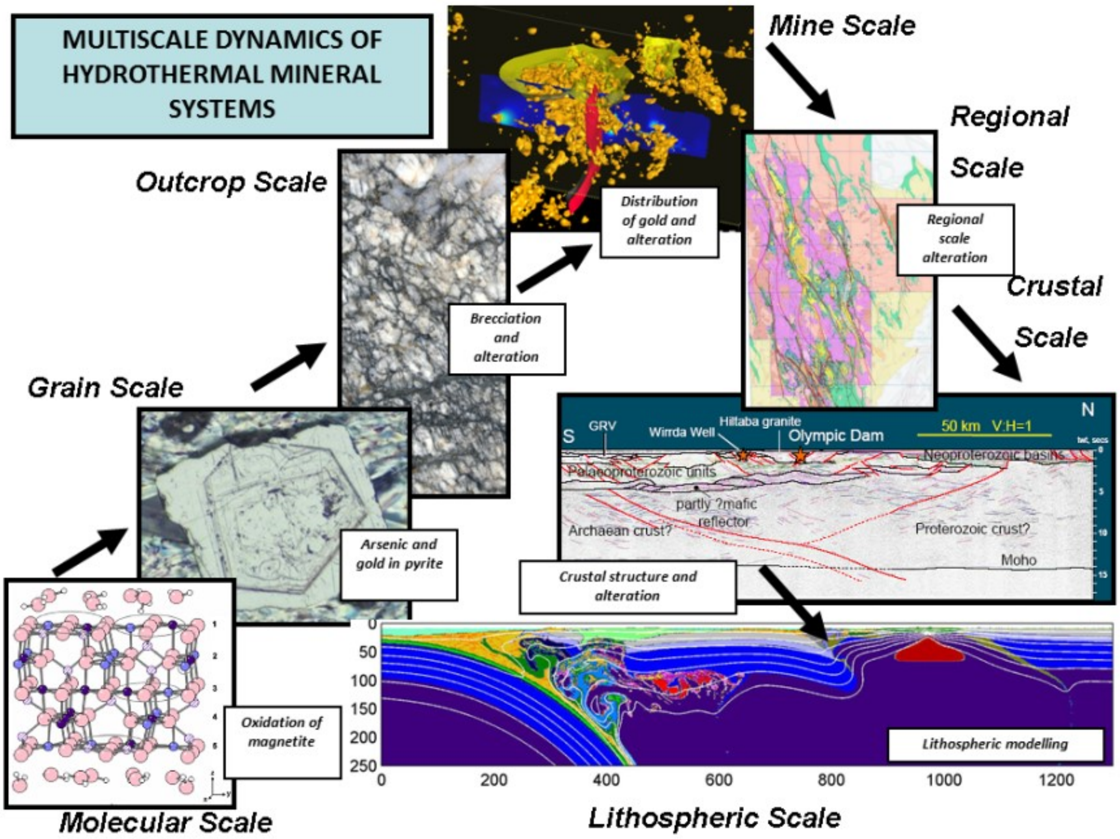
THE PRECIOUS EARTH.

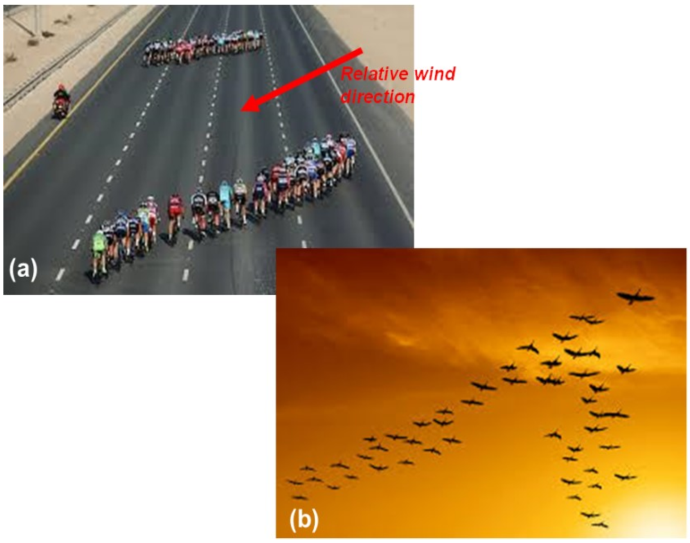
UNDERSTANDING HYDROTHERMAL MINERALISING SYSTEMS.



Preface.

Understanding hydrothermal mineralising systems presents one of the greatest challenges in the geosciences since their operation comprises first order interactions between deformation, hydraulic, thermal and chemical reaction processes. These systems act as giant open flow chemical reactors that are held far from equilibrium by fluxes of momentum, fluids, heat and chemical nutrients. As such they are archetype nonlinear dynamical systems that exhibit all the characteristics of chaotic behaviour both in space and time. In this book we develop an approach to hydrothermal mineralising systems based on chaotic, nonlinear dynamics.

Pattern formation is one characteristic of systems held far from equilibrium. The patterns form because of competition between influences that force the system to evolve and processes that tend to kill the system through dissipation of energy. Examples are the formation of *echelons* in bicycle race pelotons and in bird formations as shown in the Figure below. In both examples the forcing influences are provided by the need to finish the race or the flight and the competing processes are those to do with minimising the energy expended by each rider or bird by adopting positions where individuals are assisted by air pressure eddies generated in the wakes of neighbouring individuals. The nonlinearity that drives the pattern development arises since the power required to move through the air increases nonlinearly with the velocity. If the relation was linear the impetus to form an echelon would not exist. As in any system there are constraints on how the system behaves. In the cycling example a constraint on the size of an echelon is the width of the road.



The bicycle analogue contains most of the features of nonlinear systems including finite size effects (the number of echelons is limited by the number of riders) and cascade dynamics. By this is meant that the system is forced at a large scale (the necessity to win the race, which commonly means the rider with the fastest speed) but energy expenditure is cascaded at finer and finer scales. The coarsest scale is that of an individual rider against wind resistance but energy is expended against friction of the tire on the road, and by friction in the drive train and wheel axles and at finer scales by turbulence generated by the bike frame and wheel spokes. The individual rider attempts to minimise entropy production but the system as a whole is characterised by maximum entropy production.

A hydrothermal mineralising system shows all of these features. The system is driven at the coarsest scale by plate tectonic movements and the thermal structure of the Earth.

Energy is dissipated at finer and finer scales. At the coarsest scale this cascade occurs through energy dissipated by fluid influx and heat transport into the crust. Chemical reactions occur at finer scales, liberating heat through exothermic chemical reactions and brecciation and storing heat in the precipitation of metals and other endothermic reactions. Finite scale effects arise from the finite size of the crust and constraints consist of the permeability structure of the crust and the geometry of resulting fluid flow geometries.

At the regional scale the first order effect of fundamental importance in the formation of a successful mineralised system is the fluid focussing effect that arises when more permeable layers are embedded in less permeable material. This effect arises from an increase in pore pressure gradient within the layer and is approximately proportional to the aspect ratio of the layer for permeability contrast of up to 10^3. Thus in a crustal section with a permeability of 10^{-19} m^2 with an embedded fault with a permeability of 10^{-16} m^2 much of the fluid that enters the base of the crust is focussed into the fault leaving much of the low permeability crust fluid free. If the fault is 20 km high and 10 m wide then the focussing factor is approximately 1000 which means that 1000 times more fluid goes through a 1m^2 cross section of the fault in unit time than if the focussing effect did not exist whilst almost no fluid goes through the surrounding crust. The focussing effect has an additional fundamental influence in that such high fluxes increase the temperature at the top of the fault above ambient so that conditions for the initiation of chemical reactions are enhanced. The presence of thin but deep faults is therefore of fundamental exploration significance since the upper tips or hanging walls of these faults are ideal sites to operate a chemical reactor.

At the scale of the ore system the fundamental nonlinearity is the exponential dependence of chemical reaction rates on temperature. Since most of the early alteration reactions are exothermic (the formation of hydrous silicates such as sericite or chlorite or the deposition of carbonates and iron oxides) the increased temperature arising from fluid focussing needs to be sufficient to initiate the first alteration reactions and the system is then self-enhancing. Such an exothermal reactor is intrinsically unstable and tends to evolve into an oscillatory mode as the increased reaction rates consume the supply of nutrients and/or heat thus resulting in decreased reaction rates, and decrease in temperature until the supply of nutrients or heat rises to increase the reaction rate again. If more than two reactions occur (provided one is exothermic) the system behaviour becomes chaotic. Such chaotic reactors can produce higher yields than ones operating at “steady state” so it is probable that large high grade deposits operated in a chaotic mode for a large part of their evolution.

The importance of chaotic modes of operation lies in the nature of the resulting patterns of alteration, deformation, veining and mineralisation. The thermodynamics of chaotic systems shows that multifractal geometries are a natural consequence of chaotic behaviour and the characteristics of the multifractal spectrum that forms for a particular feature are diagnostic of whether the system operates in sub-critical, critical or super-critical manner. The really high grade hydrothermal deposits operate in a super-critical manner and so the multifractal spectrum is a diagnostic tool to understand how a mineralised system operated. It is fortunate that the widespread collection of chemical and mineralogical data in drill-holes allows such a tool to be used to explore the interior of a mineralised system whereas the chemical engineer has to rely on measurements made at the outlet of the reactor or at a few places in the reactor to monitor the operation of the reactor.

In order to expand and explore these aspects of hydrothermal systems this book is structured as follows.

Chapter 1. Introduction. Thermodynamic systems are classified as open flow systems or as isolated systems. Open systems approach non-equilibrium stationary states whereas isolated systems must always approach equilibrium stationary states. We outline the behaviour of hydrothermal systems as giant open flow chemical reactors that operate far from equilibrium. The various modes of operation are discussed. These systems operate as nonlinear dynamical systems governed by well-defined chemical and physical processes. As such they are deterministic. We present some simple models of the development of chaotic behaviour in deterministic systems.

Chapter 2. Thermal transport. Since hydrothermal systems are driven in part by the input of heat we first consider thermal aspects of these systems. We are concerned with the length scales and time scales associated with thermal effects and the constraints these arguments have for hydrothermal systems at all length scales from the lithospheric downwards. The sources of heat within the Earth are discussed including the development of "plumes" of various kinds, delamination and rising fluids from subducting slabs. An important aspect is that the heat release rate form hydrothermal systems is above that from radiogenic decay in the crust.

Chapter 3. Fluid flow. Fluid flow is the other important driver for hydrothermal systems and here we consider the processes that drive fluid flow in the crust and in the lithosphere. We are particularly interested in this chapter in the focussing of fluids in more permeable layers and the associated advection of heat in moving fluids. We also consider topics such as the possibility of convection in systems that are over-pressured, fluid flow in faults and convection in three dimensions.

Chapter 4. Mineral geodynamics. Hydrothermal systems form in a number of tectonic settings but one that seems to be of great importance but only recently recognised is that of *intra-cratonic* settings. We discuss what the term "lithosphere" means from the mechanical, chemical and thermal points of view and in particular focus on what initiates instabilities in the lithosphere and how these processes control the thickness of the lithosphere and its chemical and thermal evolution. We emphasise intra-cratonic processes relevant to the formation of hydrothermal systems. However, the processes that operate in and below the lithosphere have a clearly defined secular nature. Although intra-cratonic processes may have dominated early Earth history (say pre 3 Ga), subduction processes dominate modern Earth tectonics. Both intra-cratonic and subduction processes seem to have been important in producing hydrous, carbonate, potassic and sodic metasomatism and so we spend some space in considering these issues. In particular, slab roll back offers an effective process for generating short lived, spatially localised, pulses of CO_2. A detailed knowledge of such processes is a fundamental exploration tool and indeed forms part of the paradigm shift we seek in this book.

Chapter 5. Nonlinear dynamics, complexity and critical systems. At some stage the lithosphere must develop sufficient permeability to enable very large volumes of fluid to be transported so as to develop a hydrothermal system. This clearly is a critical stage in the development of these systems and is one that perhaps offers the clearest possibilities for recognition in regional data sets. It is also one of the most poorly understood and defined part of hydrothermal system evolution. We explore some recent developments in understanding fracture systems as critical systems. We emphasise that *self-organised criticality* is but one form of critical behaviour and that other forms leave their marks in the rocks and should be described and mapped.

Chapter 6. Fractals and multifractal distributions. The book proceeds to discuss hydrothermal systems as open flow chemical reactors held far from equilibrium during their evolution and lifetime by the influx of heat and mass. These systems are forced to maintain their permeability in order to accommodate the imposed flow and this means they must evolve through a number of stages that leave their imprints in the rock and generally involve competition between exothermic and endothermic chemical and physical processes. We discuss the principles behind such evolutionary processes and emphasise that the behaviour of an individual system is a sensitive function of both the fluid flux through the reactor and the temperature distribution within the reactor. Small changes in fluid flow and temperature distribution can result in completely different types of behaviour and efficiency of the chemical reactions.

Chapter 7. Fluid mixing. Fluid mixing is commonly proposed as an important process in producing successful hydrothermal mineral deposits yet the mechanism for such mixing is far from clear. We discuss the details of the mixing process and the effects that such processes have on the mineral reactions that are progressing at the same time. Special mixing geometries (typical of stock-works, breccias and some veins) can enhance chemical reaction rates by a million-fold. Additional somewhat unusual effects can mean that the reaction site remains stationary in a moving flow so that these sites become spatially fixed regions of *singularly enhanced* reaction rates. The distribution of such sites is fractal (or multifractal) so that the distribution of mineralisation appears to be quite irregular. We consider unstable reaction scenerios that lead to spatial distributions of pH without the need for fluid mixing.

Chapter 8. Chemical reactions in hydrothermal systems. This chapter forms a tutorial for understanding the elements of nonlinear dynamical systems. We emphasise the influence of nonlinear relationships and the phase transitions these systems undergo including sub-critical → critical → super-critical transitions. Such behaviour is associated with the development of long range interactions and correlations. The automatic development of multifractal behaviour and the importance of intermittent behaviour typical of gold deposits are discussed.

Chapter 9. Multifractals and dynamical systems. Our contention is that hydrothermal systems are nonlinear dynamical systems that leave chaotic signatures in the rock record. This chapter considers some well-established techniques for considering such systems including establishing their fractal and multifractal characteristics, attractors and measures of whether the system had become critical or not. Such techniques are essential in determining whether hydrothermal system had been operating as a highly efficient chemical reactor or had just sat in the crust of the Earth resembling more a smouldering camp fire. We show that large, well-endowed mineral systems have completely different multifractal characteristics to smaller, less endowed systems.

Chapter 10. The Yilgarn gold deposits as a case study. Here we use the vast amount of data at all scales accumulated for the Yilgarn gold deposits over the past 100 years to illustrate the points made in this book.

Chapter 11. Nonlinear dynamics of key mineral phases in the Yilgarn. This chapter complements the previous chapter and consider the mineral distribution framework associated with the gold deposits. The common vein-hosted mineralogy (calcite and ankerite), host-rock alteration mineralogy (sericite), regional-scale metamorphic assemblages (chlorite and amphibole) and Au in hydrothermal systems are shown to organize spatially as multifractals. Further, the degree to which the multifractal signatures (spectrum range) of two mineral phases or elements in an ore body align with one another may be utilised as a measure of the degree to which the processes responsible for their spatial organization are linked.

Chapter 12. Episodic behaviour in alteration and coupled alteration-deformation processes. The intrinsic instability of chemical reactions in open flow systems is explored to illustrate the episodic behaviour of hydrothermal systems. Oscillations in temperature lead to oscillations in fluid pressure and in the equilibrium solubility of gold. We present a model that allows the concentration of deposited gold to be examined and the influences of operating conditions on the grade of the deposit explored.

Chapter 13. Discussion and synthesis. We finish the book with a synthesis of this nonlinear approach. This chapter includes a summary of important aspects of the book and outlines a new paradigm for mineral exploration.

Acknowledgements. This book is the outcome of projects funded by grants from the Australian Research Council (Project: LP100200785, Multiscale Dynamics of Ore Body Formation), and MRIWA (Project: M424, Multiscale Dynamics of Hydrothermal Mineral Systems). We thank The Geological Survey of Western Australia, First Quantum Minerals Ltd., AngloGold Ashanti, and Silver Lake Resources for financial support and access to data. We also thank Greg Hall, Julian Vearncombe and Marcus Willson for encouraging us to explore non-linear systems. Sarah Firth, Sandi Occhipinti, Tony Roache, Catherine Spaggiari, Ian Tyler and Cam McCuaig are thanked for discussions and facilitating access to data.

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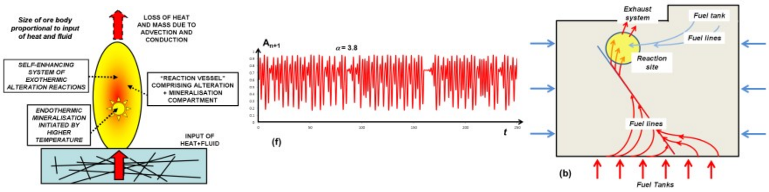

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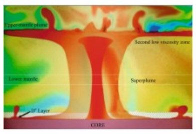

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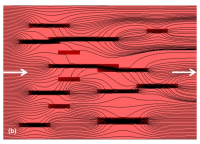

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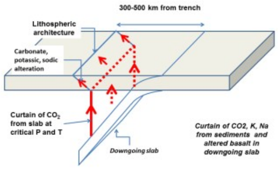

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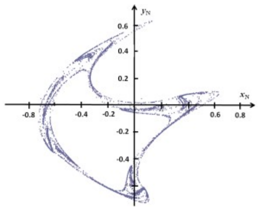

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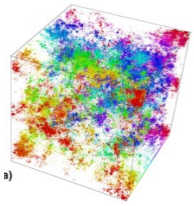

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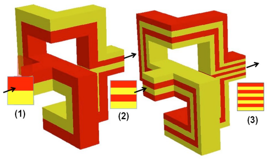

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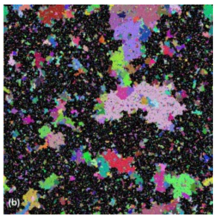

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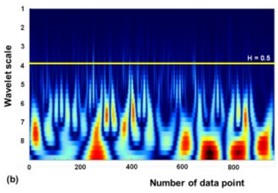

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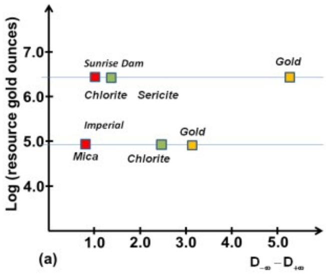

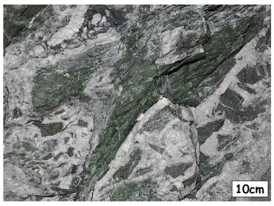

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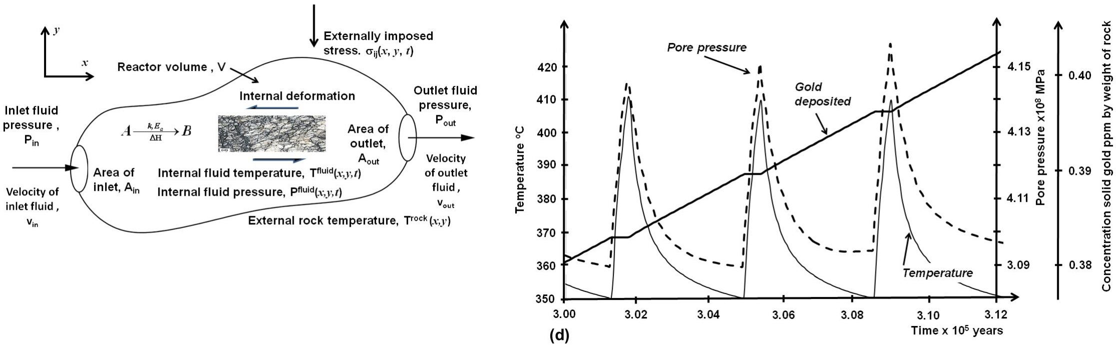

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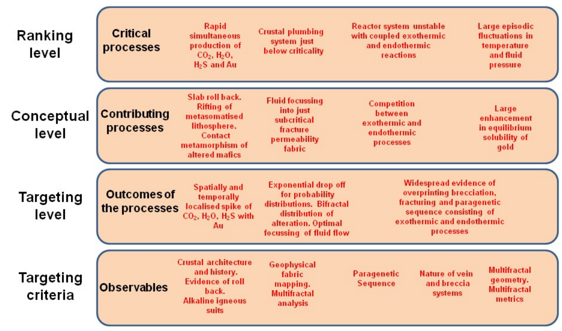

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