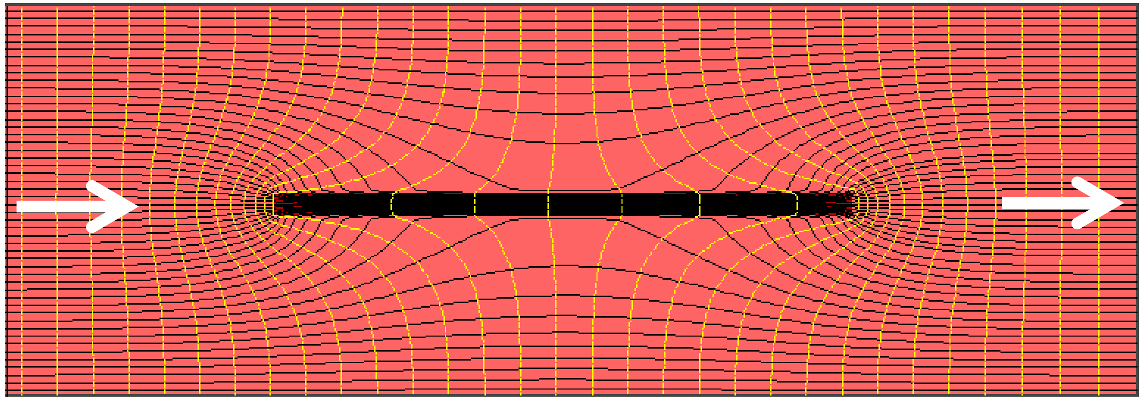
2 clinozoisite + 3 pyrite + 2 calcite + 3 quartz +5 H_2O + 1.5 H_2 → 3 epidote + 2 CO_2 + 6 H_2S

This reaction is endothermic with ΔH = 5937.5 kJ.

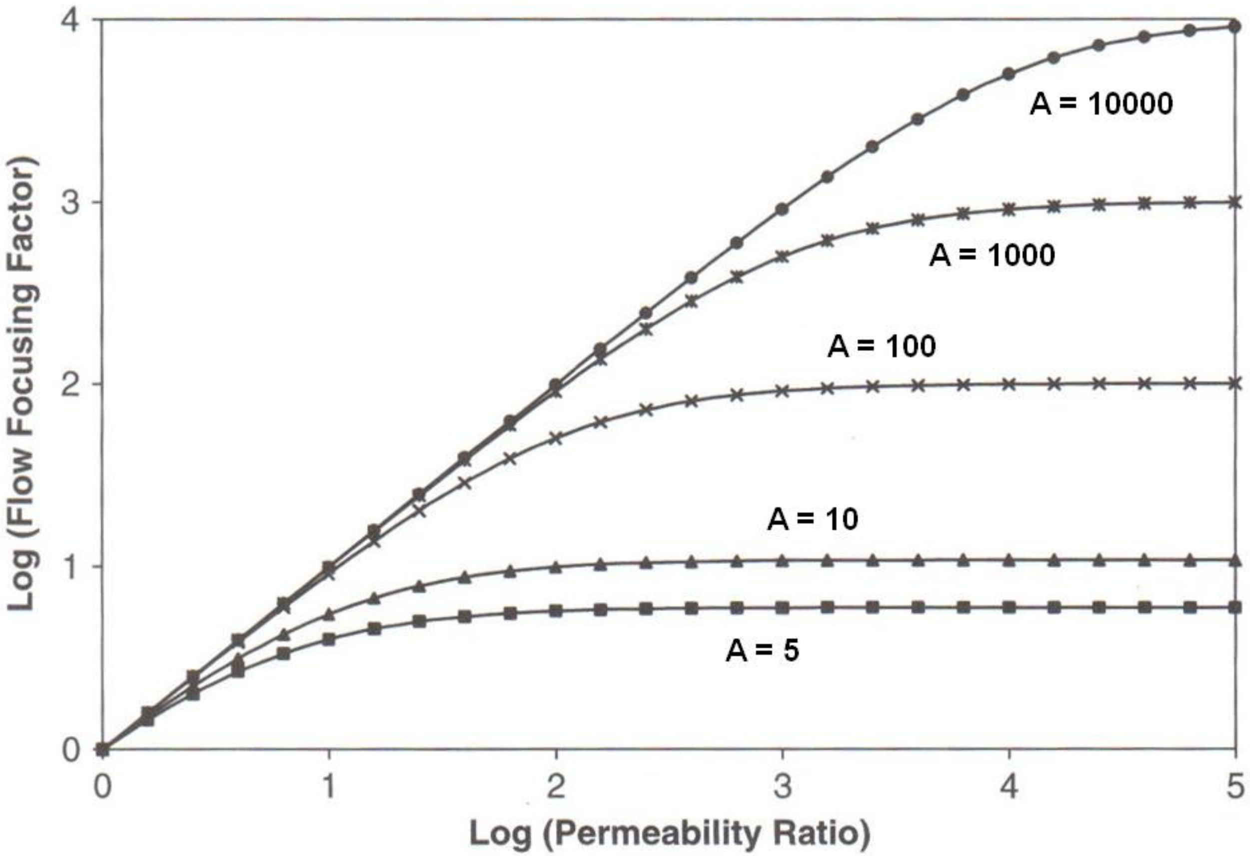
Synchronisation of pore pressure in mineralising system over 10 km



Focussing of fluid flow into high permeability lens

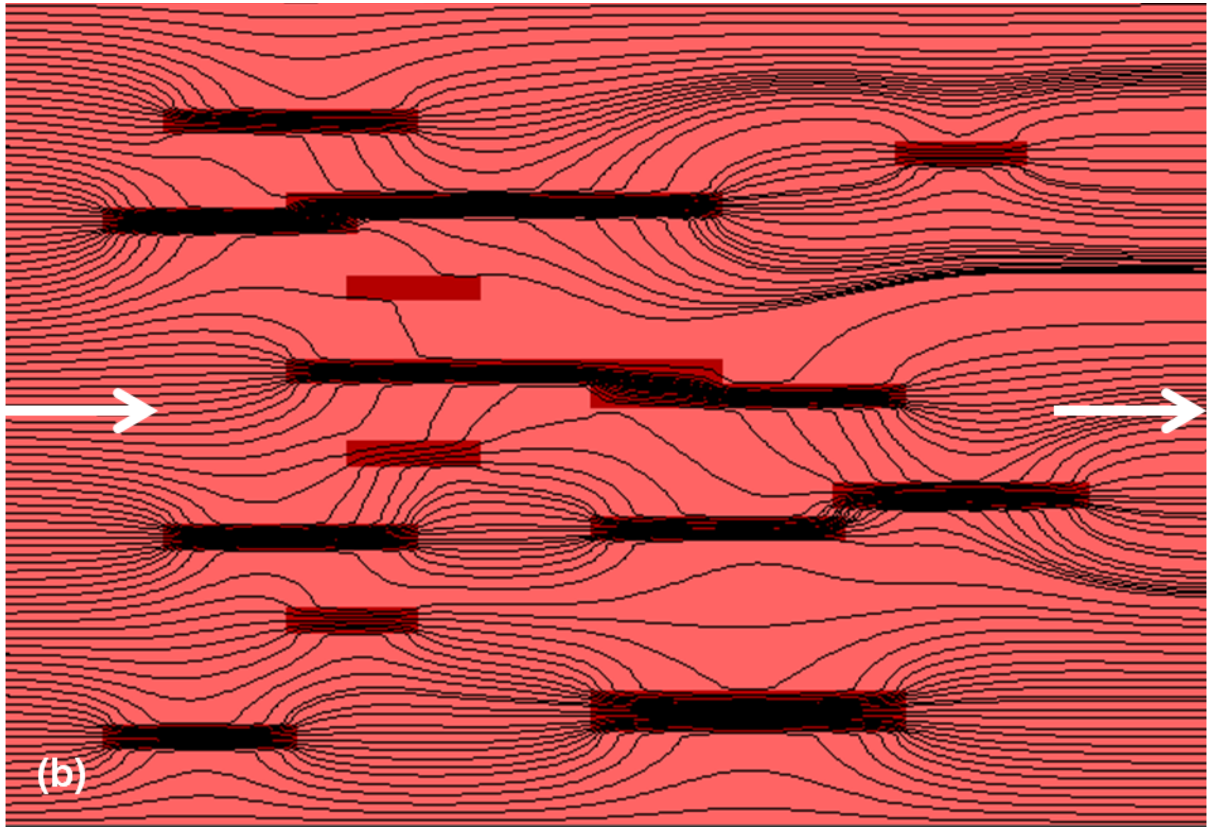


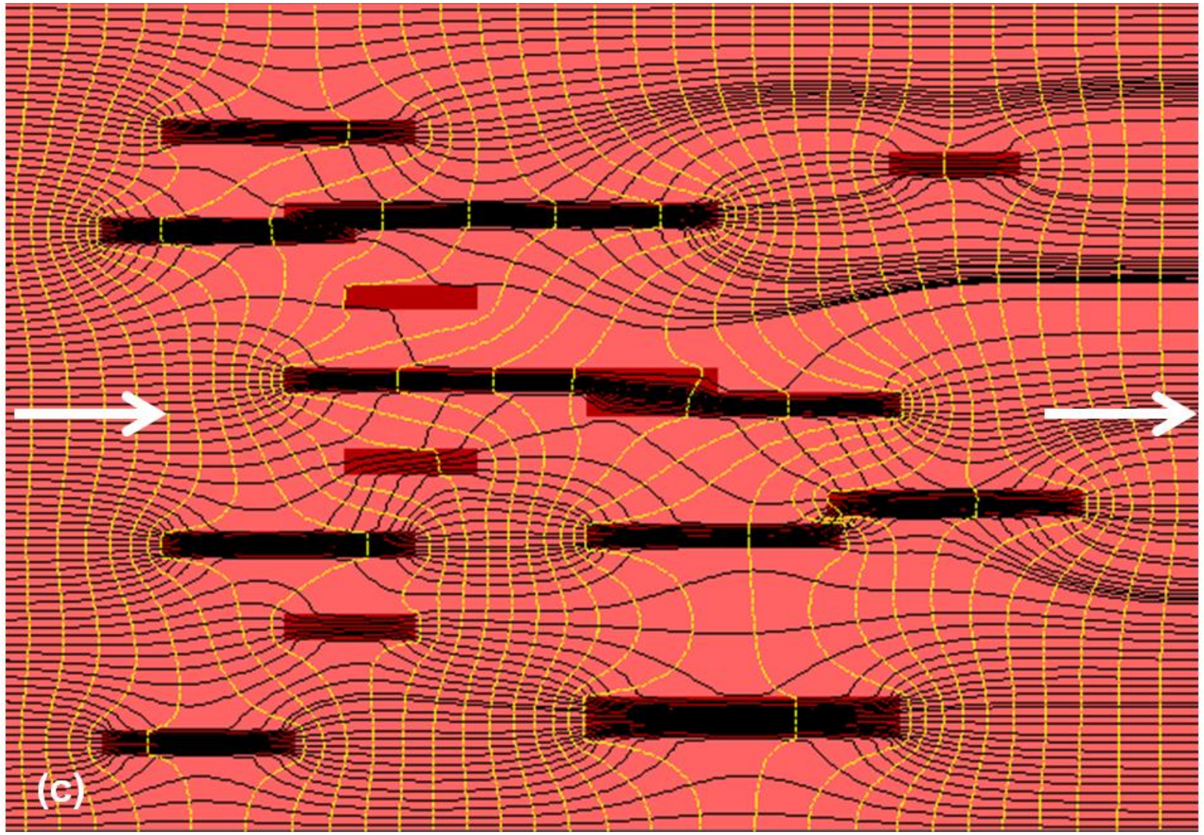
(a)



Focussing increases as permeability ratio increases and as aspect ratio, A, increases

Fluid focussing into multiple lenses





Black; Stream lines.   Yellow: fluid pore pressure contours
Notice some lenses miss out on fluid, some areas are relatively stagnant.

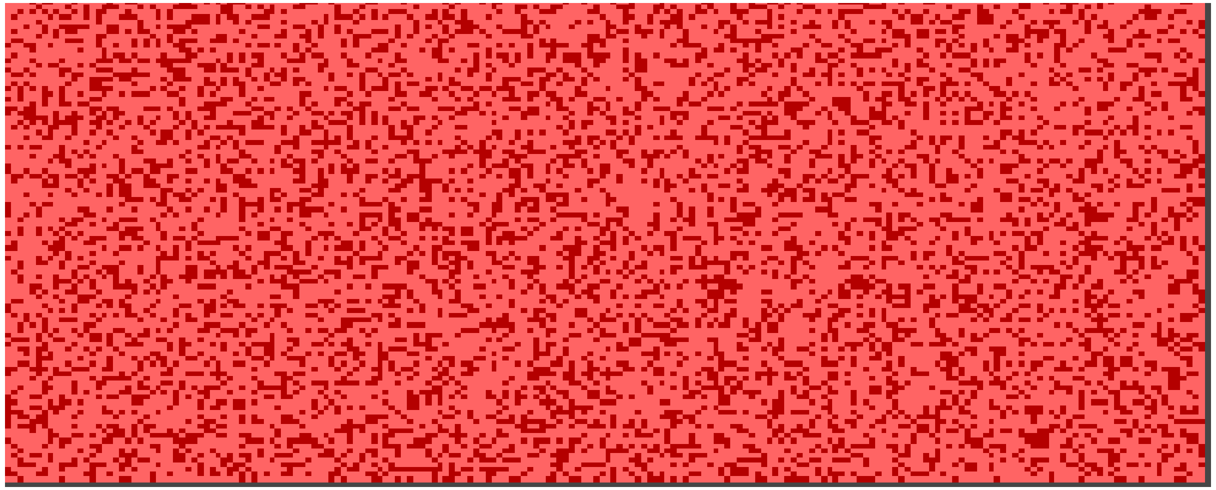
Focussing patterns indicate a region of stagnant flow next to areas of maximum focussing.

Stagnation regions are adjacent to areas of maximum permeability contrast and maximum interface between permeabilities.

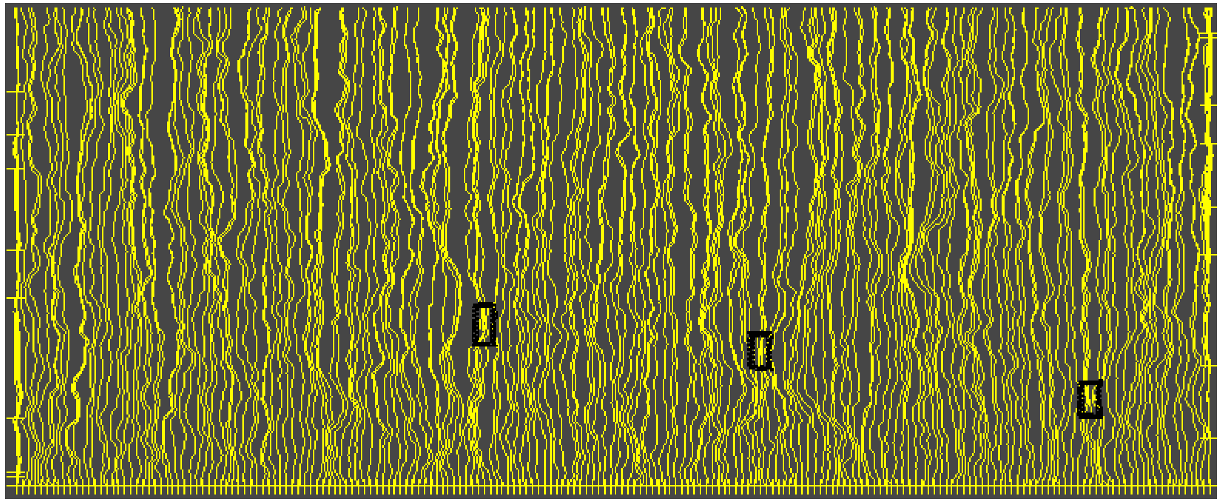
This suggests that the spatial distribution should be some form of Gibbs point process.

We run some models below to see the influence of heterogeneity in permeability upon flow patterns.

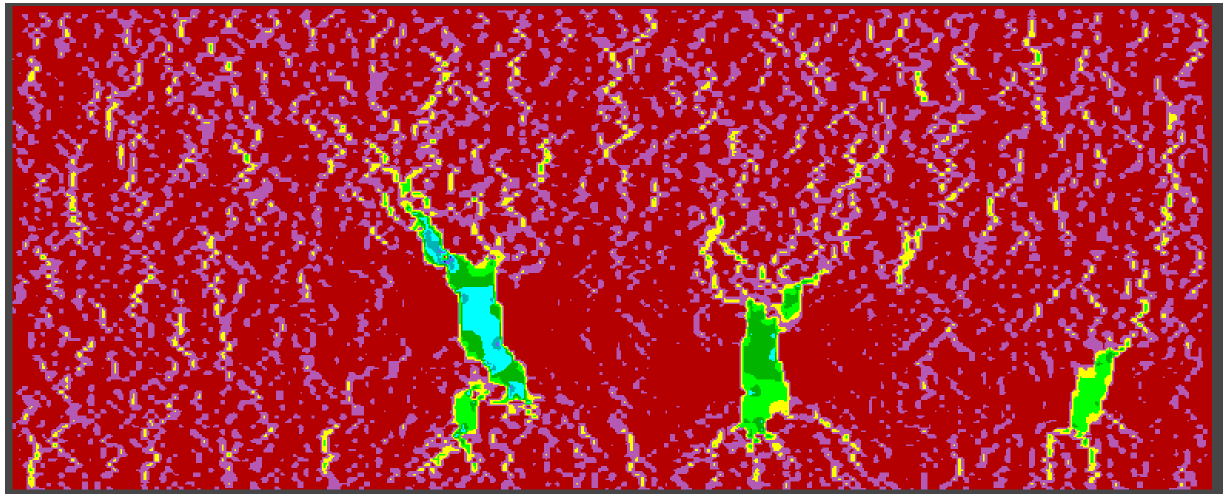
If the flow is greater than some critical value reactions occur to increase the permeability



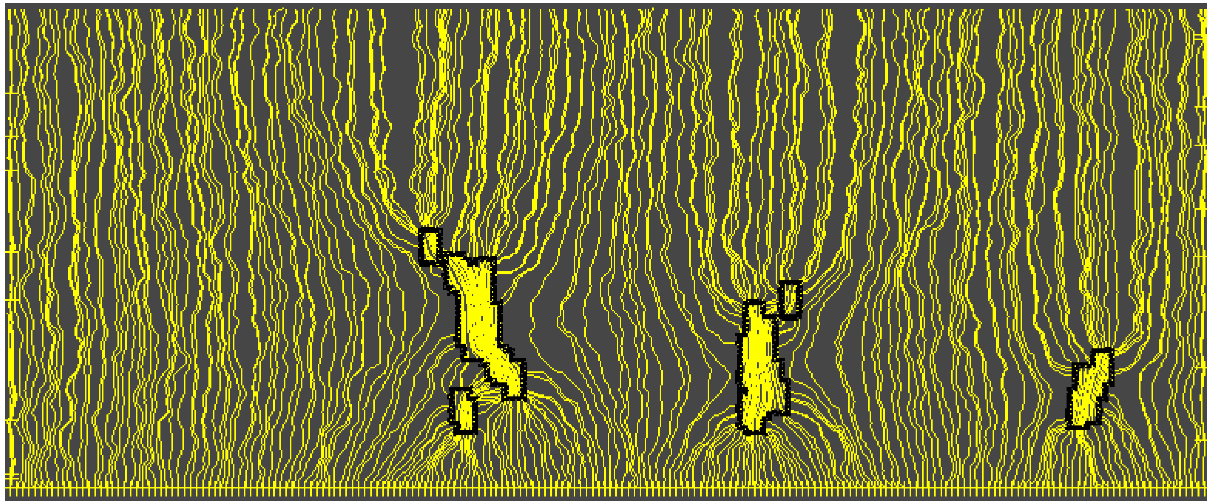
Initial permeability distribution
Pink: 10^{-19} m^2; red: 10^{-18} m^2



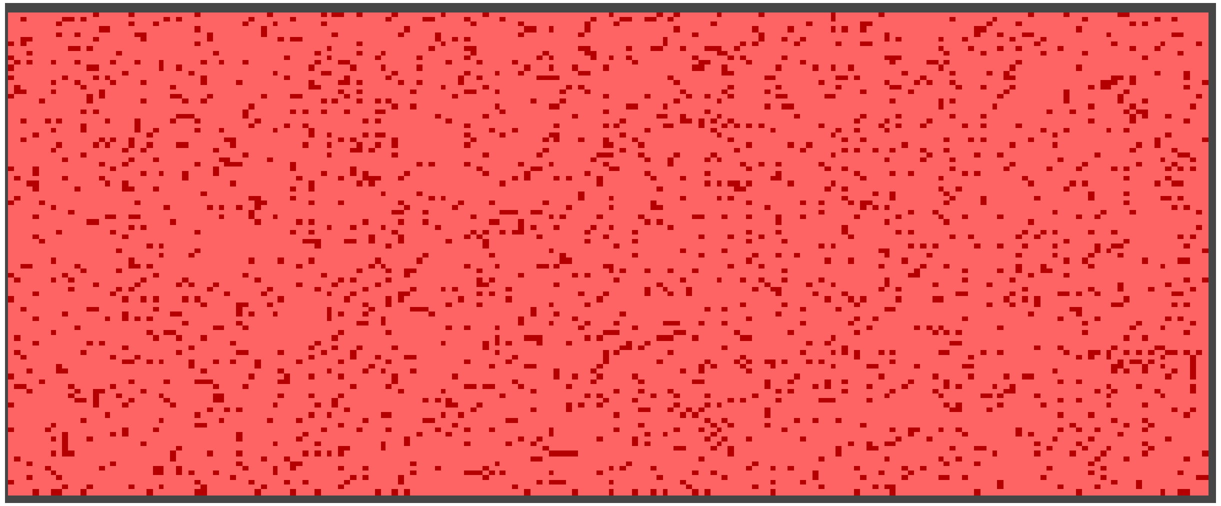
Early stream lines
Black outlines permeability has increased to 10^{-17} m^2



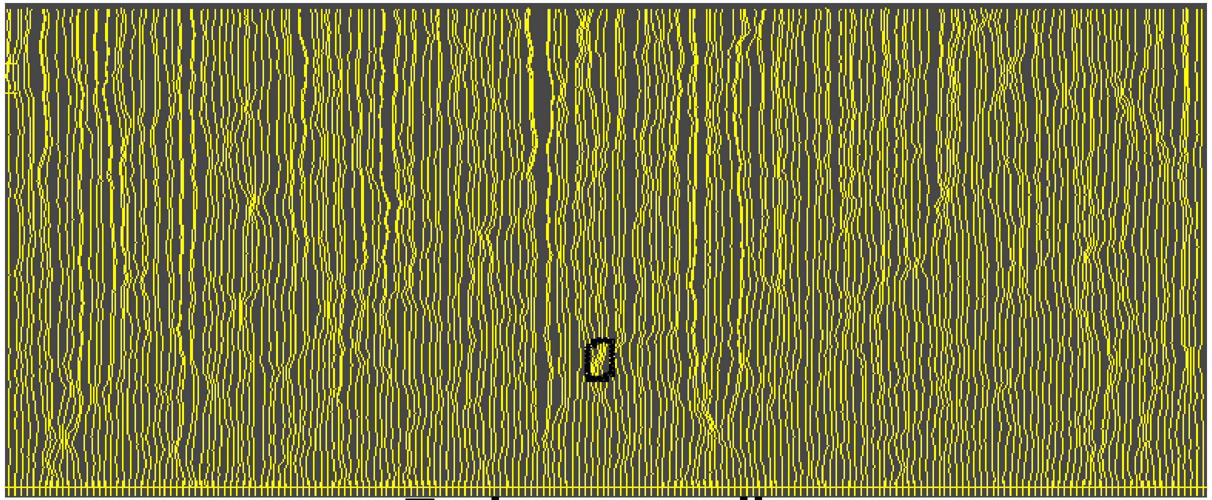
Late distribution of fluid velocity
Blue is highest



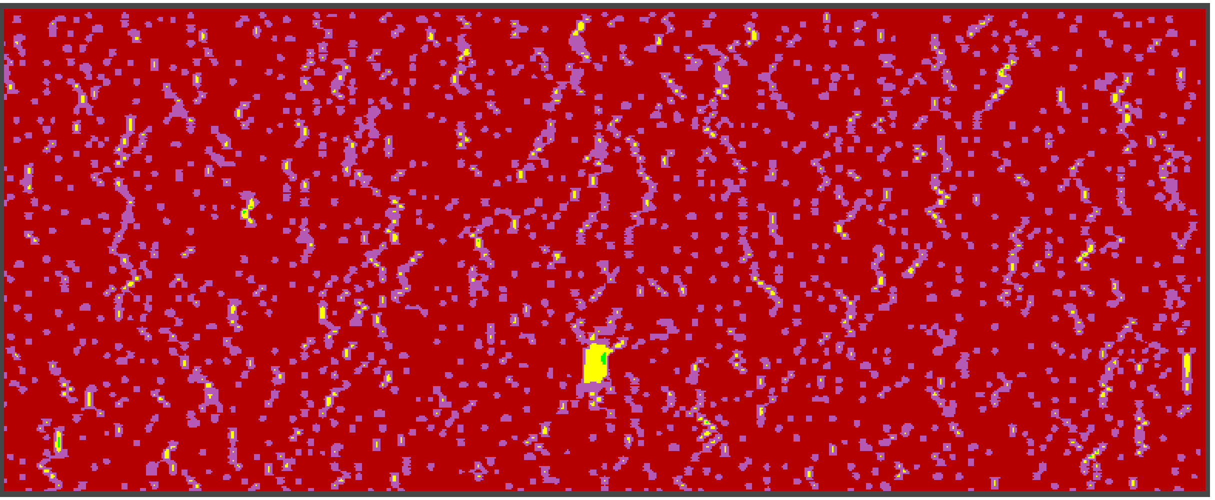
Late distribution stream lines and Permeability change



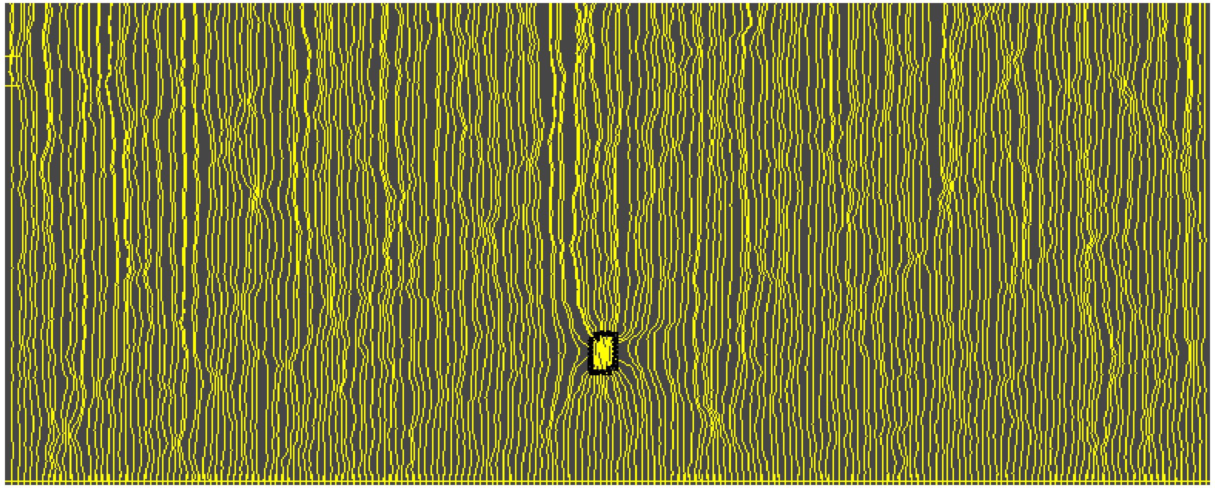
Initial permeability distribution
Pink: 10^{-19} m^2; red: 10^{-18} m^2



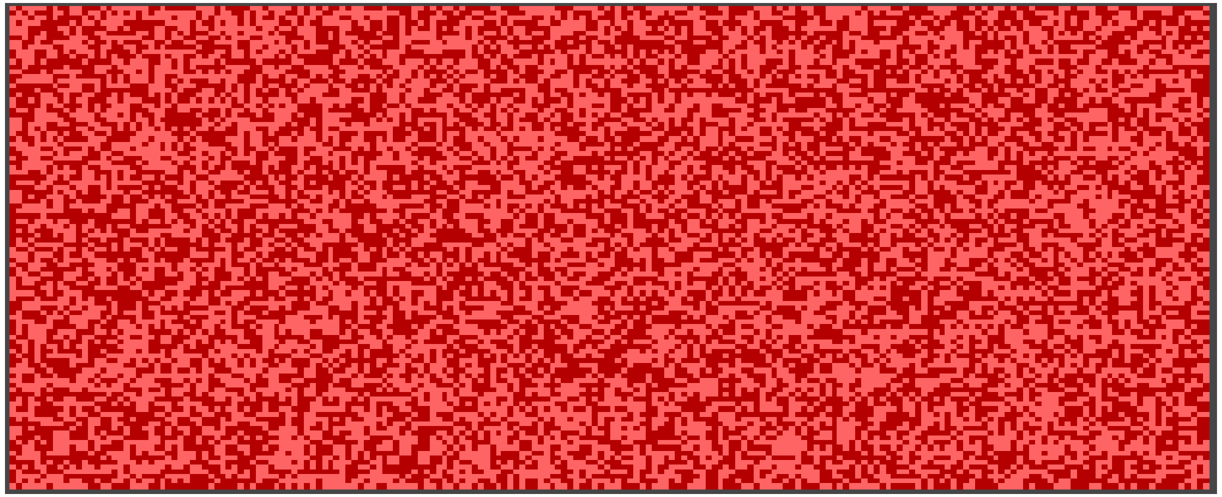
Early stream lines
Black outline permeability has increased to 10^{-17} m^2



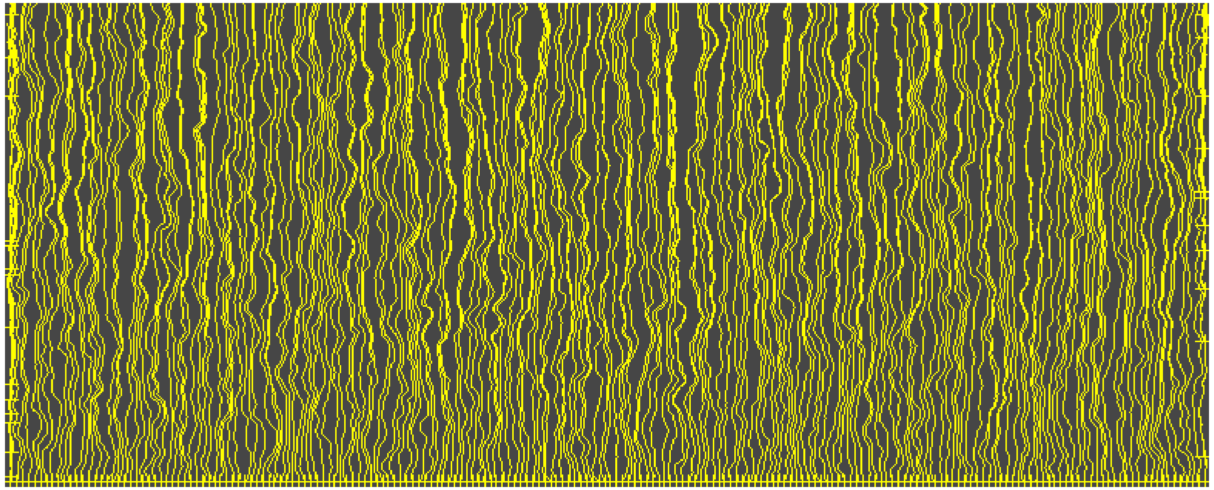
Late distribution of fluid velocity
Green is highest



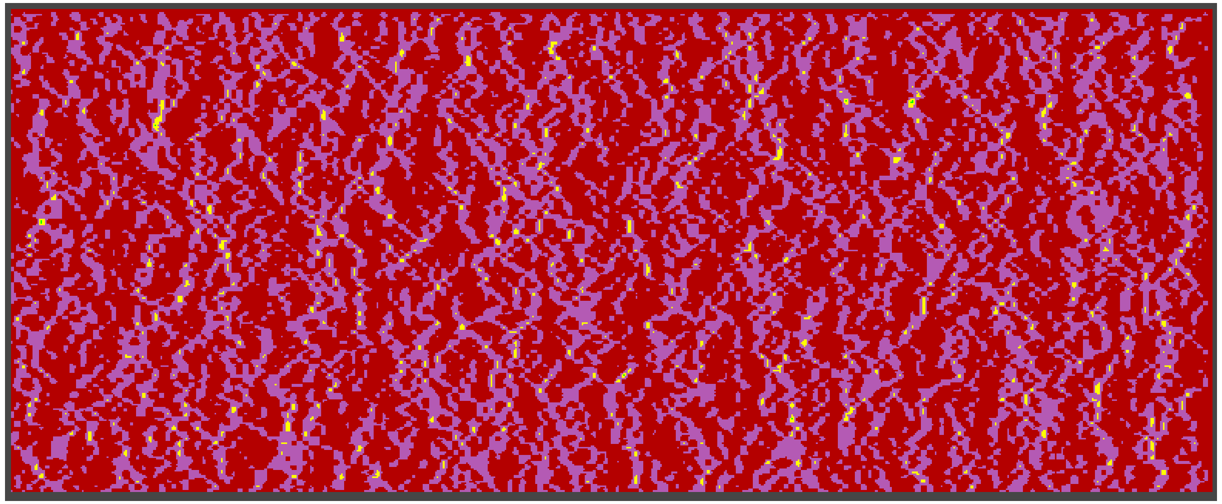
Late distribution stream lines and
Permeability change



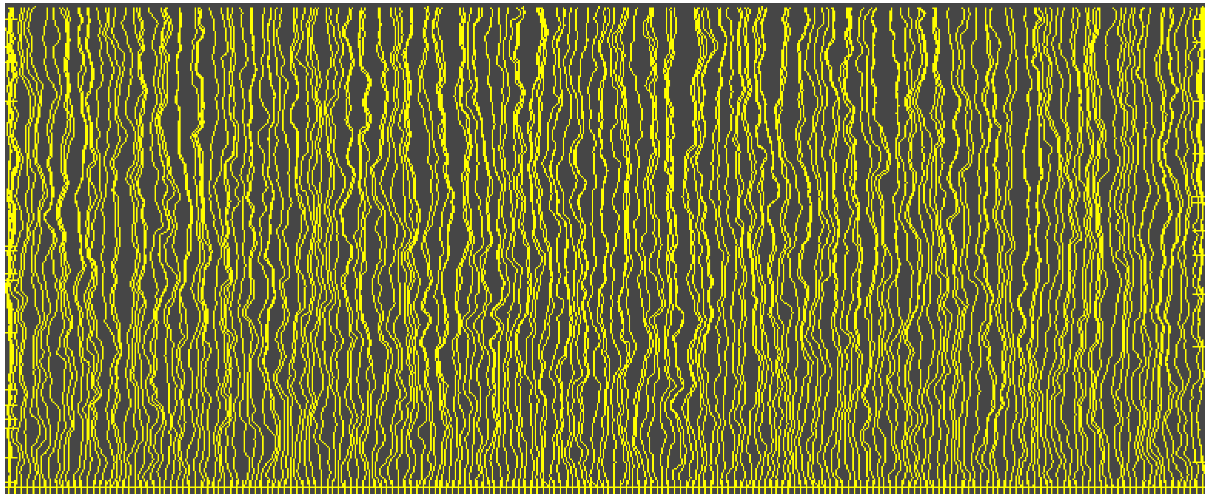
Initial permeability distribution
Pink: 10^{-19} m^2; red: 10^{-18} m^2



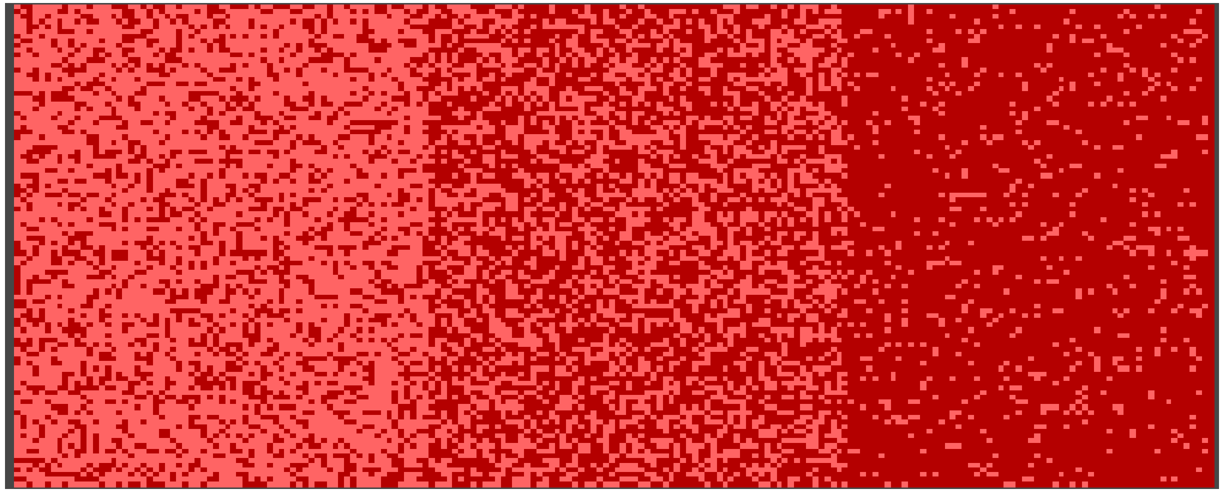
Early stream lines
No early increase in permeability



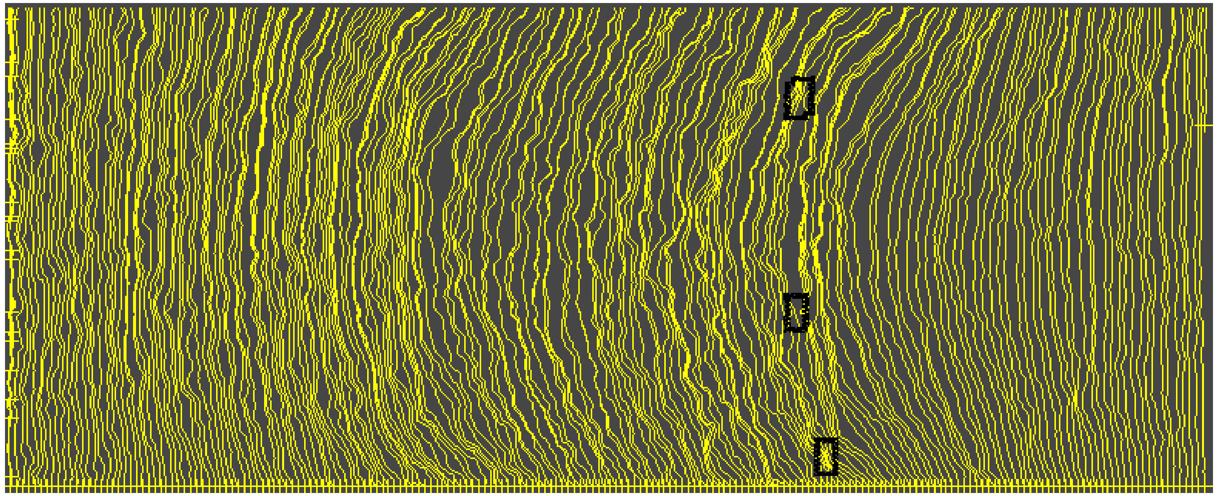
Late distribution of fluid velocity
Yellow is highest



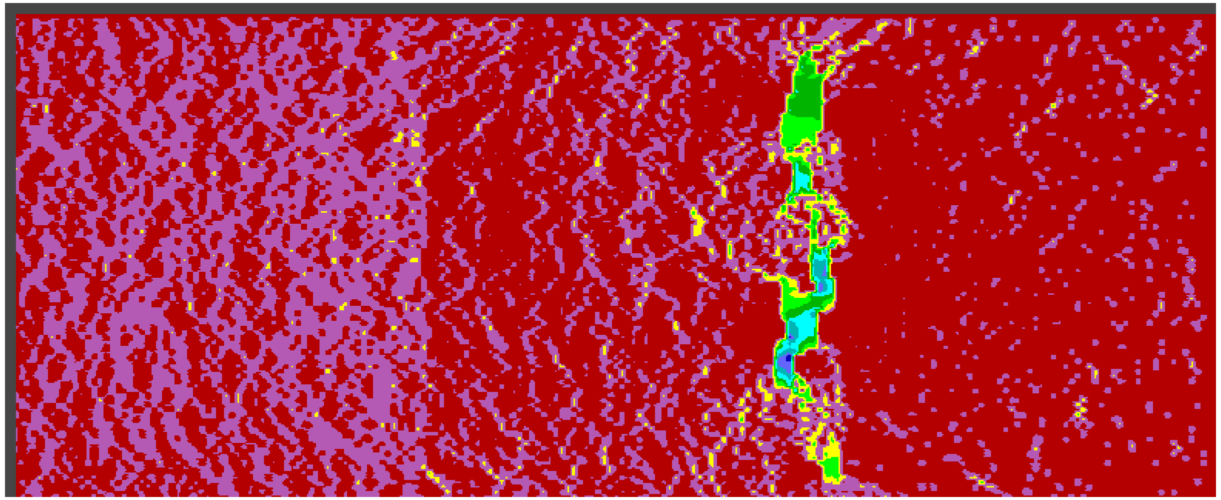
Late distribution stream lines.
No permeability change



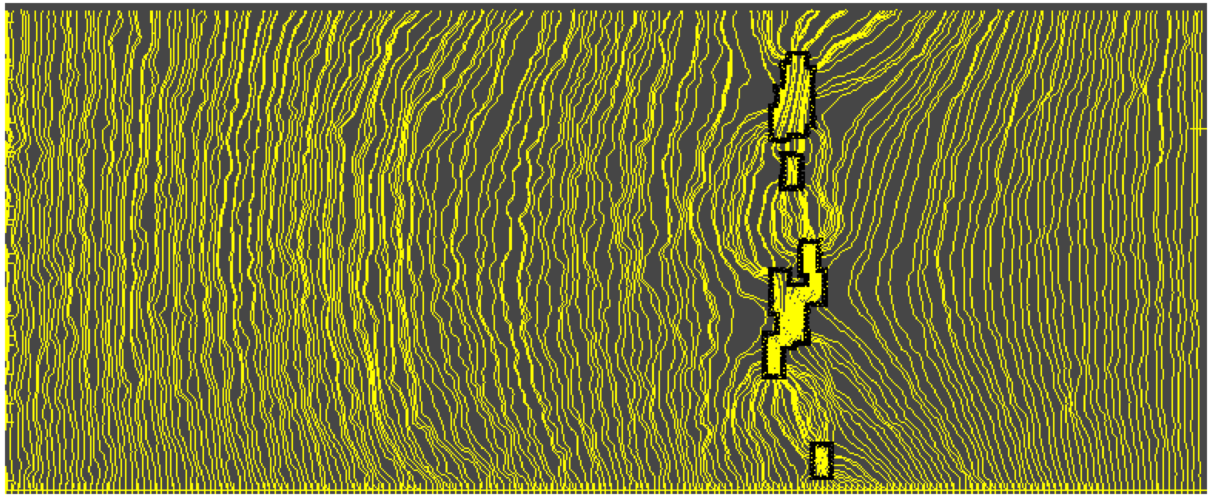
Initial permeability distribution
Pink: 10^{-19} m^2; red: 10^{-18} m^2



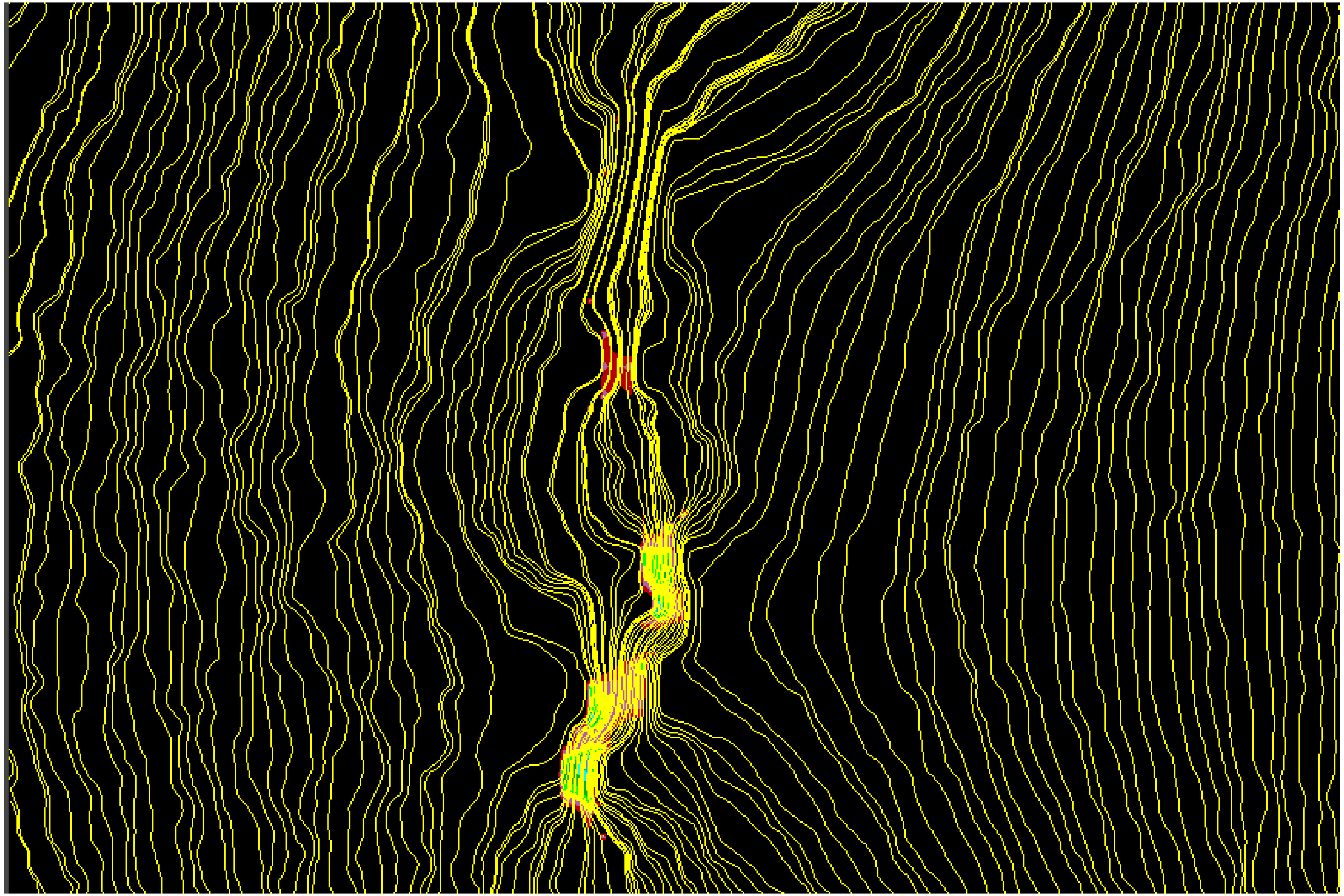
Early stream lines
Black outlines permeability has increased to 10^{-17} m^2



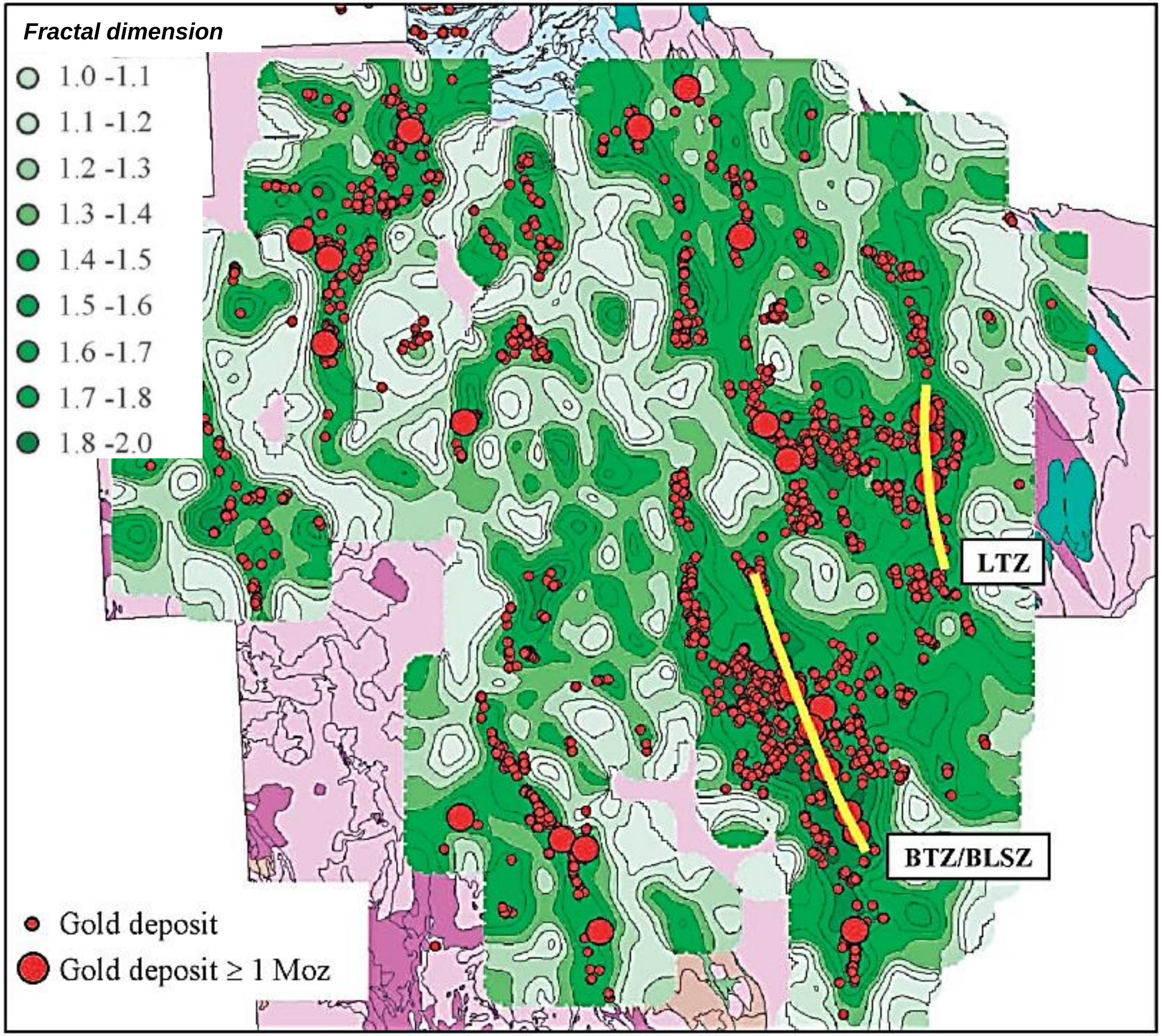
Late distribution of fluid velocity
Dark blue is highest



Late distribution stream lines.
Black: permeability change



Detail of stream lines and fluid velocity: green is highest

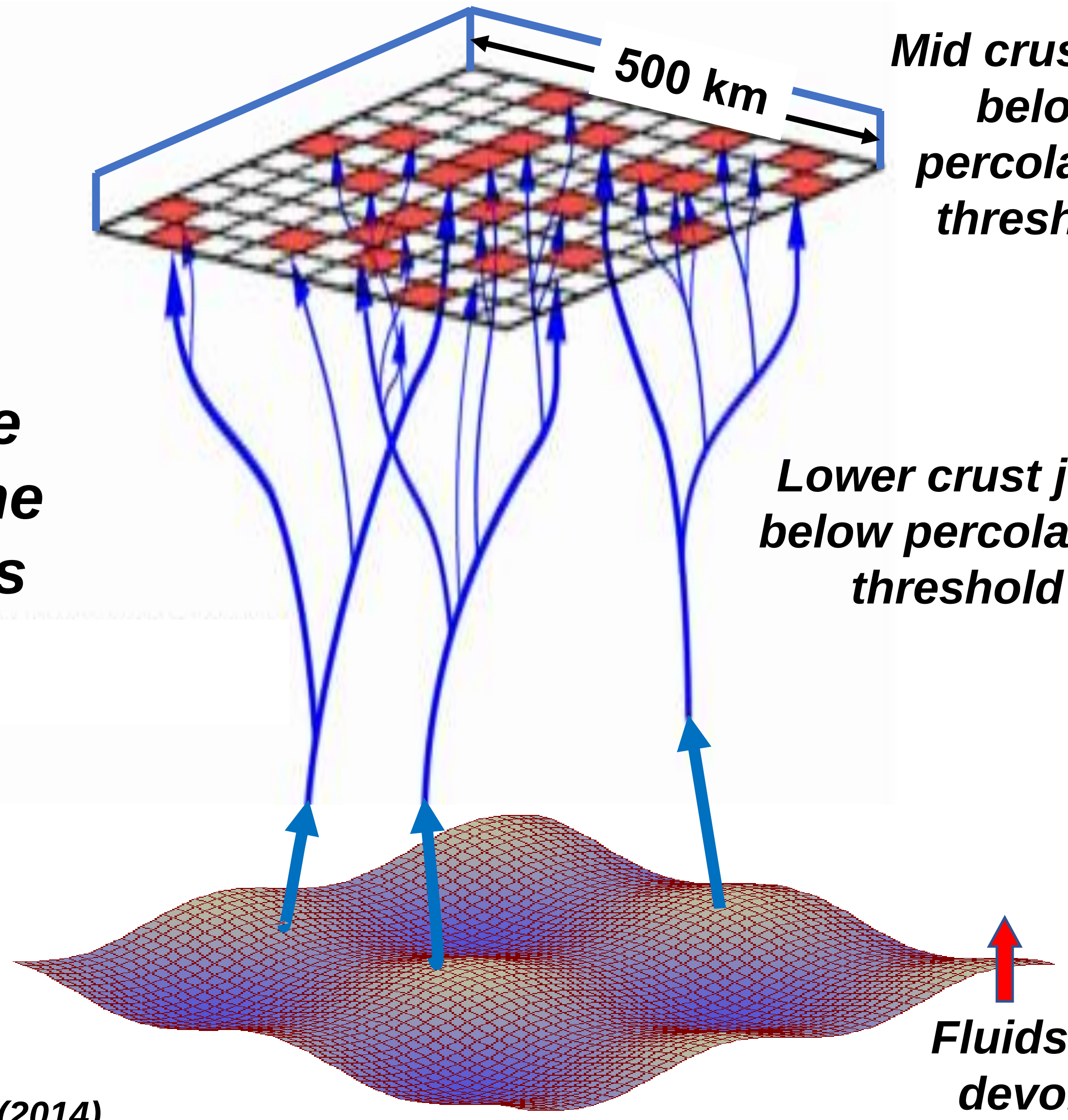


Yilgarn distribution of mineralised sites on gradients between regions of high and low damage density.

From Hodkiewicz et al., 2005

DETECTION OF HIDDEN NODES IN A MINERALISING SYSTEM

How could we tell if one of the red zones was covered?



From Blenkinsop (2014)

Would adding or removing a part of the image significantly change the adjacency matrix?

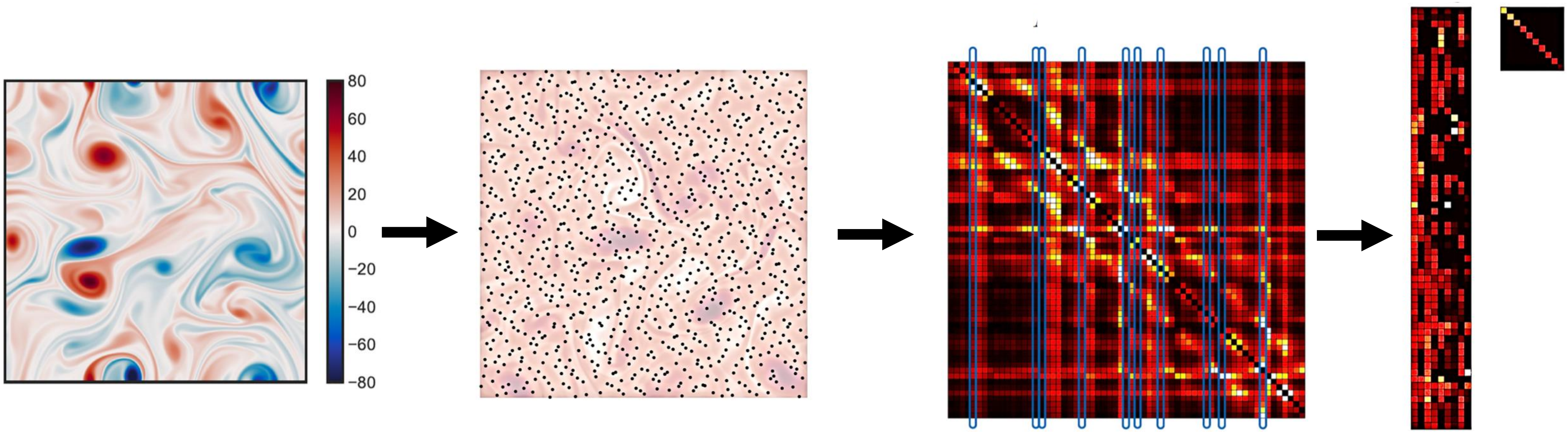


Image | **Image with overlay of random points** | **Adjacency matrix** | **Eigenvectors and eigenvalues**

THE HIDDEN NODE PROBLEM

Consider a network whose topology is completely unknown but whose nodes consist of two types: one accessible and another inaccessible from the outside world.

The accessible nodes can be observed or monitored, and we assume that a data set is available from each node in this group.

The inaccessible nodes are shielded from the outside and they are essentially “hidden.”

The question is: can we infer, based solely on the available data set from the accessible nodes, the existence and locations of the hidden nodes?

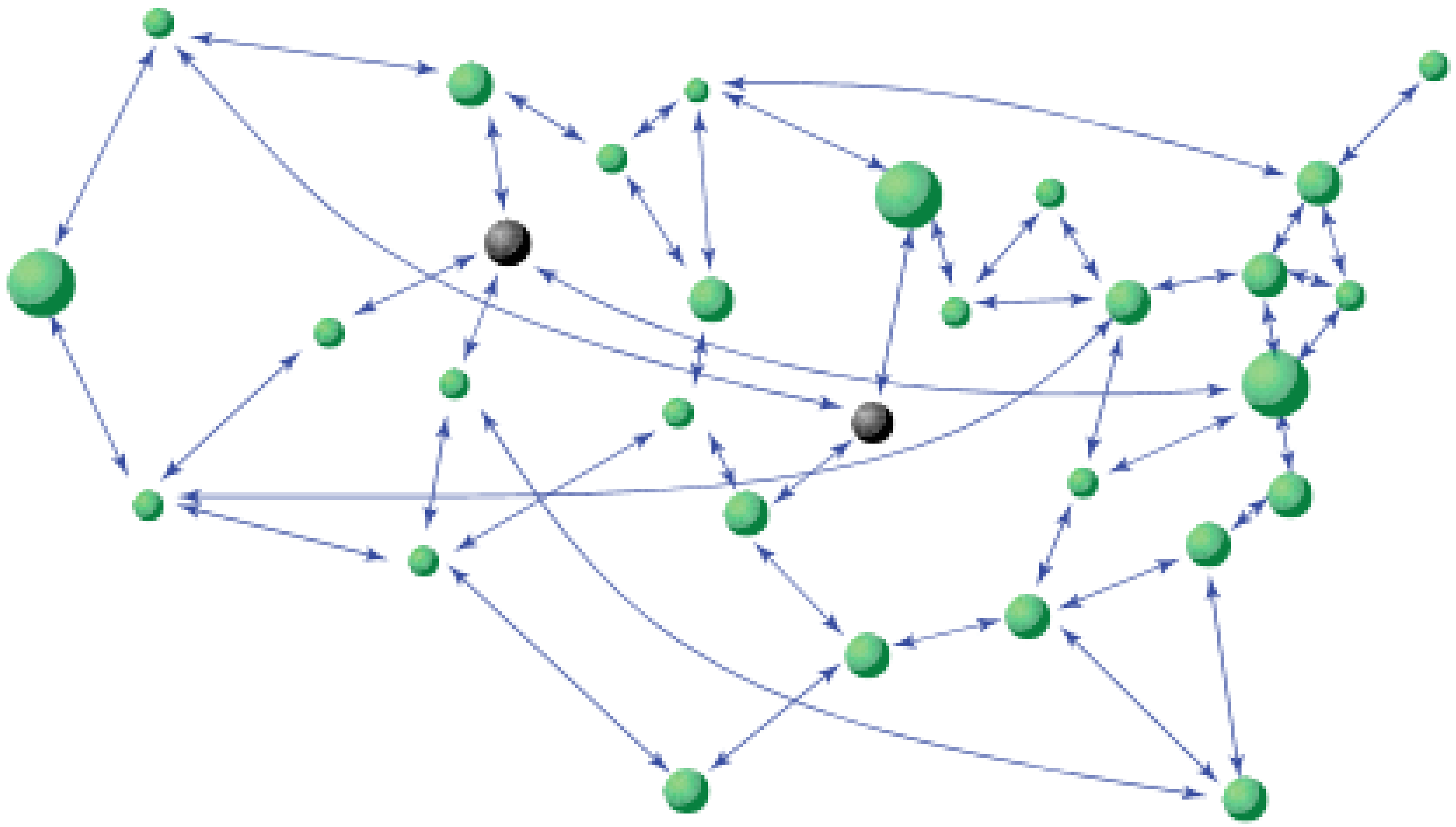
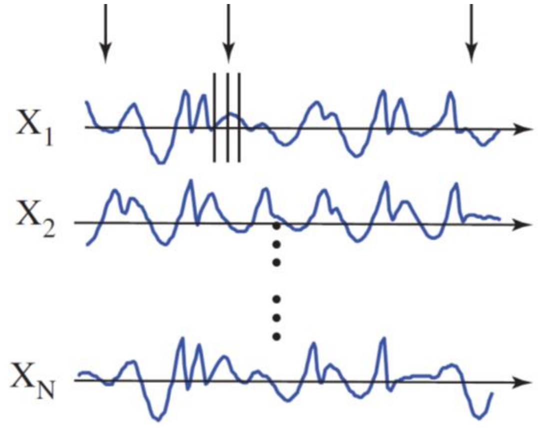


Figure 1. A schematic illustration of a complex geospatial network. The connection topology, the positions of the nodes in the physical space and nodal dynamical equations are unknown *a priori*, but only time series from the nodes can be collected at a single node in the network (e.g. a data-collecting centre). The challenges are to reconstruct the dynamical network, to locate the precise position of each node and to detect hidden nodes, all based solely on time series with inhomogeneous time delays. The green circles denote 'normal' nodes and the dark circles indicate hidden nodes.

White mica signal from each hole



After Su et al., R. Soc. Open Science. 3, 150577

The network of interacting ore bodies can be represented by

$$\mathbf{X} = \mathbf{G} \cdot \mathbf{a}_i + \xi,$$

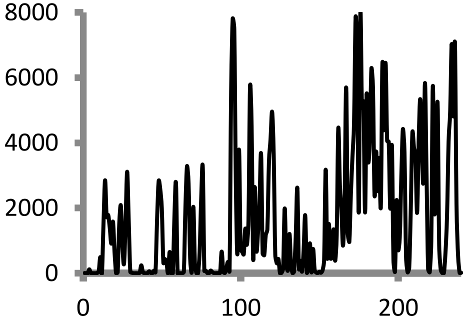
Noise

$$\mathbf{X} = \begin{pmatrix} \dot{x}_i(t_1) \\ \dot{x}_i(t_2) \\ \vdots \\ \dot{x}_i(t_M) \end{pmatrix} = \begin{pmatrix} A_i(t_1) & B_i(t_1) & C_i(t_1) \\ A_i(t_2) & B_i(t_2) & C_i(t_2) \\ \vdots & \vdots & \vdots \\ A_i(t_M) & B_i(t_M) & C_i(t_M) \end{pmatrix} \begin{pmatrix} \bar{a}_i \\ b_i \\ c_i \end{pmatrix} + \xi,$$

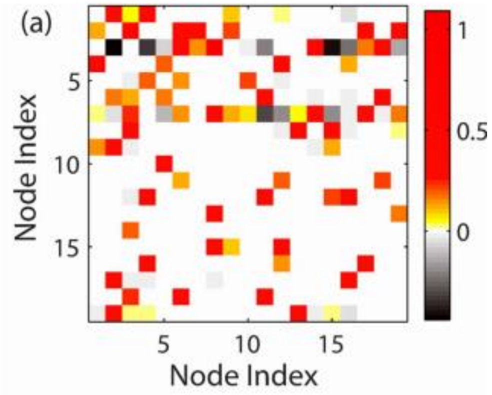
Gradient of signal from each ore body

Calculated adjacency matrix

Calculated coefficients

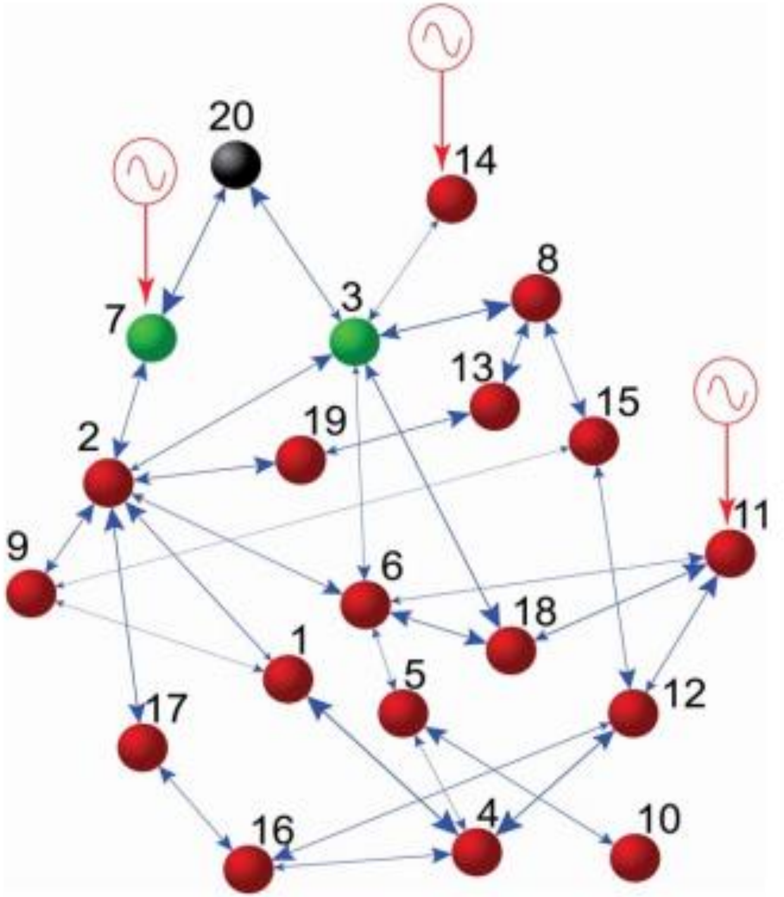


Sericite signal

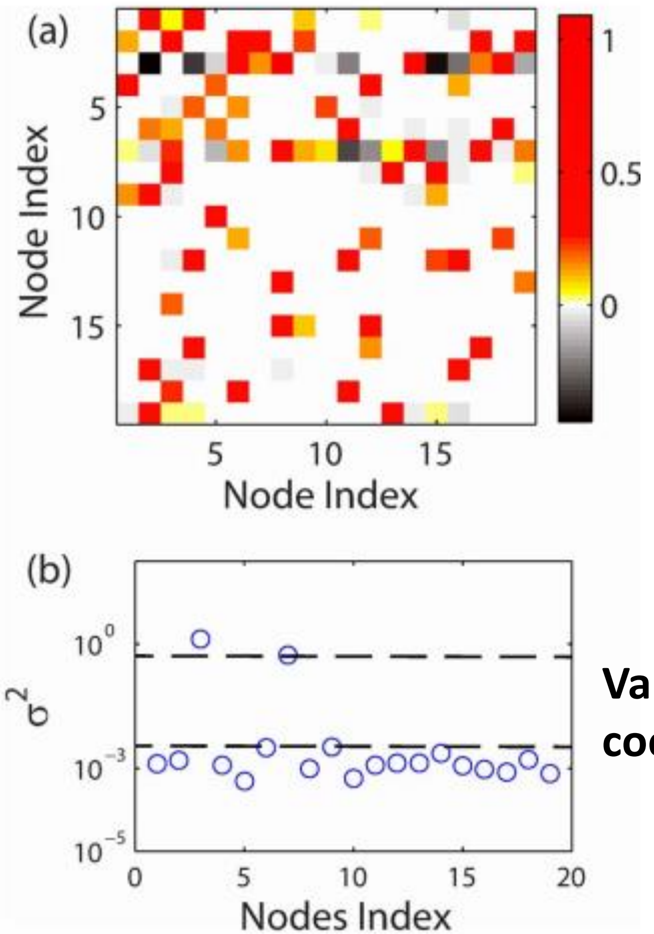


$$\begin{bmatrix} 0.667 \\ 1.332 \\ 0.031 \end{bmatrix}$$

Hidden ore body #20



Calculated adjacency matrix



Variance in coefficients

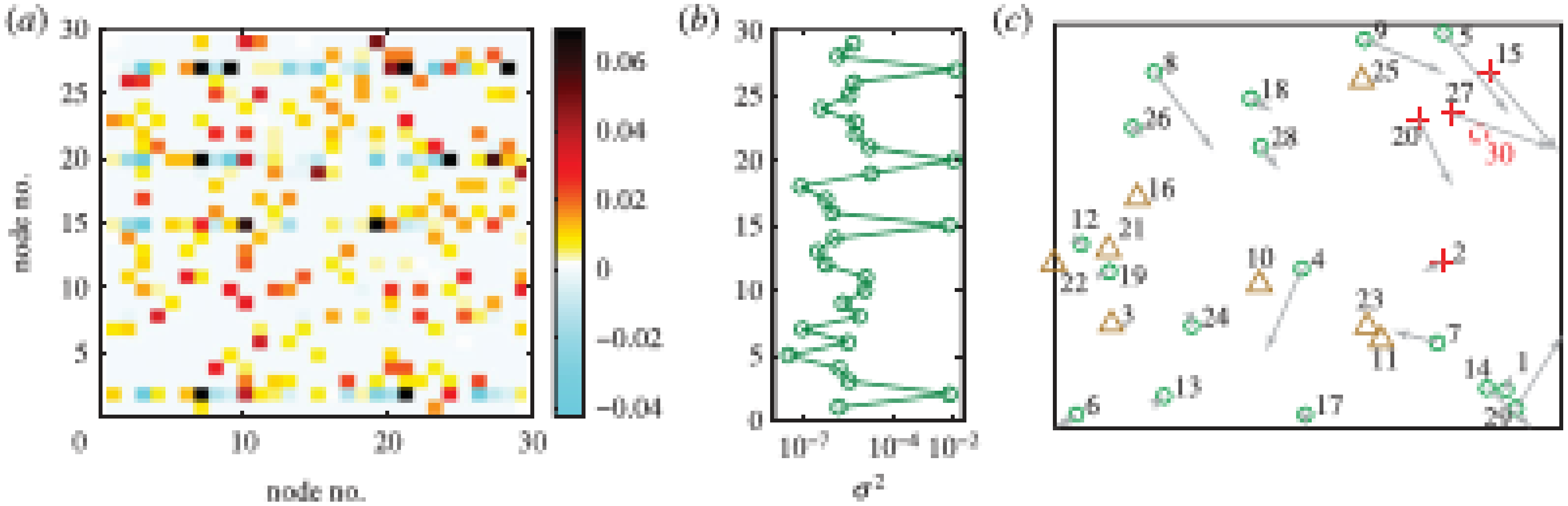
Nodes 3 and 7 are abnormal

Variance is σ^2

From Su et al., Scientific Reports, 2014

Detection of position of hidden ore body by triangulation

Calculated adjacency matrix **Variance in coefficients** **Calculated network**



Anomalous ore body signals from #2, 20, 27, 15

Hidden ore body : #30 located by triangulation

After Su et al., R. Soc. Open Science. 3, 150577

This presentation has illustrated some aspects of mineralising systems that arise because they are composed of:

- **Open flow chemical reactors that may be coupled over many 10’s of kilometres**
- **With coupled mineral reactions some exothermic, some endothermic.**
- **Deformation (including vein formation and brecciation) is also exothermic.**
- **Fluid pressure and chemical reaction rates depend on temperature.**
- **Exothermic and endothermic processes compete.**

Such behaviour is typical of nonlinear dynamical systems

There is much to learn from the regional distribution of mineralisation.

The subject is barely touched.

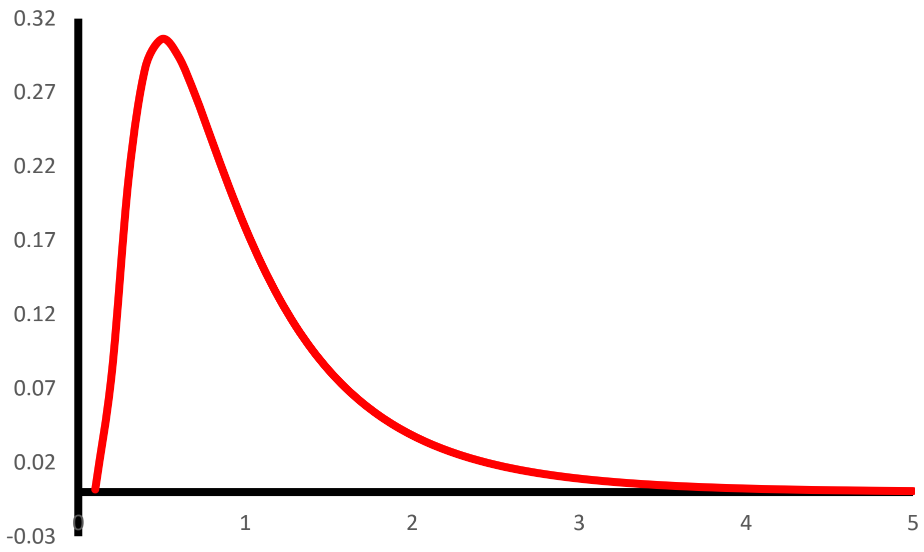
Much could be learnt by treating the distribution of mineralisation as a network.

However a considerable amount of data are required for the hidden node problem.

Not only is a lack of data a problem, cooperation between many companies is required.

Hidden node exploration is probably only applicable at present if one wants to explore close to existing mineralisation.

Thank you



Inverse Gaussian distribution