Chapter 13.
Discussion and synthesis.
October_25_2016.

13.1. Introduction.

At the time this book is written there is a crisis world-wide in the mineral exploration industry. This crisis is largely driven by low commodity prices but the situation is compounded by a lack of trust by the investment community in the ability of mineral explorers to discover significant new resources at a reasonable cost. Some even go as far as to assert that the mineral exploration process destroys wealth. The situation is exacerbated by the change in the structure of the mineral industry over the past two decades characterised by the withdrawal of the major mining houses from green-fields exploration and from supporting research. Because of the expense and risk associated with exploration the large mining houses prefer to grow by acquisition rather than from home grown discovery. The outcome is that the small companies need to become more nimble and smart in the discovery process. This in turn necessitates the development of new ways of thinking about ore genesis and translating this knowledge into new, practical exploration tools. There is also a perception amongst investors that many ore body models are to be mistrusted, further decreasing any incentive for investment. Any new advance in thinking should enable more accurate ore body models to be produced.

At least in Australia, future discoveries of mineral deposits will be under significant cover by more recent materials with no exposed geology or surface geochemical anomalies; the potential for such discoveries is very large since at least 50% of the highly prospective areas are under cover. The only direct data likely to be available is geophysical in nature with the occasional deep drill hole. These data sets need to be combined with new syntheses of the geodynamic evolution of the lithosphere gained from the new geophysical data sets. Hence we need a paradigm shift in the way we explore for minerals. Such a shift needs to be based on new ways of thinking about the processes that generate ore bodies so that targets in geophysical data sets can be better recognised and prioritised and so that information and insights are optimised in the initial stages of drilling. Thus, these new ways must be translated into a conceptual framework that links scientific understanding to the practical application of this understanding in mineral exploration but the first step is to develop new ways of delineating the basic processes and dynamics involved.

The paradigm shift we explore is to move from the largely empirical, linear models of ore formation that have dominated the discipline over the past 100 years to nonlinear models based on the progress that has been made in the study of nonlinear dynamics in other physical-chemical systems over the past 50 years. Such an approach is widely developed in material science, biology, chemistry and a range of other disciplines but has almost no exposure in mineral exploration science. This book is a first attempt at the development of a comprehensive theory of the nonlinear dynamics of hydrothermal mineralising systems.

13.1.1. Characteristics of the classical linear approach.

The classical approach to mineral exploration has the following characteristics:

(i) Since advances in technology enable us to collect very large amounts of data on a vast range of physical and chemical rock properties, these data are collected at every opportunity, at finer and finer detail, in the search for some form of pattern or association will emerge that enables a discovery to be made. Technology advances are commonly driven by the perceived need to measure quantities at finer and finer levels rather than to measure the imprint of processes that are the physical and chemical basis of the mineralising process. Fusion of data sets is common with the goal that if disparate, but empirical, geophysical and geochemical data-sets are merged then again some pattern of interest will emerge. In this regard the minerals exploration process differs from that in the petroleum industry where technology is designed to measure quantities such as porosity and permeability which are directly involved in the hydrocarbon migration and entrapment process. In the minerals exploration industry, the technology is designed to measure magnetic susceptibility, density and electrical conductivity, quantities that have nothing directly to do with fluid migration, chemical reactions and reactor exhaust processes.

(ii) Pattern search procedures dominate the approach. The concept involves looking for associations and patterns in the data that contribute to some established exploration model. These pattern searches are based on empirical associations that are developed for forms of mineralisation known from elsewhere. The associations sought might be closeness to faults or to intrusions of a favourable composition, density of fractures, brittle wall rocks of a particular composition that might host mineralisation, and key alteration assemblages or geochemical/geophysical signatures.

(iii) Classical statistics are used to make correlations between data sets and in estimating the probability of success of an exploration program with the underlying assumption that the statistics are Gaussian so that the concepts of a mean and variance have a statistical meaning. There is also an underlying assumption that the variables involved are “random” and that no correlations exist within the data. However, most of the data sets are “fractal” in nature, long range correlations exist and the concepts of mean and variance are statistically meaningless, so that such assumptions are unjustified. The use of classical statistics extends to the use of linear regression, weights of evidence, fuzzy logic and kriging in the development of ore body models. Since many fractal distributions can be approximated by a Gaussian distribution over a limited range in the data, and classical statistics can be readily applied, the use of classical statistics has great popularity even though the underlying processes are fractal. Implicit in most variogram modelling is a scale beyond which spatial dependence breaks down (the range). This is not a characteristic of fractal systems where long range correlations are the defining characteristic. We suggest this is the origin of many poor attempts at ore body models. The assumption of a Gaussian distribution also neglects contributions to the real distribution from the tail of the distribution; this is unfortunate because commonly this is where all the interesting and significant geological data sit.

(iv) Linear models of ore formation are adopted that involve classical concepts of wall rock reaction, focussing of fluids in structures, phase separation and fluid mixing with enormous detail and expense attached to establishing the chemistry of the system. Mineral reactions are written and discussed with no coupling between the reactions so that nonlinear, and hence episodic, critical and self-enhancing chemical behaviour cannot emerge. Little or no attention is paid to the physics or mechanics behind these processes. Commonly if the physics is discussed the concepts involved are physically incorrect. Examples include the postulate that fluid flow in open systems is driven by mean stress, fluid flow can be downwards continuously from the surface into a region of lithostatic pressured fluid and that convection is possible (on the planet Earth) in compartments with a lithospheric fluid pressure gradient. Commonly the models generated do not conform to the second law of thermodynamics so that the boundary conditions imposed or implied require an external agent (a Maxwell Demon) to do work on the system; examples include fixed temperature or pressure conditions on the boundaries of the system rather than heat or mass fluxes. The archetype linear postulate is that mineral systems are at equilibrium during their formation and that chemical equilibrium thermodynamics can be applied to these systems during their development. The argument commonly goes as follows: *The ubiquity of characteristic alteration assemblages and the rationalisation of such assemblages in thermodynamic terms make it clear that mineral–mineral equilibrium and metastable equilibrium apply on a local scale and can be used to understand the origins of most assemblages*. Such a notion assumes that equilibrium is the only condition that produces systematic order in a chemically reacting system. This is not the case and systems not at equilibrium but at stable stationary states display order also.

13.1.2. The nonlinear dynamics approach.

An approach based on nonlinear dynamics recognises that hydrothermal systems, while they operate, are chemical reactors held far from equilibrium by the influx of heat, of chemical components in solution and of momentum. Such systems operate far from equilibrium for as long as these inputs are maintained and suitable reactants exist within the system. The processes involved are intrinsically nonlinear so that the evolution of the system is unsteady and for the most part, chaotic. Such behaviour emerges as soon as one couples two or more nonlinear processes; periodicity arises with two coupled processes and chaos with more than two. The term *chaotic* does not mean random or without structure, it simply means that the behaviour of the system is sensitive to initial conditions and to small perturbations in the operating conditions of the system. These systems operate in well-defined ways that are governed by the competition between the energy and mass supplied to the system and dissipation of this energy and consumption of the mass by chemical, thermal, hydraulic and deformation processes within the system. A characteristic of such systems is that they evolve to a non-equilibrium state characterised by the formation of spatio-temporal patterns where the supply of energy and mass balances the dissipation and rate of consumption. Such states however are not always stable and the system oscillates about this non-equilibrium state in a periodic or chaotic manner or may switch to another non-equilibrium state. The instabilities arise from competition between mass and energy supply and consumption processes.

Chemical engineers involved in the design and operation of industrial chemical reactors have understood the principles behind stable reactor operation for close to 100 years. Thus Liljenroth, in 1918, realised that in order to control the sometimes violent oscillations in temperature that occurred in his ammonium oxidation plant, he had to control the rate at which heat was removed from the reactor. In some common chemical reactors the uncontrolled oscillations in temperature can be as high as 300 – 500°C. The design of commercial chemical reactors is based on the fundamental principle that the rates of chemical reactions in open systems are governed by the rates of supply (or removal) of nutrients and heat and not simply by the chemical kinetics one would observe in closed systems. Chemical engineers have learnt to juggle and adjust the various inputs and outputs so that the reactor operates in a stable manner with a yield that is as high as possible whilst still maintaining stability. It is well known that even higher yields are possible in unstable reactors but the operation of an unstable commercial reactor needs to be balanced against the possibility of destruction or shut down of the reactor.

Natural chemical reactors, that is, hydrothermal systems, operate in unstable manners as is evidenced by the widespread development of compositional zoning in minerals, episodic vein growth, breccias, stock-works and of overprinting episodes of veining, brecciation, stock-works and of paragenetic sequences; by analogy with commercial chemical reactors perhaps those systems that operate in unstable manners have the highest yield (that is, ore grade). The principles that govern the operation of natural reactors are exactly those that govern the operation of industrial reactors. The paradigm shift we seek in understanding natural chemical reactors derives from the principles involved in designing and operating commercial chemical reactors. In the following we summarise much of the discussion in this book and discuss the results of exploring the behaviour of hydrothermal systems as nonlinear, non-equilibrium dynamical systems.

13.2. Implications for regional distribution of mineralising systems.

Hydrothermal systems in common with most nonlinear systems such as weather and ocean circulation systems are characterised by being forced to evolve by energy supplied at a large spatial scale; in order to do so they adopt mechanisms of evolution that involve dissipation of energy at finer and finer spatial scales. Hydrothermal systems are one mode of cooling for the planet Earth. Thus, plate tectonic motions driven by cooling of the Earth at a global scale drive the development of through-going lithospheric faults and associated damage zones that focus mantle derived fluids. Energy is dissipated by these deformation processes and by the flow of fluids through the deformed regions. Energy continues to be dissipated by exothermic chemical and deformation processes at finer and finer scales until ultimately any energy in the system is stored by endothermic reactions such as the deposition of sulphides (such as pyrite), non-hydrous silicates (such as K-feldspar) and metals (such as gold) or is dissipated by heat conduction and advection to the surface of the Earth where it is radiated into space. This process of dissipation at finer and finer scales has considerable structure within it; such energy cascades are multifractal in the energy distribution. Thus hydrothermal systems are multiscale dynamical systems and need to be studied using the insights and tools developed to study such systems over the past 50 years or so. This involves knowledge gained from statistical mechanics and the thermodynamics of chaotic systems.

Orogenic gold systems differ from regional metamorphic systems in many ways considered in Chapter 12 but the fundamental difference as far as the dynamics of the system are concerned lies in the different time scales of evolution. Orogenic gold systems operate for perhaps 1 million years at a maximum with time scales << 1 million years highly likely whereas regional metamorphic systems operate for 10's of millions of years at a minimum. Hence the heat release rates from exothermic chemical reactions in orogenic gold systems are greater than ambient heat generation rates from crustal radiogenic decay by several orders of magnitude; the heat generation rates from exothermic chemical reactions in regional metamorphic systems are less than that produced by crustal radiogenic decay. This means that the opportunity exists for orogenic gold systems to increase in temperature above ambient crustal temperatures once the alteration reactions begin.

At some stage the temperature in the hydrothermal system becomes high enough to initiate hydrothermal alteration systems. Since the rates of chemical reactions depend exponentially on temperature the rates are very slow at low temperatures but become appreciable (on the time scale of observation) once a critical temperature, T_c, is reached. This is known as the *ignition temperature*. For the reactions to proceed at an observable rate the equilibrium temperature, T_e, must be significantly overstepped. Thus the ignition temperature is always greater than the equilibrium temperature, $T_c > T_e$. The ignition state is unstable for most exothermic reactions of interest and the system jumps immediately to a higher temperature state. If the temperature is then decreased (for instance because heat is absorbed by an endothermic process) the reaction is extinguished at the *extinction temperature* and the system temperature drops to a state close to T_e. If the temperature is then raised by heat from an exothermic process the cycle is repeated and episodic behaviour emerges as discussed in Chapter 12 and summarised in Sections 13.3.2 and 13.3.3.

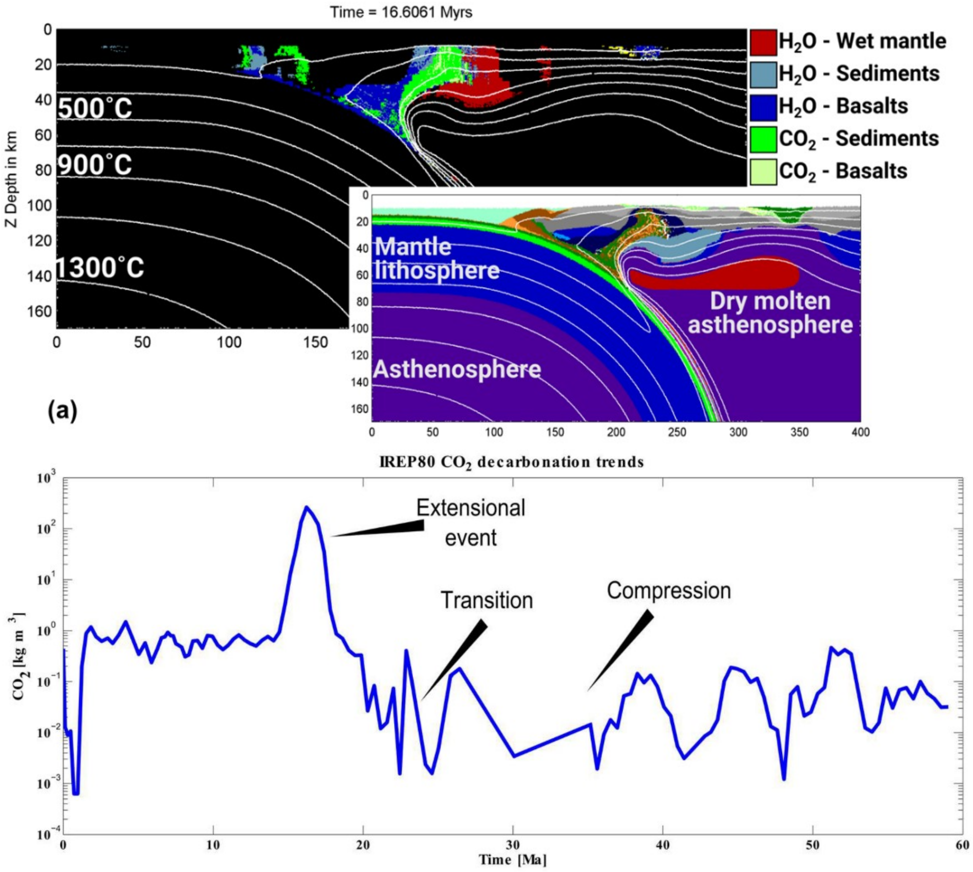
Orogenic gold systems initially involve exothermic chemical reactions whereby anhydrous silicates such as feldspar and pyroxene are converted to hydrous and carbonate assemblages containing phases such as micas, chlorites, siderite and ankerite by the influx of CO_2 and H_2O. The heat released from these exothermic reactions is sufficient to elevate the temperature of the reacting alteration package above ambient (which means above the temperature of the incoming fluids) and to initiate a new set of chemical reactions that involve the partial or complete dehydration/decarbonation of early formed alteration assemblages. Reaction of sulphur species in the incoming fluid with iron stores energy in endothermic reactions that produce iron sulphides. The episodic temperature changes during the operation of these unstable processes induce episodic changes in fluid pressure leading to episodic veining brecciation and increments of mineral (including gold) deposition.

13.2 1. The sources of CO_2.

One of the first fundamental questions to be resolved is: *Where do the hydrothermal fluids come from*? Since, for orogenic gold systems these fluids are commonly rich in CO_2 the answer lies in establishing sources for CO_2 rich fluids in the mantle or crust of the Earth. Four possibilities arise: Decarbonation of sediments and diagenetically altered igneous rocks taken down with a subducting slab. (ii) Decarbonisation of parts of the mantle that have been metasomatised in an earlier event. (iii) Decarbonation of previously altered mafic igneous rocks within the crust. (iv) Release of fluids from magmas that have incorporated CO_2 from their source melting environment.

The postulate that CO_2 is derived from regional metamorphism of altered crustal mafic rocks is quite common. The model is attractive because CO_2, H_2O, H_2S and gold can be sourced from the same rocks in the crust in the volumes required to produce a large gold deposit. *The synchronous supply of these chemical components is essential in producing a gold deposit*. However the model suffers from a direct link to a focussing mechanism and to a direct association with distinct, short lived tectonic events such as extension. Perhaps the real problem with this crustal model is the time scale required to release the CO_2. Since the release is due to regional metamorphism the rate of release is controlled by the rate at which regional isotherms can rise though the devolatilising mafic sequence. This occurs through conduction and hence is slow, measured in fractions of a millimetre per year at most. The time scale to produce CO_2 is 10’s of millions of years at a minimum whereas the ore bodies form in << 1 million years.

Recently the phase equilibria involved with devolatilisation of carbon bearing sediments and igneous rocks have been established for mantle conditions. Although H_2O is well known to be released from the downgoing slab, the low temperature of the slab in general means that CO_2 is not released until depths greater than the 310 km discontinuity. However recent modelling has shown that very large amounts of CO_2 can be released from relatively high in the slab synchronously with H_2O during a roll back event in association with local decompression melting of the mantle in the vicinity of the slab (Figure 13.1). The event is localised both in space and time and lasts for ≈ 5 million years since the devolatilising material in the slab is advected through the isotherms at rates of 5 to 20 cm per year. It is also associated with an extensional event in the lithosphere with a close association both in space and time to the potential production of alkaline igneous plutonic and volcanic rocks. The short time scale of synchronous CO_2 and H_2O production in volumes sufficient to produce a large gold deposit, the access to gold and H_2S in the slab materials, the association with a short extensional event and the potential association with alkaline igneous rocks makes this model very attractive for the production of orogenic gold deposits (Figure 13.2).



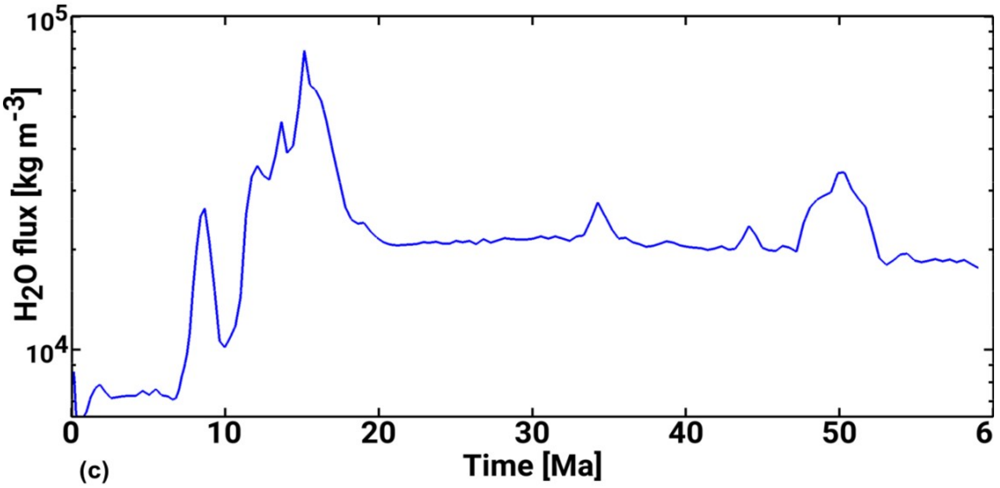


Figure 13.1. The derivation of CO_2 and H_2O from the subducting slab. (a) A snapshot of subduction geometry at the time of roll back. A plume of CO_2 and H_2O is released from the slab at the time of roll back by increased local temperatures associated with the local decompression melting of the mantle. This event is quite localised both in time and space and lasts for ≈ 5 million years. It is associated both in time and space with melting of the lithosphere and the opportunity to access mantle derived alkaline igneous rocks. The inset shows the association of roll back with short-lived decompression melting in the lithosphere. (b) The evolution of CO_2 production. The roll back event is associated with increase in CO_2 production by two and a half orders of magnitude and occurs at an extensional event in the crust. (c) The evolution of H_2O production. The roll back event is associated with increase in H_2O production close to an order of magnitude.

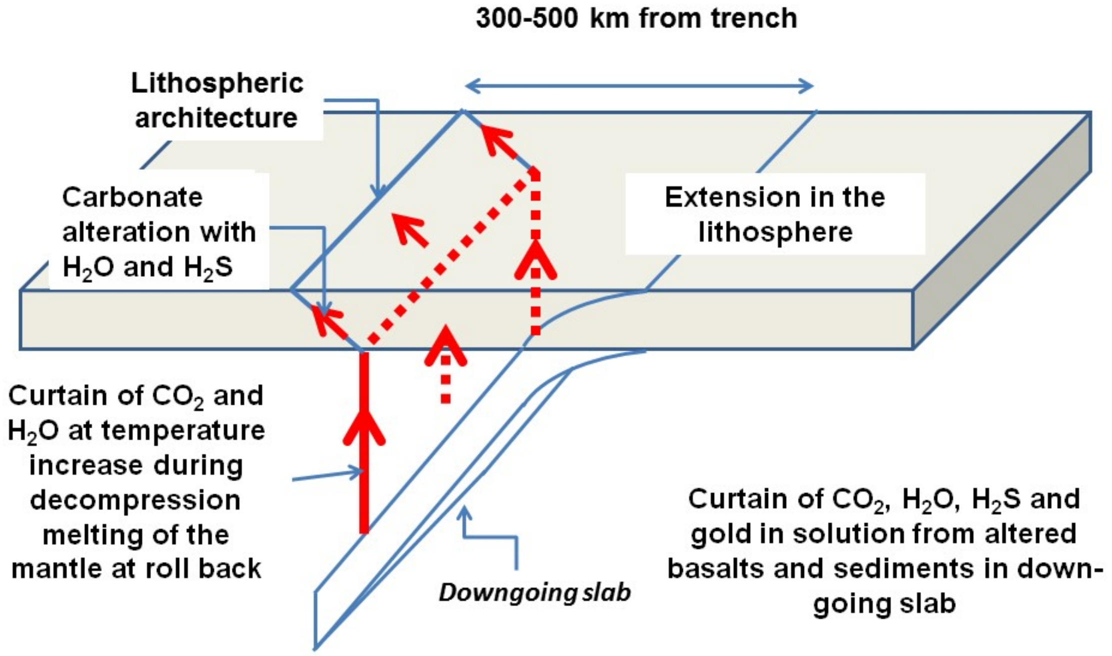


Figure 13.2. The production of CO_2 as a curtain rising off the subducting slab during roll back. The devolatilisation arises from local decompression melting of the mantle during localised roll back. Inspired by Gonzalez (2016).

The important point that distinguishes a roll back slab process from a regional metamorphic process for the origin of CO_2 is the time scale involved. Any process other than roll back that advects the devolatilising rock mass through the devolatilisation isotherm rapidly will produce similar results to the roll back model although perhaps not with the same high volume production of CO_2 as in the roll back situation. Examples include the edges of rifts in previously metasomatised lithosphere (Figures 4.18 and 4.19) and the edges of plutons intruded into altered crustal rocks.

The other mechanism for producing fluids rich in CO_2, H_2O, H_2S and Au is release from a crystallising magma rich in these components; this commonly is an alkaline granitoid or volcanic suite. Here the rate at which fluids are released is controlled by the rate at which the solidus isotherm moves through the magma as it solidifies. This is of the order of 2 – 50 cm y^{-1} (Figure 2.14) and so is comparable with rates of release of volatiles from the slab during a roll back event. It may be difficult to distinguish an intrusion related source for a slab roll back source since both are likely to occur at the same time and in the same place.

13.2.2. Critical plumbing systems.

Of particular importance is the concept that the regional control on hydrothermal systems lies in critical behaviour of the crustal plumbing system. In a region of the crust with initially low permeability subjected to deformation that increases the permeability, the focussing of fluids is controlled by the formation of patches of interconnected high permeability material. This focussing effect, which depends on the permeability contrast and the aspect ratio of high permeability patches (Chapter 3), is the first order nonlinear effect responsible for the development of hydrothermal systems.

In order for the fluid flux to be high and for interconnected porosity to remain open the fluid pressure gradient must be near to lithostatic. The system can be regarded as controlled by a flux imposed at the base of the system arising from devolatilisation of the down going slab, devolatilisation of a crustal metamorphic system or from crystallising magmas. Criticality in this system is marked by the first interconnected high permeability cluster that connects the base and top of the system. This is known as the percolation threshold. In any system approaching the percolation threshold the size of interconnected high permeability clusters increases according to a power law relation that depends on the departure from criticality. In many (if not all) systems approaching criticality the probability of occurrence of interconnected patches is characterised by what is commonly described as two power law distributions represented by two fractal exponents (Figures 13.3 a, b, c). This is sometimes called a *bifractal distribution*. In fact only one of these distributions (the low slope distributions in Figure 13.3) is fractal; the other is an exponential decay of probability with size. The cross-over between the two distributions scales with the size of the system (Figure 13.3 c). At criticality the probability distribution is characterised by a single power-law. As far as we are aware there are only two studies of the regional probability distributions of mineralisation, one in Nevada and one in Zambezi (see Figure 13. 3 b); both show two power law distributions. There is a suggestion that there may be a size effect as shown in Figure 13.3 (b). The Nevada study covers approximately 2.8 x 10^6 km^2 whereas the Zambezi study areas are approaching but less than 10^4 km^2. Clearly much more work is needed to establish if there is a universal scaling relation for the terrains that host substantial mineral resources. The effort is warranted since such universality is a fundamental step forward in understanding and exploring for mineralised terrains.

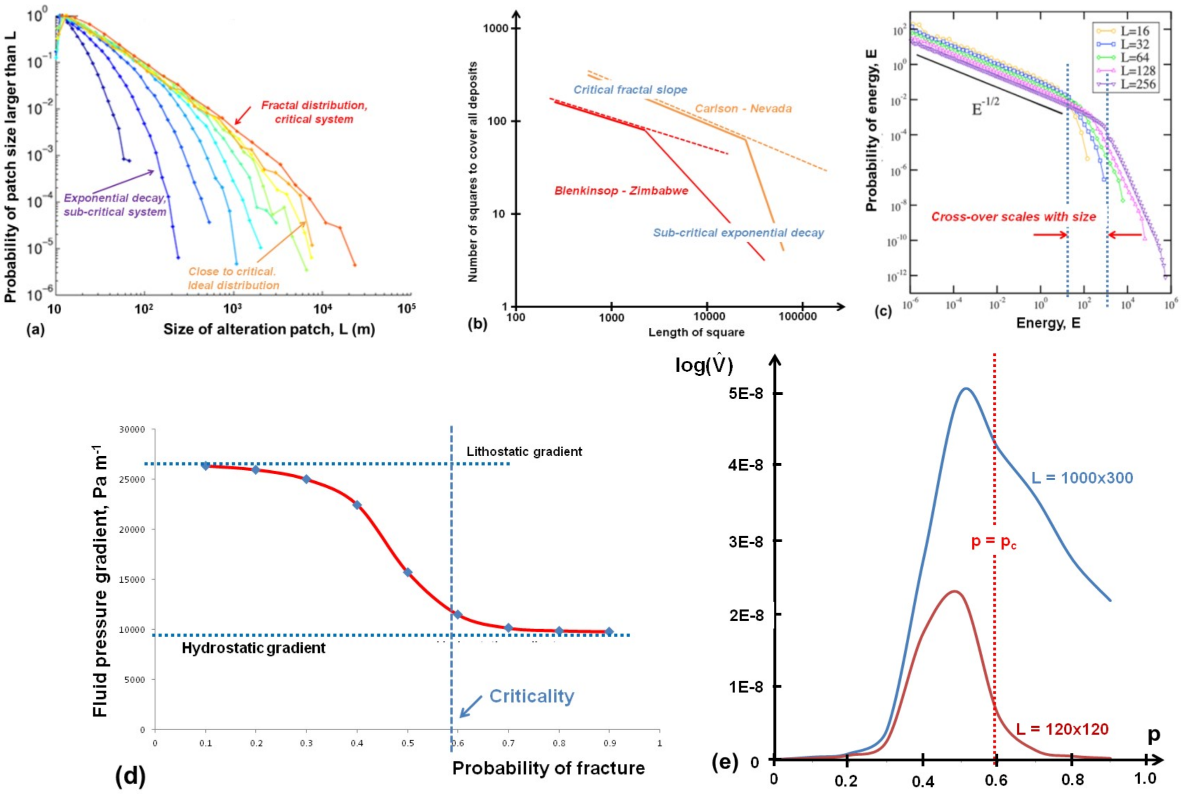


Figure 13.3. Behaviour of a system as it approaches criticality. (a) The probability that an alteration patch larger than a specified size, L, will occur as a function of L. For systems below criticality the probability falls off exponentially. For systems at criticality the probability distribution corresponds to a fractal distribution. The ideal distribution that favours a strongly mineralised terrain lies just below criticality. Modified from Girard et al., 2010. (b) Probability distributions for mineralisation patches in Nevada and Zambezi (from Carlson, 1991 and Blenkinsop, 1994). Both show two fractal distributions. There is a suggestion of finite size effects in that the cross-over for the smaller studues (Zambezi) is smaller than that for the larger study (Nevada). (c) Two fractal distributions for a random fuse network showing finite scale effects (from Picallo and Lopez, 2008). (d) Variation of pore fluid pressure gradient suppoted in a crust 40 km thich as the probability, p, of damage increases from 0.1 to 0.9 on a square lattice. The critical percolation point corresponds to a probability of 0.59. (e) The maximum Darcy velocity, $\hat{V}$, as a function of probability, p, of damage for the same model as (d). This model is discussed in detail in Chapters 3 and 5. The figure shows a size effect resulting from increasing the size of the model from 120 x 120 cells to 1000 x 300 cells.

Darcy's law demands that for an imposed fluid flux, at criticality, contrary to much of the published work, the pressure gradient in the crust, with an initial lithostatic fluid pressure gradient, drops to hydrostatic (Figure 13.3 d) and the fluid flux through the crust becomes very small (Figure 13.3 e). A system as high as the crust with a hydrostatic fluid pressure gradient cannot withstand the stresses generated in the rock column and the permeability collapses by mechanical fracturing or crushing or by chemical means (precipitation of quartz) until the permeability becomes low. Thus the fluid pressure drop associated with criticality results in sealing of the porosity by compaction of some kind and/or precipitation of quartz/carbonates. The permeability decreases and the process repeats itself. The system cycles through criticality as deformation proceeds, a process some would call self-organised criticality. It is fundamental to appreciate that the formation of hydrothermal systems occurs in the build up to criticality rather than at or post criticality when the fluid fluxes have collapsed. Veins that form here result from precipitation of quartz/carbonate in veins formerly propped open by the lithostatic fluid pressure. Since the temperatures are normally low in systems we are interested in at this stage in their development gold is deposited at trace levels. Such veins tend to be horizontal. These veins might be called *critical collapse veins*.

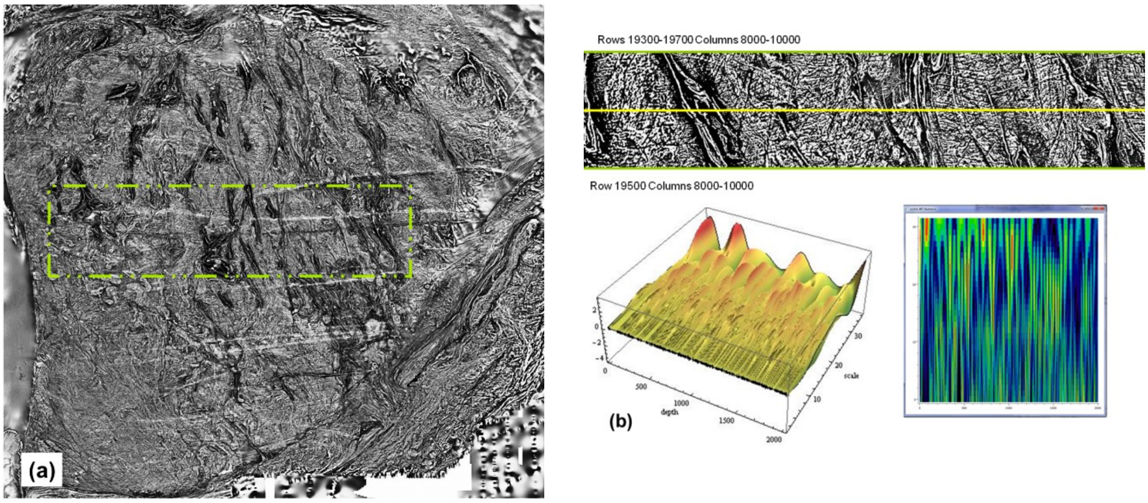
At the regional scale the essential problem is to determine if the particular portion of crust under investigation has evolved to a stage where the permeability structure is such as to allow alteration systems to evolve. A secondary, but of course fundamental problem is to decide if these altered regions are mineralised. The necessary permeability structure is one where the velocity of incoming hydrothermal fluids is such that the hydrothermal alteration chemical reactions can proceed at a significant rate. As we have seen, these reactions are exothermic and are highly sensitive to the rates of supply of nutrient and heat. If these rates are too high then the reactions do not proceed because the residence time of reactive chemical species is too small. If these rates are too low then the reaction proceeds very slowly. The optimum input velocity corresponds to a distribution of permeability that is below the percolation threshold where fluid pressure gradients can be maintained that are well above hydrostatic and significant fluid focussing occurs. At the percolation threshold the hydraulic head in the crust drops to near hydrostatic and the fluid flow rates drop to low values (Figures 13.3 d, e). Far below the percolation limit the fluid is not well focussed and the rates of fluid flow are small. The optimum permeability and degree of fluid focussing occurs just before the percolation limit.

The problem therefore reduces to understanding the distribution of damaged areas in an unexplored terrain and forming an estimate of whether this distribution is near (but below) a percolation threshold. This is not an easy task especially since we are commonly dealing with an anisotropic situation where pre-existing structure has a strong influence on permeability distribution, and hence on the percolation limit, and will require a lot more data on the spatial distribution of alteration and modelling than we have at present in order to become routine. Yet establishing whether a system is near criticality would seem to be a fundamental first step in establishing an exploration program in virgin area under cover. We suggest a way forward below.

The crucial first point to establish in any new region of interest from a mineral exploration perspective is whether any hydrothermal alteration systems are present and what is their size and spatial probability distributions. We indicate ways of doing this based on geophysical data below. Large successful mineralising systems develop in regions that are approaching and near to criticality, as far as the fluid transport regime is concerned. As such the distribution of alteration patches scales with an exponential decay (or "bifractal" manner) as one approaches criticality and scale in a fractal manner at criticality (Figure 13.3 a, c). There is considerable support for this notion in the few probability distributions of mineralisation published from Nevada and Zambezi. These distributions are of the form shown in Figure 13.3 (b) and are interpreted as representing bifractal distributions. Another (equivalent) interpretation is that these distributions are exponential decay curves just below criticality.

Thus various measures of alteration patch size, spacing or frequency will allow an estimate of how close to critical the region is and so contribute to a risk assessment of whether to invest further in drilling. If the alteration patch size probability distribution is a strong exponential drop off with size (the blue curves to the left of Figure 13.3 a), the region is not prospective. If the distribution is an exponential drop off but quite close to fractal (the green curves to the right of Figure 13.3 a) the risk of proceeding with an exploration program is decreased. The best regions to explore are those below criticality where the distribution is an exponential decay but can be approximated by two linear fits to the data (the yellow curves of Figure 13.3 a). The problem therefore reduces to establishing the spatial distribution of alteration patches (or surrogates to alteration patches). Especially in areas of cover, the surrogates to alteration may comprise geophysical anomalies such as arise from the presence or absence of pyrrhotite or magnetite or the presence of washed out areas on seismic images. As an adjunct and compliment to such surrogates we propose that *geophysical multifractal fabric mapping* is essential.

Geophysical multifractal fabric mapping is a developing tool. The term *fabric mapping* is used instead of *texture mapping* to distinguish the present day use of the term to refer to the mapping of texture in geophysical images based on image processing from an approach based on the miltifractal characteristics of the image.We discuss the application here specifically with respect to magnetic methods but the discussion is relevant to any potential field method and to electro-magnetic and seismic methods as well. The spatial distribution of very large numbers if magnetic sources and the presence of singularities (edges) in these distributions means that such potential field signals are multifractal; wavelet methods have been extensively applied to processing such data for some years but without a multifractal connotation. The results shown in Figure 13.4 show that in fact these data sets are multifractal. The popular applications to date mainly concern the detection of edges in the data and interpretations of the upward continuation of the data with respect to inversion and identification of the sources of the magnetic signals.



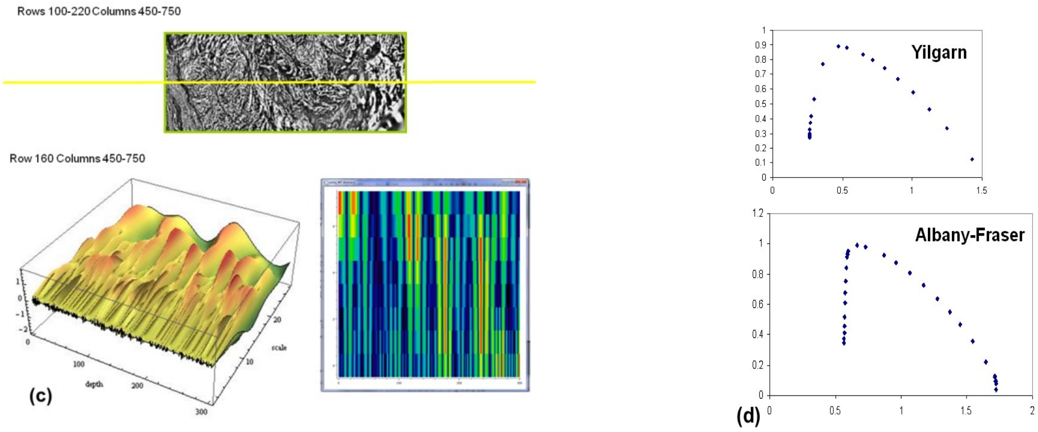


Figure 13.4. The mutifractal characteristics of airborne magnetic images. (a) Regional image of part of ther Yilgarn and Albany-Fraser terrain of Western Australia. (b) A traverse ≈ 800 km long in the Yilgarn with 3D and 2D representations of the wavelet transform scalogram. (c) A traverse ≈ 200 km long in the Albany-Fraser terrain with 3D and 2D representations of the wavelet transform scalogram. (d) Singularity spectra for the Yilgarn and Albany-Fraser terrains.

The wavelet transform across a geophysical image supplies a vertical “wavelet transform map” of the way in which the magnetic, density or electrical conductivity sources are organised at each point in the traverse. At each point on the ground surface this wavelet transform map can be interrogated to establish the wavelet coefficients and the way in which they vary with the scale of the wavelet (Figure 13.5). This means each point on the ground can be classified according to measures that delineate features of interest; one, for instance, can map areas on the ground that are monofractal in their geophysical response as opposed to those that are multifractal. Or one could classify areas according to the local value of α in the singularity spectrum. In this way fabric maps of geophysical images can be prepared that reflect the physical and chemical processes involved in producing the geophysical response.

As an example of multifractal fabric mapping we present in Figure 13.4 wavelet transforms for traverses across magnetic images of parts of the Yilgarn and the adjacent Albany-Fraser terrain. The singularity spectra are quite distinct and illustrate the possibility of fabric mapping at greater resolution. The application of mutifractal fabric mapping to geophysical images in the detection and mapping of alteration is inspired by work on breast cancer where wavelet analysis has shown that benign cancers destroy the underlying structure and are monofractals whereas malignant cancers form branching structures into the underlying structure and are multifractal (Figure 13.5). We propose that similar interpretations may be possible in identifying alteration patches in geophysical images. Alteration will tend to either ‘wash out” underlying structure in the geophysical signature by destroying the initial fabric or enhance or overprint various aspects of the undeflying fabric by selective replacement or veining/brecciation in exactly the same way that a cancer does. Thus, using the wavelet transform as it is intended, that is, as a generalised mathematical microscope, one can zoom into parts of the image and map the multifractal (or monofractal) characteristics. Work is underway in extending the preliminary results in Figure 13.4 to areas containing known alteration patches.

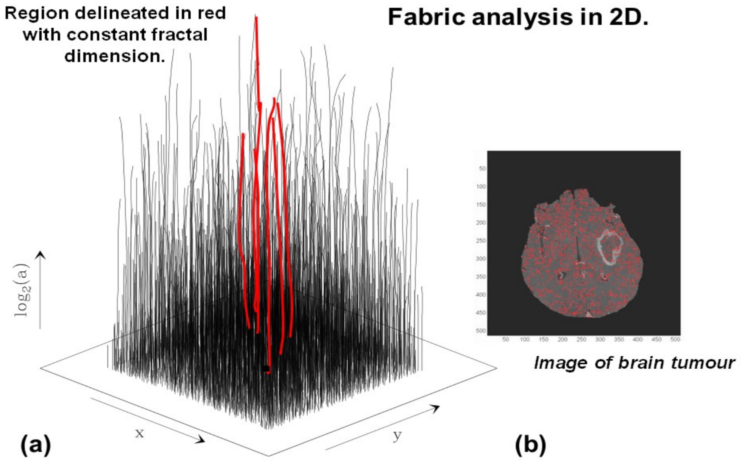


Figure 13.5. Examples of multifractal fabric mapping. (a) Two dimensional wavelet scalogram of geophysical image with regions marked in red characterised by a constant fractal dimension. (b) Example of an X-ray scan of a brain tumor. The tumor is marked in white as a region with similar multifractal characteristics.

13.3. Implications for size and grade of individual systems.

The small equilibrium concentration of gold in low salinity CO_2 rich fluids at temperatures of 250 – 300 ^{o}C and fluid pressures of 200 - 300MPa, typical of those involved in the formation of orogenic gold deposits, introduces a problem in generating deposits with concentrations of many grams per tonne of rock. Typically the equilibrium solubility of gold under the above conditions is in the range 1 - 10 ppb by weight of fluid which translates to ≈ 4×10^{-5} to 4×10^{-4} ppm of gold by weight of rock assuming a rock density of 2700 kg m^{-3} and a porosity of 0.1. Many processes for either increasing the equilibrium solubility of gold in the incoming fluid or of enhancing the deposition of gold have been proposed but most involve adiabatic pressure drops arising from seismic events with resultant phase separation (boiling or unmixing of H_2S).

In fact there is no issue with the mass of gold added to these systems by incoming fluids. The controlling factors governing the mass of gold added to the system is not so much the equilibrium concentration of gold in solution but the volumetric flow rate and the time of operation of the system. With a lithostatic fluid pressure gradient (2.7×10^{4} Pa m^{-1}), a permeability of the rock mass of 10^{-15} m^{2} and a fluid viscosity of 10^{-4} Pa s, the volumetric rate of addition of gold into the system carried by the fluid is 2.7×10^{-10} ppm (by weight) m^{3} m^{-2} s^{-1} (or 7.3×10^{-10} g m^{-2} s^{-1}) assuming an equilibrium gold solubility of 10^{-3} ppm by weight of fluid. If the system lasts 10,000 years (3.16×10^{11} s) this represents a total gold concentration of ≈ 8.5 ppm by weight of rock. If the system lasts for 100,000 years we have a potential ore body with grades running at ≈ 2.7 oz/ tonne of rock. The problem, as recognised by many workers is to find mechanisms that deposit the gold from solution with maximum efficiency. As indicated, these mechanisms commonly involve adiabatic drops in pressure induced by seismic activity but as far as we know the efficiency of such processes has not been discussed.

Episodic behaviour in hydrothermal systems is widely recognised and is generally attributed to seismic events that lead to catastrophic drops in fluid pressure in fault valve pumping or suction pump/piston processes. This concept has the effect of focussing one's attention on the geometry of fault systems such as fault jogs, step-overs and irregularities rather than on the processes that operate within the hydrothermal system. It is also widely appreciated that mineralisation is relatively rare on major structures and tends to occur on second or higher order structures associated with major faults so that seismic processes by themselves do not seem to be the final answer. Episodic behaviour induced by such seismic activity we call *extrinsic* behaviour since it results from processes such as plate tectonics that are external to the hydrothermal system. However, hydrothermal systems are unstable systems and exhibit episodic, aseismic behaviour in their own right. This behaviour, which originates within the hydrothermal system we call *intrinsic* behaviour. There is of course no reason why extrinsic and extrinsic processes cannot be coupled. It is well documented that unstable chemical systems that are forced by external processes such as fluctuating inputs of heat and/or mass can evolve to new resonant forms of instability characterised by high efficiency in the reaction process. We consider intrinsic behaviour in detail in Chapter 12. Below we summarise the main arguments.

As we have seen, large hydrothermal systems cannot form until the permeability structure of the crust reaches a stage where interconnected high permeability patches are large enough that significant fluid focussing can occur but not so large that the percolation limit is reached where the fluid pressure gradient drops (at least for a short time) to close to hydrostatic. This marks criticality in the permeability structure of the crust. The fluid flux to the system needs to be maintained for a time that enables multiple cycles through criticality. Thus the most likely environment for large ore bodies is where a long geological history of fluid activity can be shown and the distribution of alteration patches is bifractal (Figures 13.4 a, b, c).

In contrast to many metamorphic systems that are closed to the influx of fluids, metasomatic systems are open to the flow of both fluids and heat from outside the system. Clearly retrograde and melting metamorphic systems are the exceptions. Closed systems must always approach a state that does not change with time (a stationary state) that is also an equilibrium state. Open flow systems also approach stationary states where the in-flux and out-flux of heat and fluids are balanced by the consumption/production of heat and fluids within the system. However these stationary states are non-equilibrium states. In a closed system the rates of chemical reactions are largely governed by the rate constants of the reactions and the approach to equilibrium is controlled by these constants. Some transient complexity in closed systems may arise on the path to equilibrium due to competition between the internal, local (millimetre scale) supply and consumption of chemical species and heat but ultimately the approach to equilibrium is monotonic and driven by the smooth decay to a minimum of the Gibbs energy difference for the reaction. By definition, the equilibrium state is stable to small perturbations from equilibrium.

For an open flow system the rates of chemical reactions are largely controlled by the rates of supply and extraction of nutrients and heat and the rate constants for the reactions are of secondary importance. If the rates of supply are too small the reactions smoulder and never proceed very far. If the rates of supply are too large the reaction is “blown out” or extinguished because the residence time for nutrients is small and there is not enough time for the reaction to proceed. In between these two extremes a number of stationary states may be possible, some are stable and some are unstable so that the system oscillates (in a periodic or chaotic) manner about that state or switches to a new state. The stability of the system is controlled by the rates of the mineral reactions relative to the rates of supply of nutrients and heat. If the rate outstrips the supply the reaction stops until the supply can grow again. This results in oscillatory or, if more than two processes/reactions are competing, chaotic behaviour. The yield of the system is highly sensitive to initial conditions and to changes in conditions so that, as a whole, the system is chaotic both in a spatial and a temporal sense. This chaotic behaviour is reflected in the spatial distribution of alteration mineral assemblages and of mineralisation within hydrothermal systems.

The rate at which mineralisation occurs in a given ore body is highly sensitive to local conditions of mass and energy supply but the principles that govern the grade of mineralisation in a hydrothermal system can be seen from the following scenario. Most hydrothermal mineralising systems evolve through two modes marked by the nature of the alteration mineral reactions involved. Mode I corresponds to the conversion of initial assemblages to hydrous (micas, chlorites) and carbonate (calcite, siderite, ankerite) assemblages. Mode II corresponds to the partial or complete dehydration or decarbonation of these early formed assemblages and so is commonly a fluid producing mode.

Three important processes operate during the progression through Modes I and II. They may or may not interact depending on the type of mineral reaction taking place. The important characteristics of such reactions are the sign and magnitude of ΔV, whether they are quartz consuming or quartz producing, whether they are exothermic or endothermic, and whether they are fluid producing or fluid consuming. These characteristics control the following three processes: (i) Temperature cycles arising from the instability of the mineral reactions. The temperature cycles induce fluid pressure cycles where the magnitudes of the cycles are controlled by whether the system is “drained” or “undrained”; as such, the magnitude of the fluid pressure fluctuations is controlled by the permeability of the wall rocks of the system (ii) Compaction instabilities arising from negative ΔV of mineral reactions; this leads to the formation of displacive veins. (iii) Fracturing to produce breccias and fracture veins; this arises from fluctuations of fluid pressure that produce effective stresses enabling brittle failure. Clearly these processes can be strongly coupled. We treat the chemical response in this section and leave a detailed discussion of compaction to Section 13.4.

13.3.1. The paragenetic sequence.

Whether a particular chemical reaction occurs or not and the rates at which it proceeds is controlled by the activation energy for the reaction. Reactions with relatively small activation energies tend to begin at low temperatures and proceed with small incubation periods between the equilibrium temperature for the reaction and the time when the reaction proceeds at a significant rate (Figure 13.6). Reactions with large activation energies begin at higher temperatures with a large incubation period between the equilibrium temperature for the reaction and the time when significant rates develop (Figure 13.6).

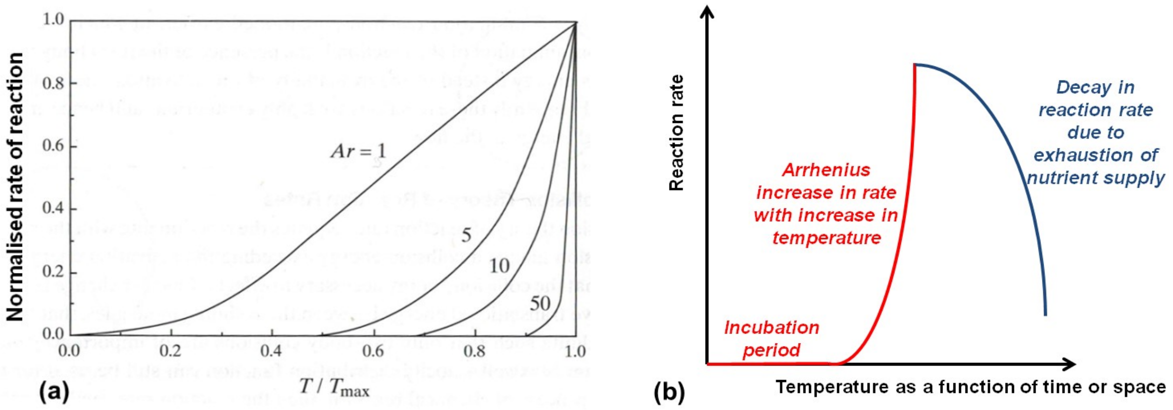


Figure 13.6. The physical basis of the paragenetic sequence. (a) The dependence of reaction rate on the Arrhenius Number, Ar, for the reaction. The dimensionless reaction rate, R, in (13.1) is plotted against T/T_{max}. Reactions with low Arrhenius number begin early in a temperature history and reactions with large Arrhenius Number are localised in the temperature history near to the maximum temperature, T_{max}, of the system. (b) As the temperature is increased the exponential rise in reaction rate for a reaction is capped by the inability of the system to supply nutrients for the reaction.

The relative magnitude of the activation energy, E_a, is measured by the Arrhenius Number, Ar, given by

$$Ar = \frac{E_a}{\mathrm{R}T_{max}}$$

where R is the gas constant and T_{max} is a reference temperature which corresponds to the maximum temperature for the system. The normalised rate of a given reaction, R, is

$$R = \exp\left[Ar\left(1 - \frac{T_{max}}{T}\right)\right] \qquad (13.1)$$

(13.1) is plotted in Figure 13.6 (a) for a range of values of Ar. Reactions with small Ar begin early in a temperature history and slowly evolve until the maximum temperature is reached. Reactions with large Ar have a long incubation period and finally react quickly near to the maximum temperature of the system. For a first order reaction where the reaction rate is given in terms of a reactant concentration, c, by

$$\frac{\mathrm{d}c}{\mathrm{d}t} = -Bc\exp\left(-E_a / \mathrm{R}T\right)$$

the reaction begins exponentially but the reaction rate is finally capped by the dwindling supply of the the reactant (Figure 13.6 b). Thus the paragenetic sequence is an experession of the array of Arrhenius Numbers for the reactions involved. If the temperature in Figure 13.6 is interpreted as a function of space and/or of time, the plots in Figure 13.6 indicate that reactions with large values of Ar are strongly localised in space and time.

13.3.2. Mode I. Exothermic hydration and carbonation reactions. Disseminated gold.

Many hydrothermal deposits begin their evolution with mineral reactions that involve the hydration of feldspars or of mafic minerals. Typical reactions (neglecting fluids) are

K-feldspar → *muscovite* + SiO_2;

$\Delta V = +50.4\%$ with SiO_2 as a solid; $\Delta V = +29.6\%$ with SiO_2 removed in solution.

5 enstatite + 4 albite → *2 chlorite + 16* SiO_2;

$\Delta V = +10.2\%$ with SiO_2 as a solid; $\Delta V = -40.9\%$ with SiO_2 removed in solution.

These reactions have the following four characteristics: (i) they are exothermic, (ii) they produce quartz, (iii) they consume H_2O (or H^+), (iv) they have positive ΔV's as far as the solid products are concerned but if SiO_2 is removed by dissolution then some have (large) negative ΔV's. This means that they are autothermic with reaction rates that increase as the temperature rises, they produce SiO_2 but some potentially clog the porosity as they proceed because of the positive ΔV whereas others create porosity as the reaction proceeds because of the negative ΔV. If reactants such as SiO_2 are removed in solution the process represents a form of chemical compaction that we revisit in Section 13.4.

In Chapters 8 and 12 we show that these reactions are unstable and lead to temperature fluctuations; fluid pressure fluctuations arise due to the thermal expansion of the fluid. Thus oscillations in both temperature and fluid pressure occur. The rate of change of fluid pressure is given by the following balance:

$$\begin{bmatrix} \textit{Rate of change} \\ \textit{of fluid pressure} \end{bmatrix} = \begin{bmatrix} [1]\,\textit{Rate of fluid pressure change} \\ \textit{arising from diffusion of} \\ \textit{fluid pressure} \end{bmatrix} + \begin{bmatrix} [2]\,\textit{Rate of fluid pressure change} \\ \textit{arising from temperature change} \end{bmatrix}$$
$$+ \begin{bmatrix} [3]\,\textit{Rate of fluid pressure change} \\ \textit{arising from supply of fluid} \\ \textit{from outside the system} \end{bmatrix} \tag{13.2}$$

In rocks with low permeability the processes in brackets [1] and [3] in (13.2) have little influence and the thermal expansion of the fluid with respect to the solid is the only important effect. The situation corresponds to an undrained experiment. This is well represented by the reaction *K-feldsar → muscovite + quartz*. Since the coefficient of thermal fluid pressure increase is of the order of 0.1 to 1.0 MPa $^{o}C^{-1}$ the fluid pressure increase for (say) a $25^{o}C$ increase is at most 25 MPa. This is a substantial increase in fluid pressure that can lead to brecciation and fracturing if the ambient fluid pressure is at or near lithostatic. In Chapter 12 we show that the system oscillates as shown in Figure 13.7 in a manner where the maximum temperature occurs nearly coincident with the maximum fluid pressure.

For the conditions in Figure 13.7, the equilibrium solubility of gold in solution oscillates between 2.5×10^{-3} ppm and 2×10^{-2} ppm and the deposition sites correspond to intergranular pores and fractures. The result is a disseminated deposit with low gold grades even after 500,000 years of operation.

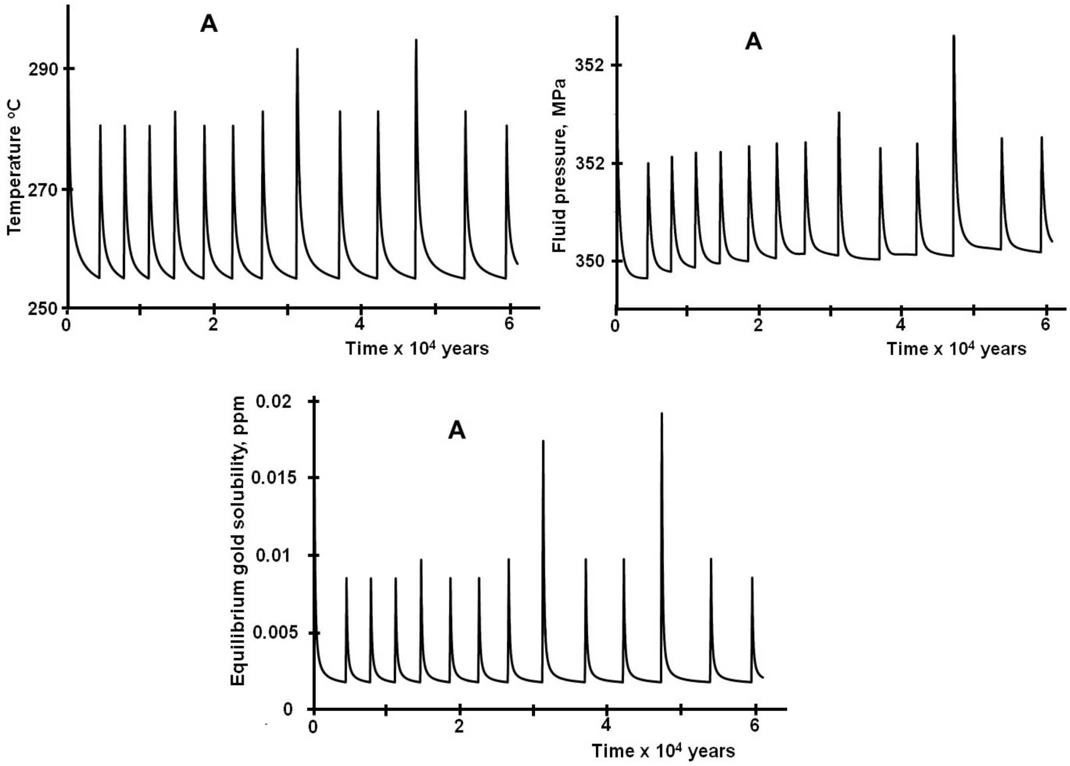


Figure 13.7. Episodic behaviour in a low temperature system with only exothermic alteration reactions and no deformation. (a) Temperature history. (b) Fluid pressure history. (c) History of the equilibrium solubility of gold. The ignition temperature is 250°C and the extinction temperature is 300°C. No fluids are released during the reaction. The equilibrium solubility of gold remains small. This type of behaviour, if it lasts for 1 million years) leads to a strongly altered system with low concentrations (≤ 1ppm by weight of rock) of gold.

In Figure 13.8 we suggest an attractor that reproduces the behaviour of Mode I in a simple manner. This is a Rössler attractor that is explored in greater depth in Section 13.5. This is the simplest form of the Rössler attractor where the behaviour is strictly periodic.

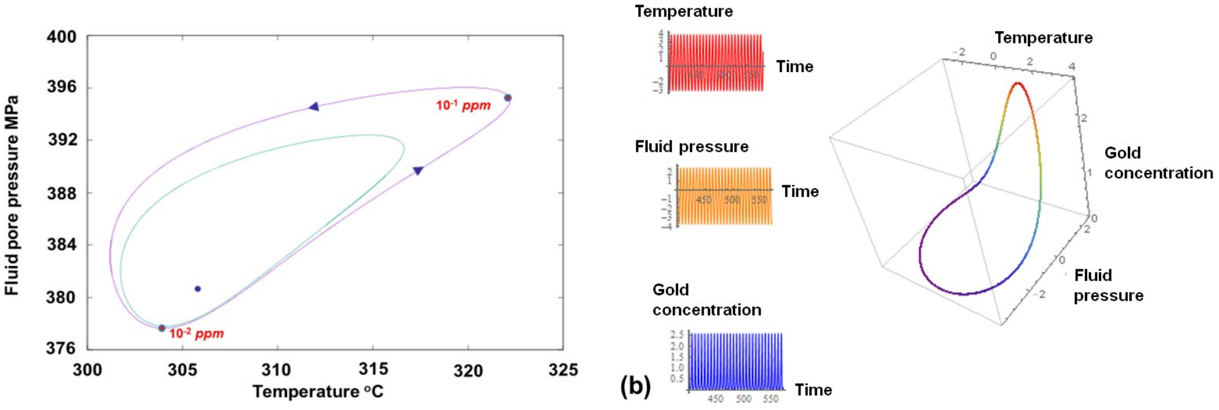


Figure 13.8. A suggestion for the type of attractor that arises from Mode I of a hydrothermal gold system. (a) A two dimensional attractor in pore pressure - temperature phase space with gold grades indicated. With just two processes operating the sytem cycles with a single period; temperature and pore pressure fluctuations are in phase. Gold precipitates during the pressure-temperature relaxation phase. Gold grades estimated from Loucks and Mavrogenes for the complex $AuHS(H_2S)_3^o$. The situation corresponds to a crustal depth of ≈ 15 km (assuming the pore pressure is lithostatic) with a thermal gradient of ≈ 21 $^oC\ km^{-1}$. (b) A three dimensional attractor that produces the results shown in (b). This is a Rössler attractor described in Section 13.5. It has the parameters $a = 0.2$, $b = 0.2$, $c = 2.0$ in (13.5). The behaviour is strictly periodic.

If the rocks have high permeability, and the reactions do not involve the production of fluid as is the case for the reaction: *5 enstatite + 4 albite → 2 chlorite + 16* SiO_2, and if SiO_2 is removed in solution, then all three processes in brackets, [1], [2], [3] in (13.2) are important. This corresponds to a drained experiment. The form of (13.2) becomes that of a reaction-diffusion-transport reaction and many possibilities of spatio-temporal chaos exist. Oscillations in temperature are present because of the instability of the reactions but oscillations in pore pressure are less dramatic than in Figure 13.7 because the pressure can readily diffuse away. Spatial fluctuations in fluid pressure now arise because of compaction instabilities arising from the negative ΔV of mineral reactions. Thus displacive veins (Section 13.4) are expected to be characteristic of these reactions. Fluid pressure in displacive veins is less than in the adjacent collapse zones. Brecciation is unlikely because large fluctuations in fluid pressure do not arise. Fluctuations in temperature result in deposition of gold but so long as the temperatures are in the range 300 – 350^{o}C the concentration of gold in solution remains small and a disseminated ore body develops with low grades.

Thus Mode I behaviour is characterised by:

- Relatively low temperatures that increase as the exothermic reactions proceed.
- Relatively small fluctuations in fluid pressure since such fluctuations result only from temperature fluctuations rather than from the addition of fluid from reactions.
- Relatively small equilibrium concentartions of gold.
- A highly altered deposit with disseminated low grades of gold.
- Displacive veins (see Section 13.4) with low grades of gold in the veins.

Once ignited, the system proceeds with little impediment during Mode I; the reactions accelerate as the temperature of the system rises; the increase in temperature leads to the initiation of Mode II.

13.3.3. Mode II. Endothermic dehydration and decarbonation reactions. Large cycles of temperature and fluid pressure. High grade gold stage.

At higher temperatures many alteration reactions involve the dehydration or decarbonation of previously formed hydrous phases or carbonates and are of the form

$$2\ \text{clinozoisite} + 3\ \text{pyrite} + 2\ \text{calcite} + 3\ \text{quartz} + 5\ H_2O + 1.5\ H_2 \rightarrow 3\ \text{epidote} + 2\ CO_2 + 6\ H_2S$$

This reaction is endothermic with ΔH = 5937.5 KJ.

Other reactions involve the formation of other hydrous phases together with the formation of vein filling materials such as SiO_2 and $CaCO_3$:

$$3\ \textit{tremolite} + 2\ \textit{epidote} \rightarrow 3\ \textit{chlorite} + 10\ CaCO_3 + 21\ SiO_2$$

ΔV = +36.7% with SiO_2 and $CaCO_3$; ΔV =–8.7% without SiO_2 ; ΔV =–42.2% without $CaCO_3$

$$3\ \textit{chlorite} \rightarrow 2\ \textit{muscovite} + 15\ \textit{pyrite} + 3\ SiO_2$$

ΔV = +10.9% with SiO_2; ΔV = +1% without SiO_2

The latter two reactions produce fluid ± SiO_2± $CaCO_3$. If one considers SiO_2 and $CaCO_3$ as part of the solid reactant assemblage then these reactions commonly have a positive ΔV and some have suggested that these types of reactions can shut the system down. However if one considers that these minerals can be removed in solution the volume change in the reaction can be strongly negative (see Table 8.2). As an example of a reaction that produces no quartz, the reaction, *muscovite → pyrophyllite* produces no fluid and consumes quartz. ΔV for the reaction is −19.4% (solids only). This reaction is characteristic of the high temperature phase of hydrothermal alteration in the Witwatersrand gold deposit where quartz veins associated with the mineralisation are rare. Zones of intense alteration to pyrophyllite show evidence of compaction deformation.

For the reactions of Mode II that are fluid producing, providing the permeability is not too large (approximating an undrained experiment), the fluid pore pressure increases simply because of the fluid released by the reaction. This fluid pressure increase is in addition to the increase in fluid pressure that occurs because of the temperature increases in the system arising from the exothermic reactions and/or deformation. The pressure change in the system is given by the balance between the rate of production of the fluid, the rate of thermal expansion of the fluid and the rate at which fluid can diffuse from the system. This means, because of the extra fluid production term, [4], in (13.4, and marked in red) compared to (13.2) the fluid pressure increase is larger in Mode II than in Mode I as is the temperature.

$$\begin{bmatrix} \textit{Rate of change} \\ \textit{of fluid pressure} \end{bmatrix} = \begin{bmatrix} [1]\,\textit{Rate of fluid pressure change} \\ \textit{arising from diffusion of} \\ \textit{fluid pressure} \end{bmatrix} + \begin{bmatrix} [2]\,\textit{Rate of fluid pressure change} \\ \textit{arising from temperature change} \end{bmatrix}$$

$$+ \begin{bmatrix} [3]\,\textit{Rate of fluid pressure change} \\ \textit{arising from supply of fluid} \\ \textit{from outside the system} \end{bmatrix} + \begin{bmatrix} [4]\,\textit{Rate of fluid pressure change} \\ \textit{arising from devolatilisation} \end{bmatrix} \tag{13.4}$$

These conditions lead to two effects:

(i) The temperature fluctuations are no longer in phase with the pressure fluctuations as shown by comparing Figures 13.8 and 13.9 and the pressure fluctuations are greater than in Mode I.

(ii) The equilibrium solubility of gold in solution is higher than in Mode I.

Thus, brecciation is more likely in Mode II than in Mode I but very large compaction strains can be produced especially by reactions such as $3\ \textit{tremolite} + 2\ \textit{epidote} \rightarrow 3\ \textit{chlorite} + 10\ CaCO_3 + 21\ SiO_2$. A variety of deformation modes can exist including brecciation, fracture veins and displacive veins. However in general the gold grades are higher in Mode II than in Mode I because of the inreased temperatures and the larger fluctuations in both temperature and pressure. The operation of a Mode II system is shown in Figure 13.10 which is discussed in detail in Chapter 12. It is extremely doubtful that the fluids are saturated with gold at the temperatures and fluid pressure represented in Figure 13.10 but the large drops in equilibrium solubility build up high grades with multiple episodes as discussed in Chapter 12 and summarised below. By analogy with similar calculations performed for slow eathquake sequences, in some systems one might expect an oscillation in temperature and fluid pressure approxiamtely once a year in very thin systems. Over 10,000 years considerable grades can accumulate.

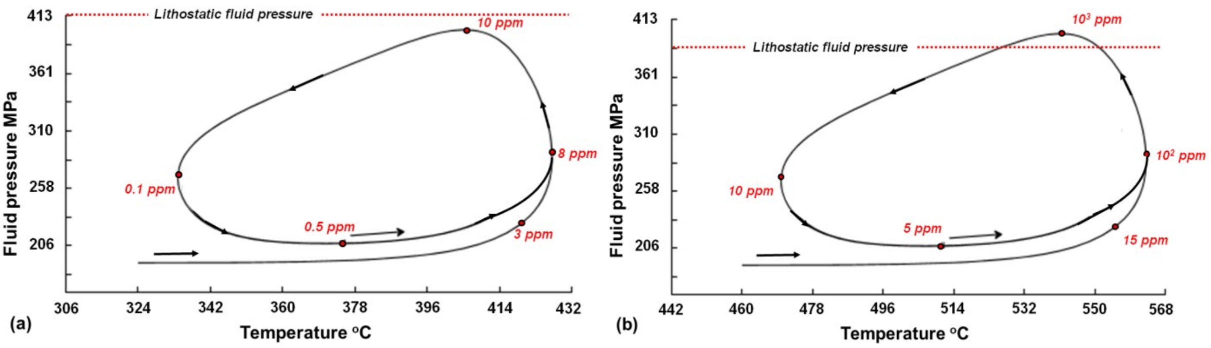
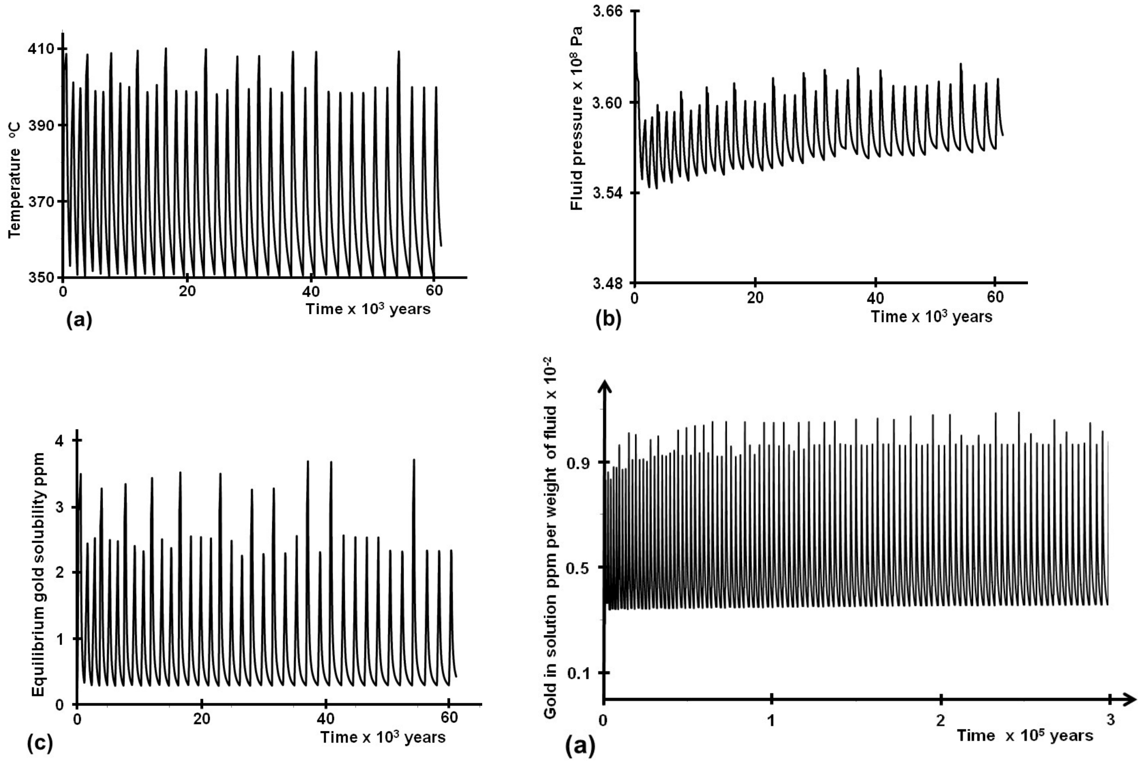


Figure 13.9. The evolution of fluid pressure and hydrothermal system temperature during an unstable devolatilisation reaction. (a) Corresponds to a depth of 15.6 km. Hydrostatic pressure corresponds to ≈ 153 MPa. (b) Corresponds to a depth of 14.6 km. Hydrostatic pressure corresponds to ≈ 143 MPa. The temperatures indicated here are of the hydrothermal system, not that of the country rock which is less than that of the hydrothermal system. This means that (a) corresponds to an average crustal thermal gradient of < 22 °C/km and (b) corresponds to an average crustal thermal gradient of < 33 °C/km. Gold grades estimated from Loucks and Mavrogenes for the complex $AuHS(H_2S)_3^o$.

Figure 13.10 shows the results for a system where the production of heat due to deformation competes with the consumption of heat from an endothermic reaction that also produces fluid. The input concentration of gold is 1 ppb by weight of fluid, the rock permeability is 3.7 x 10^{-16} m^2 and the fluid pressure gradient is lithostatic. The production of fluid by the reaction means that the fluid pressure rises slightly with time although in this case this rise has a relatively small influence on the equilibrium solubility of gold (Figure 13.10 c). The model of gold deposition discussed in Chapter 12 produces a gold concentration in solution history shown in Figure 13.10 (d) and a history of solid gold deposition shown in Figure 13.10 (e); details of this deposition history are shown in Figure 13.10 (f). This history of episodic behaviour leads to a gold deposit of 22 grams per tonne of rock after 300,000 years



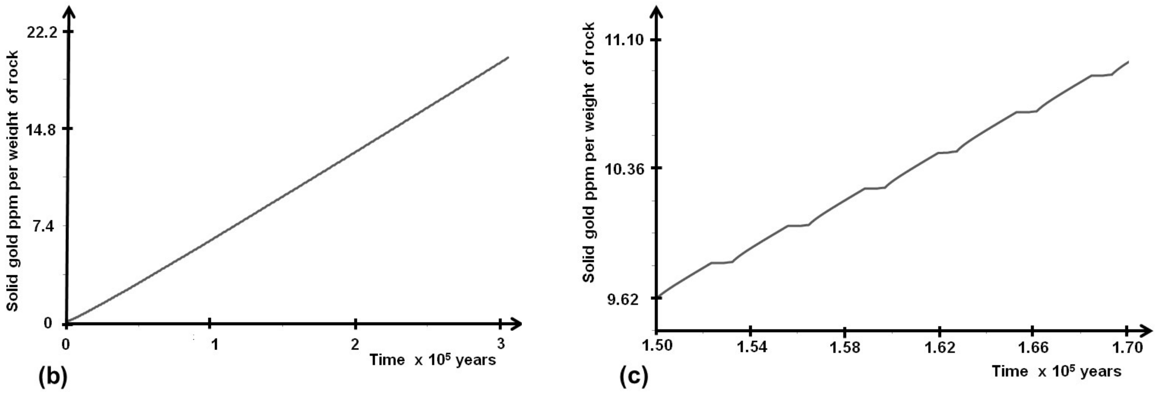


Figure 13.10. Episodic behaviour of a hydrothermal system where the production of heat arising from deformation (brecciation and sliding on fractures) competes with an endothermic reaction that also produces fluid. The ignition temperature for the reaction is 350°C and the extinction temperature is 420°C. See Figure 12.10 for more details. After 300,000 years the gold concentration is 22 grams per tonne by weight of rock. (a) Temperature history. (b) Fluid pressure history. (c) History of the equilibrium solubility of gold. (d) History of actaul gold in solution using the model proposed in Chapter 12. (e) The history of solid gold deposition for this system. (f) Details of the gold deposition history.

Calculations given in Chapter 12 show that the efficiency of reactions such as that depicted in Figure 13.10 are ≈ 60% efficient. That is, the ratio of the mass of gold per unit volume in the deposit after a given time to the mass of gold per unit volume added to the deposit in that time is ≈ 0.6; the remainder of gold added to the system is lost in the outlet stream. The efficiency can be increased to 70 % by decreasing the thermal conductivity of the wall rocks so that the thermal fluctuations are more frequent and/or by decreasing the permeability of the wall rocks so that the fluid pressure fluctuations are larger in amplitude. Both processes increase the equilibrium solubility of gold in the system. Thus a situation where the wall rocks are black shales (low thermal conductivity and low permeability) is an ideal environment to operate high efficiency reactors.

The coupling of exothermic and endothermic reactions in an open fluid flow system has an interesting outcome that offers a mechanism for the production of bonanza grade gold deposits. An example is the coupling of exothermic reactions such as

$FeCO_3 + 2H_2S + 0.5\ O_2 \xrightarrow{k_1} FeS_2 + CO_2 + 2H_2O$; (exothermic, $\Delta H = -\ 245.95$ KJ)
siderite + hydrogen sulfide + oxygen → pyrite + carbon dioxide + water
or
$CaFe(CO_3)_2 + 2H_2S + 0.5O_2 \rightarrow FeS_2 + CaCO_3 + CO_2 + 2H_2O$; (exothermic, $\Delta H = -245.43$ KJ)
ankerite + hydrogen sulfide + oxygen → pyrite + calcite + carbon dioxide + water

with the deposition of gold which is endothermic:

$AuHS(H_2S)_3^0 + 0.5H_2 \xrightarrow{k_2} Au + 4H_2S$ (endothermic, $\Delta H = 105.5$ KJ)
gold complex in solution + hydrogen → gold(solid) + hydrogen sulfide

Here the H_2S produced by the deposition of gold (an endothermic process) is used to react with siderite to produce pyrite (an exothermic process). The pyrite forming process releases ≈ 246 KJ of heat which is used to amplify the gold deposition process which requires ≈ 106 KJ of heat. The remaining 140 KJ of heat can be used to increase the temperature and hence increase both the siderite to pyrite and gold deposition rates. This kind of coupled reaction system when coupled with advective transport leads to a thermal soliton where the pyrite production process proceeds in the tail of the soliton and drives the gold deposition process in the soliton front (Figure 13.11 b). This kind of process needs to be integrated into the episodic behaviour reported in Chapter 12.

A similar process involves the heat released by localised deformation (Figures 13.11 c, d) as gold in solution is advected into the high temperature spike associated with the deformation. The increased heat in the upstream tail of the spike is used to drive the endothermic gold deposition process in the downstream front of the spike. An example where such localisation processes may have operated is given by Fougerouse et al. (2016) for the Obuasi gold deposit. Here there is widespread evidence of remobilisation of gold associated with localised deformation at the scale of 1 km and at the cm-scale associated with crenulation cleavages. Early high grades of gold (5 to 6 g/ton) are associated with the exothermic reaction: H_2S + ankerite → arsenopyrite and synchronous pervasive deformation, whereas grades of 15 g/ton are associated with later localised deformation (Fougerouse et al. 2015; 2016 a, b).

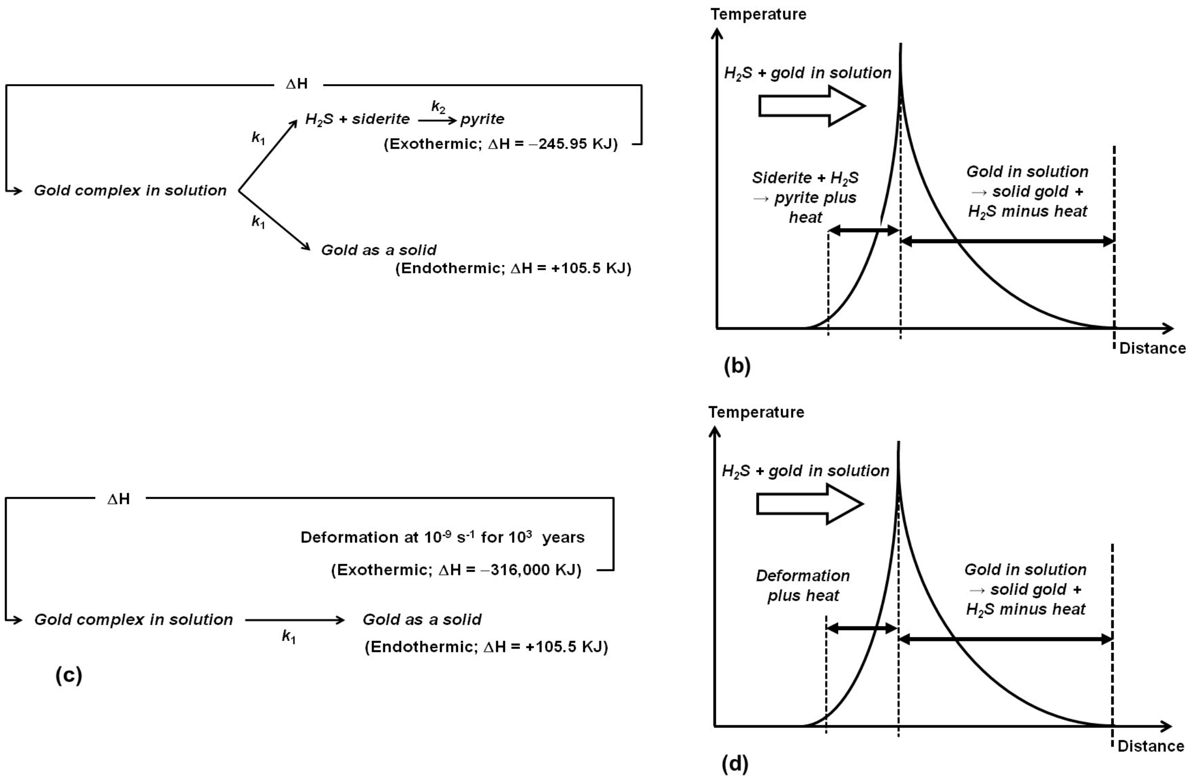


Figure 13.11. The development of thermal solitons. (a) Thermal feedback between gold deposition reaction and pyrite formation reactions. (b) Formation of a thermal soliton with spatial distributions of the siderite to pyrite reaction (exothermic) and the gold deposition reaction (endothermic). The direction of fluid flow is shown advecting H_2S and gold in solution. (c) Thermal feedback between gold deposition reaction and deformation. (d) Formation of a thermal soliton with spatial distributions of deformation (exothermic) and the gold deposition reaction (endothermic). The direction of fluid flow is shown advecting H_2S and gold in solution.

13.4. Implications for vein formation.

In what follows we distinguish two end member classes of veins; recognition of these two types is fundamental to understanding many mineralised systems particularly in establishing why mineralisation is or is not vein hosted. The two end members are:

(i) *Type I veins; Displacive veins* controlled in their development by displacement of the walls of the vein resulting from reactions in the wall rocks that lead to chemical compaction. These veins grow incrementally *in situ* by the incremental addition of material (quartz and/or carbonates) derived from reactions in the wall rocks. The material making up the vein commonly grows as fibres that track the direction of opening of the wall rocks. No fracturing is necessary to nucleate or maintain the vein; the vein grows because the material being added from the wall rock reactions can accommodate a space problem generated by the extending and compacting the wall rocks. Since no fracturing occurs the effective stress state does not need to be such as to nucleate fracture. In fact, the fluid pressure in the growing vein needs to be less than in the reacting wall rocks so that fluid flows into the vein from the surrounding wall rocks and material is precipitated in the vein arising from the fluid pressure drop (see Figure 13.12). The microstructure at the margins of these veins comprises a gradual merging of vein material with wall rock material. These veins grow as a form of compaction instability discussed in Chapter 8 and illustrated in Figure 13.12. Since these veins occur with the production of fluids they are more likely to contain high grades of gold than those discussed below which are not associated with reactions involving fluid production. This follows since fluid producing reactions are associated with elevated fluid pressures and hence higher equilibrium solubilities of gold.

(ii) *Type II veins; Fracture controlled veins* that develop by one or many episodes of fracture with deposition of vein filling material during each episode of fracture. These include the classical crack-seal veins but also include veins with crystallographic terminations that grow into a vein filling fluid. Since the formation of these veins does not require compaction in the wall rocks, the growth of these grains is controlled by fluid pressure drops in the system as a whole. The fracture events require the fluid pressure to generate the effective stress necessary for fracture whilst the deposition of material requires the rapid collapse of this pressure to lower values. There is no need for the fluid pressure in the vein to be less than in the wall rocks. Fluid flow in the veins is driven by a regional fluid pressure gradient (or hydraulic head if gravity is important). There is a sharp boundary between vein material and wall rock material in fracture controlled veins.

In discussing the origin of Type I veins it is important to note that many alteration mineral reactions involve large decreases in volume. This is not always appreciated since the systems are treated as closed chemical systems at equilibrium rather than as dynamically evolving open flow systems. Thus the reaction

$$3\ \textit{tremolite} + 2\ \textit{epidote} \rightarrow 3\ \textit{chlorite} + 10\ CaCO_3 + 21\ SiO_2$$

involves a 36.7% *increase* in volume if the $CaCO_3$ and SiO_2 remains locally in the system as calcite and quartz with the chlorite. However if the system is open and the $CaCO_3$ and SiO_2 are removed in solution the volume change is a massive decrease of 42.2%. Thus, if material is removed from this reaction then the reaction represents a *chemical compaction deformation* (Figure 13.12).

The recognition of chemical compaction processes is important because of the development of *compaction instabilities* (Figure 13.12). Any homogeneous fluid saturated, compacting system under stress is unstable to local perturbations in fluid pressure and spontaneously switches (undergoes a bifurcation) to a spatial pattern of regions with high and low fluid pressure. These regions correspond to collapsing and expanding regions and initially grow exponentially. The regions can have many shapes and spatial distributions but we focus on systems that split into layered regions.

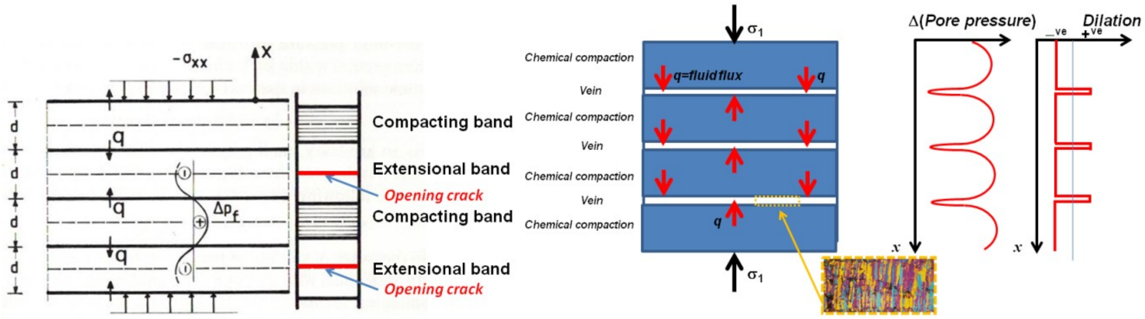


Figure 13.12. Compaction instabilities and the development of displacive veins. (a) The geometry of compaction and extensional banding in a saturated compacting porous medium. A fluid saturated porous medium undergoing compaction due to a stress σ_{xx} is unstable and splits into alternating compacting and extending bands. The pore pressure adopts a sinusoidal distribution so that fluid is expelled from the compacting zones and flows into the extending zones. We envisage the compacting zones to be compacting chemically due to an alteration reaction such as one described in Table 8.2. The extension is such that a crack nucleates in the extending band and this ultimately grows to form a vein, utilising the dissolved material in the fluid expelled from the compacting band. Modified from Vardoulakis and Sulem (1995, figure 5.8.5). (b) The formation of hydrothermal crack-seal veins by chemical compaction. The compaction process in a fully saturated material is intrinsically unstable and chemical compaction bands develop under stress. For large compaction values the regions between compacting layers fail in extension and generate open fractures which drain adjacent fluids with dissolved mineral species and hence develop into veins. If the alteration process is episodic then crack seal microstructures develop.

Chemical compaction deformations are also important for situations where constant volume replacement of individual minerals occurs (probably the norm in hydrothermal alteration systems). Consider the reaction biotite → chlorite which if written such that Al and SiO_2 are preserved amongst the solid phases is:

$$2\ KMg_3A1Si_3O_{10}(OH)_2 + 4H^+ \rightarrow Mg_5A1_2Si_3O_{10}(OH)_8 + 2K^+ + Mg^{2+} + 3SiO_2$$

Biotite *Chlorite* *Quartz*

This involves a volume change for the solid phases of ≈ –9.5%. If the reaction is written with (approximately) an equal volume of chlorite replacing biotite:

$$1.4\ KMg_3A1Si_3O_{10}(OH)_2 + 0.8\ Mg^{2+} + 0.6\ Al^{3+} + 3.6\ H_2O \rightarrow Mg_5Al_2Si_30_{10}(OH)_8 + 1.4K^+ + 2H^+ + 1.2\ SiO_2$$

Biotite *Chlorite* *Quartz*

then the volume change, if SiO_2 remains as a solid with the chlorite, is ≈ +10%. If the SiO_2 is removed in solution the volume change is ≈ –2.2%. Thus even for pseudomorphic reactions involving the constant volume replacement of one mineral by another the volume changes associated with the reaction as a whole can be appreciable.

For the above reaction the configuration corresponds to collapsed layers of chlorite with alternating layers of expansion where quartz precipitates. Such layers appear as displacive quartz veins embedded in a sea of chlorite rich material. If there is a gradient in the removal of quartz from the compacting layers with more quartz removed from the edges of the collapsing layer than the centre of the layer then chlorite selvages appear on the vein walls. Veins that grow in this manner do not necessarily involve fracture to nucleate the vein and grow simply because of the local expansion involved in the compaction instability. These are hydrothermal displacive (displacement controlled) veins that grow incrementally to accommodate the local extension as SiO_2 is incrementally removed from the adjacent compacting layers. They contrast with veins that remain open for extended periods (characterised by euhedral crystal growth faces) and veins that episodically open and close with structure-less growth of quartz or calcite.

The compaction instability that is a characteristic feature of alteration systems occurs in an environment where the chemical reactions that generate the instability are themselves episodic in nature as discussed in Section 13.3.

13.5. Implications of multiscale processes.

One important goal in understanding the operation of hydrothermal systems as nonlinear dynamical systems is to determine the attractor that describes the evolution of the system in the phase space relevant to the dynamics of the system. The reason that establishing the attractor for hydrothermal systems is important is that the attractor carries all the information necessary to make predictions about gold grade and its relation to other structural/mineralogical/chemical features of the system. Since the behaviour of hydrothermal systems is chaotic absolute prediction is in principle impossible since the system will evolve to different states depending critically on initial conditions but the attractor is a plot of the probability that a particular state will occur and takes into account all possible initial conditions. Thus probabilistic arguments can be made about the relation of ore grade to other features of interest.

The attractor we are interested in is that relating the concentration of alteration minerals such as sericite and siderite to that of deposited gold. In Chapter 12 we gave attractors for temperature, fluid pressure and the equilibrium solubility of gold from model results. We have not so far been successful in determining an attractor involving deposited gold from natural data sets through the construction of delay maps mainly because the data sets we have access to, although substantial, are still too small to adequately define the attractor. However we can say something about the general form this attractor must take.

We saw in Figure 13.8 that the behaviour of the system in Mode I can be described by the behaviour of a simple Rössler attractor. This is attractive because Rössler proposed this attractor to describe the behaviour of some nonlinear chemical reactions in the first place and the attractor has been used by others since to discuss chemical reactions. The Rössler system is defined by

$$\begin{aligned} \frac{\mathrm{d}x}{\mathrm{d}t} &= -(y+z) \\ \frac{\mathrm{d}y}{\mathrm{d}t} &= x+ay \\ \frac{\mathrm{d}z}{\mathrm{d}t} &= b+xz-cz \end{aligned} \qquad (13.5)$$

where a, b and c are positive constants.

We can see from the hyperspectral data collected for alteration assemblages that the behaviour is similar to what is called a homoclinic attractor where the abundance of minerals such as chlorite or sericite continuously oscillates about a mean value rather than intermittently switch from above the mean to below the mean. Switching from one type of behaviour to another is the characteristic of attractors such as the Lorenz attractor (Figure 13.13 b) or the double homoclinic or double heteroclinic attractors of Figures 13.13 (c, d).

The other attractive aspect of the Rössler attractor is that although the behaviour of x and y are chaotic, the variation is about a mean value whereas the behaviour of z is intermittent. This reproduces hydrothermal systems studied to date where the behaviour of chlorite and sericite resembles that of x and y whereas that of gold is intermittent and resembles that of z. Hence at this stage of investigations we opt for an attractor that resembles the Rössler attractor rather than more complicated ones. Clearly more work is needed, ideally on very large data sets in order to clarify this issue and it is an important next step to take.

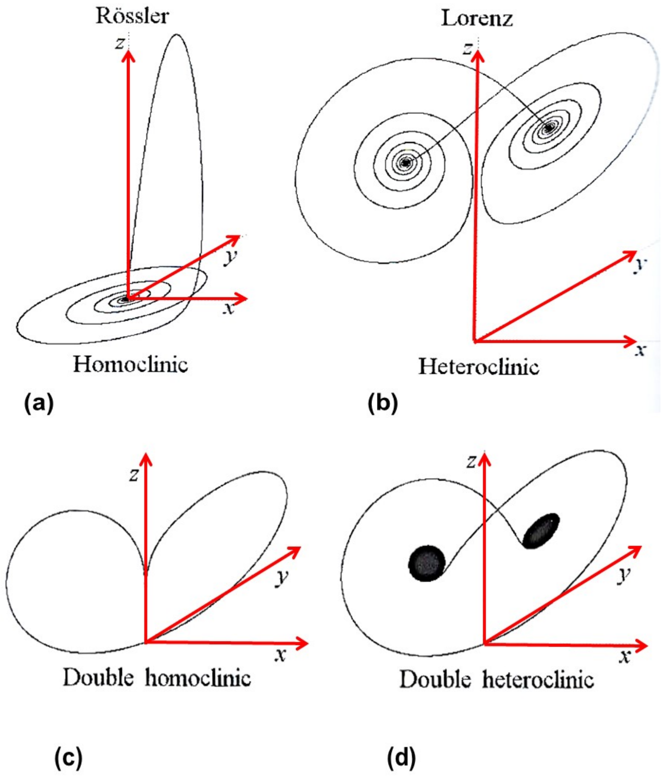


Figure 13.13. Various possibilities for attractors that might descibe the operation of hydrothermal systems.

In Figure 13.14 we present two Rossler systems that are more complicated than that shown in Figure 13.8. Now the behaviour is chaotic rather than periodic. We propose that temperature is equivalent to x, pore pressure is equivalent to y and solid deposited gold concentration is equivalent to *z*. The behaviour of gold is intermittent for both examples and the gold concentration increases as *c* is increased as does the width of the singularity spectrum. The resultant singularity spectra resemble those recorded for gold in the hydrothermal deposits studied form the Yilgarn.

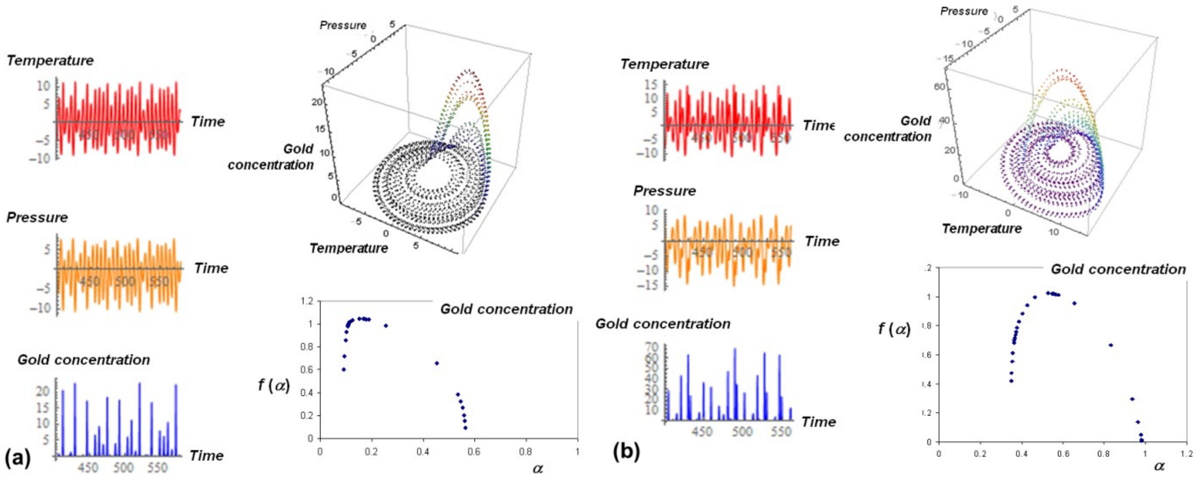


Figure 13.14. Examples of different behaviours of the Rössler attractor and the resultant character of the singularity spectrum. (a) a = b = 0, c = 5.7 ; width of singularity spectrum = 0.53 (b) a = 0,335, b = 0.2, c = 5.7 ; width of singularity spectrum = 0.65.

The difficulty in establishing attractors for hydrothermal systems may yet be resolved using approaches based on the concept of *recurrence plots*. Recurrence is a fundamental property of nonlinear dynamical systems and arises because the system continuously revisits states that are close to each other in phase space. Those states that a visited with high probability correspond to densely populated parts of the attractor. The degree of recurrence between various parts of a signal is plotted in two dimensions as shown in Figure 13.15. These plots have the advantage that results can be obtained with relatively small data sets. In Figure 13.15 we show results for four different systems and preliminary results for chlorite and gold from Sunrise Dam. Clearly the method offers great advantages in visual representations of complex data but also has the advantage of well-developed methods for quantitative analysis and for the construction of attractors from the recurrence plots.

In these plots diagonal lines from bottom left to top right indicate periodicity or quasi-periodicity in the signal (Figures 13.15 a, b), abrupt changes in the dynamics, such as transitions from one chaotic state to another or intermittency, are represented as white areas or bands (Figures 13 15 e, f) and homogeneous recurrence plots are typical of random signals such as white noise (Figure 13.15 d). We see that the recurrence plots of chlorite and gold (Figures 13.15 e, f) contain many chaotic transitions. It is expected that future studies involving recurrence plots and co-recurrence plots (recurrence plots comparing more than one variable in one system) will reveal differences between well-endowed and poorly endowed deposits as well as allow us to reconstruct the dynamics of these systems.

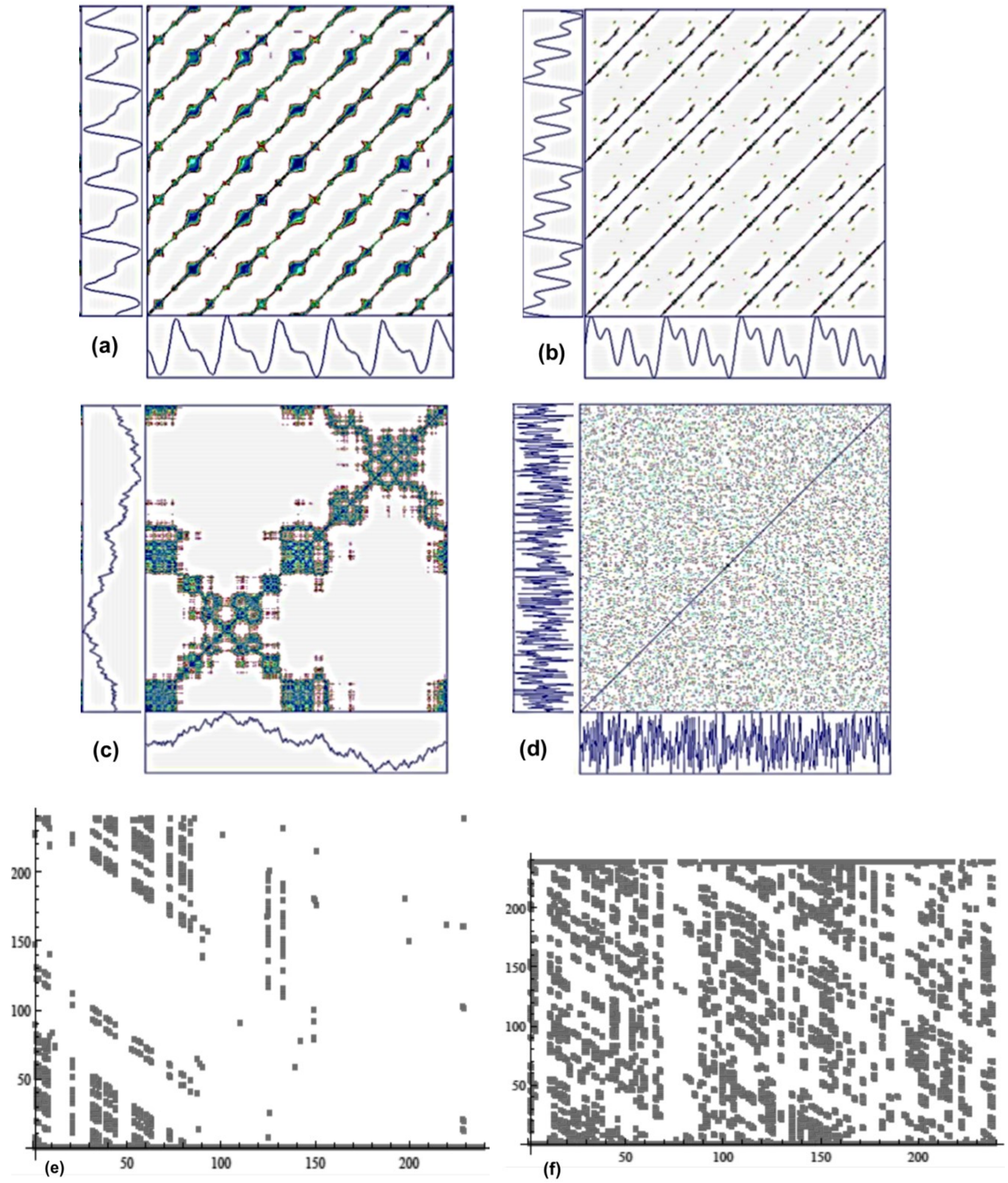


Figure 13.15. Examples of recurrence plots. The signal being analysed is in the bottom of each frame. (a) Tracheal pressure in a rodent. (b) Pink noise. (c) Hénon attractor. (d) White noise. (e) Chlorite abundance plot. (f) Gold recurrence plot. (e) and (f) are from the same drill hole at Sunrise Dam.

13.6. Implications for statistical tools of use in hydrothermal systems.

The behaviour of hydrothermal systems as chaotic systems means that the spatio-temporal evolution of the systems is best represented in terms of multifractals. In classical equilibrium thermodynamics the enormous number of molecules in a chemical system is best represented as suitable averages to define quantities such as temperature, pressure and entropy. These are macroscopic state variables that are very convenient measures of a chemical system that have no meaning at the molecular level. Quantities analogous to these can be defined for a non-equilibrium chaotic system. The enormous number of chaotic states in a nonlinear dynamical system is the analogue of the enormous number of molecules in a chemical system. The statistical temperature, pressure and entropy can be defined for the nonlinear chaotic system in exactly the same way as for a chemical system. Again, these are very convenient measures of the state of a chaotic system that have no meaning at the fine scale. The analogue of the entropy function in a chemical system is the multifractal singularity spectrum in a chaotic system. Thus there are strong reasons based in thermodynamics and statistical mechanics for using concepts based in multifractal theory to analyse and describe hydrothermal systems.

There are many well established methods for measuring the multifractal spectrum of a chaotic system but the easiest way for our purposes is to use wavelet analysis. A wavelet is a suitable mathematical function, commonly in the form of a localised wave packet that has geometrical similarity with the chaotic signal that is to be analysed. One selects a length scale for this package (the size is known as the *scale*) and forms the convolution of the wavelet with the signal at that scale. This gives a measure of how well the signal "resonates" with the wavelet at that scale. This procedure is repeated at all scales and one can then establish how the convoluted measure varies with scale. If the signal is multifractal then a spectrum of fractal dimensions at each scale is established. This spectrum has the same form as an entropy function for a chemical system. The metrics of the multifractal spectrum gives information on the multiplicative processes that produced the multifractal signal. One can see that the wavelet acts as a generalised box by analogy with the box–counting procedure in normal fractal analysis. The wavelet acts as a generalised microscope that can zoom into details of the multifractal geometry. Wavelet analysis is a way of conducting a multiscale analysis of a particular geometry of interest and is particularly suited to multifractal geometries. There are many ways of determining the singularity spectrum of a multifractal; we have used wavelets with an emphasis on the WTMM method (Chapter 9).

The metrics of use in quantifying a multifractal signal are the width, the degree of asymmetry of the spectrum, and the values of α and $f(\alpha)$ at various points on the spectrum where a tangent of slope, q, touches. The values of $f(\alpha)$ at these points are often called D_q (Figures 9.6 and 9.10). In Chapters 10 and 11 we show that there are clear differences in these various metrics for well-endowed and poorly-endowed deposits (Figure 13.16).

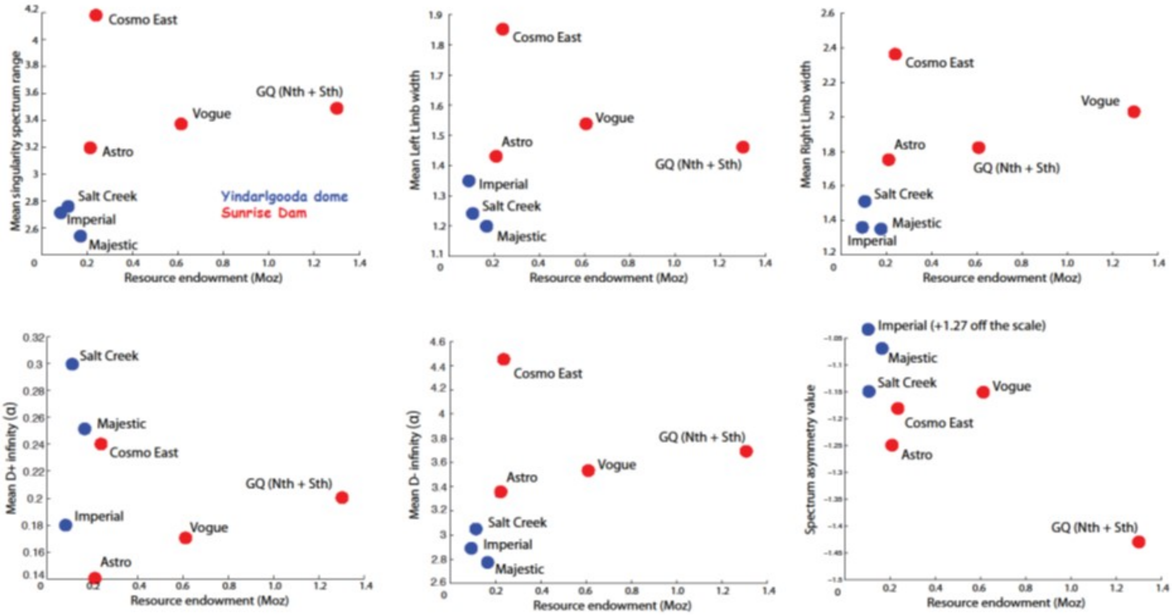
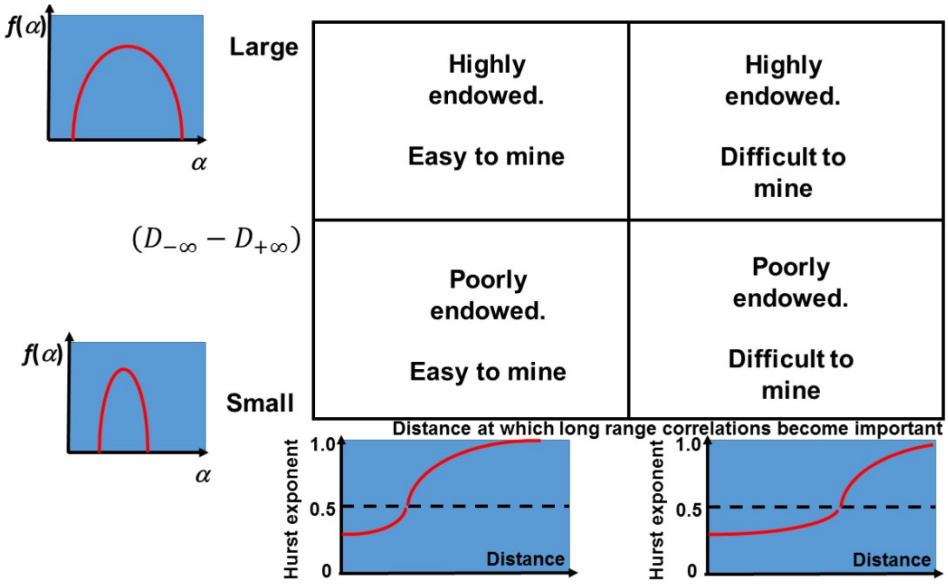


Figure 13.16. Plots of mean singularity spectrum metrics for each ore body versus its resource endowment (MOz’s). Yindarlgooda Dome ore bodies are blue; Sunrise Dam ore bodies are red. Higher endowed ore bodies from Sunrise Dam show distinct signatures to lower endowed ore bodies from the Yindarlgooda dome (Salt Creek and Majestic). Resource endowments from Ellison, P., 2016. Sunrise Dam resource inventory. AGA unpublished data.

Classical spatial statistics applied to the generation of ore body grade and block models assumes that it is possible to define a mean (or expected value) for the grade distribution and that there are no long range correlations in the distribution of mineralisation. Both these assumptions have been shown in this book to be unwarranted. Rationalisation of this observation with classical statistical approaches is yet to be achieved. For the moment we observe that four different categories of mineralisation can be distinguished on the basis of the singularity width, $\left(D_{-\infty} - D_{+\infty}\right)$, and the spatial scale at which long range correlations become important; we call this scale $L^{correlation}$. If $\left(D_{-\infty} - D_{+\infty}\right)$ is small then it is obsereved that the ore body is not well endowed and *vice versa*. If $L^{correlation}$ is on the scale of mining operations then prediction of grade is relativley easy and the ore body can be mined with reasonable confidence. If $L^{correlation}$ is large compared to the mining operations then prediction seems to be difficult and the ore body is not easy to mine. These distinctions are shown in Figure 13.17.



Large	Highly endowed. Easy to mine	Highly endowed. Difficult to mine
Small	Poorly endowed. Easy to mine	Poorly endowed. Difficult to mine

Figure 13.17. A classification of ore bodies on the basis of width of the singularity spectrum and whether long-range correlations appear at small or large spatial scales relative to the scale of day-to-day mining operations. The plot is that of the width of the singularity spectrum for gold. $(D_{-\infty} - D_{+\infty})$, against the distance at which long range correlations in gold distribution cut in relative to the scale of day-to-day operations.

13.7. Connecting new understanding with practical exploration procedures.

The approach adopted in this book is based on concepts developed in the study of nonlinear systems. The message is that all the features observed in hydrothermal systems, at all spatial scales, depend on nonlinear relationships between four critical processes. Without these four critical nonlinear processes significant orogenic gold deposits do not develop. These first order nonlinearities are:

- ***Regional/continental scale***: Competition between lithospheric movements generated by plate tectonics and the dissipation of energy by subduction and decompression melting in the lithosphere. This results in slab roll back and a spatially and temporally localised spike in CO_2 production from the slab.
- ***Crustal scale:*** The focussing effect of fluids into clusters of high permeability generated by fracturing; the degree of focussing is a function of the aspect ratio of the clusters and the permeability contrast between the cluster and the intact rock.
- ***Crustal scale:*** The nonlinear relation between fluid flow and the degree of fracturing; this results in a peak of fluid flow just before the percolation threshold is reached and the optimal fluid flow velocities for mineral reactions to occur.
- ***Deposit scale:*** The nonlinear coupling between exothermic and endothermic processes: this leads to episodic fluctuations in temperature with resultant fluctuations in fluid pressure and the equilibrium solubility of gold. Although the actual concentration of gold in solution never reaches the highest values of the equilibrium solubility and, in fact, stays at relatively low levels, the equilibrium solubility has an important influence on the rates of sold gold deposition and dissolution through nonlinear logistic types of rate laws. If the temperature is high enough large gold grades result from this episodic behaviour.

The portrayal of orogenic gold systems as open flow chemical reactors held far from equilibrium by the influx of mass and energy provides a sound thermodynamic basis for understanding many aspects of such systems including:

- Regional controls on the characteristics of the optimal plumbing systems.
- The significance of the paragenetic sequence.
- The mechanisms of gold deposition and the significance of episodic behaviour.
- The relation of gold deposition to other aspects of the system such as the nature of alteration mineral reactions, vein types and brecciation.
- The controls on the efficiency of gold deposition.
- The significance of irregularity in the spatial distribution of gold and of alteration assemblages and methods of analysing and characterising such irregularity in terms of multifractal concepts.
- Features that distinguish a highly endowed from a less endowed deposit and features that distinguish an easily mined deposit from a difficult to mine deposit based on multifractal metrics and the scaling of the Hurst exponent.

The necessary next step is to express this understanding in terms of practical exploration procedures. In Table 13.1 we present the relationships between processes/concepts and exploration indicators that can be acted upon at various spatial scales ranging from the regional to the nano-scale. In Figure 13.18 we use the conceptual framework developed by McCuaig et al. (2010) to map the relationships between critical processes necessary for the formation of successful orogenic gold systems, specific processes that contribute to these critical processes, the outcomes of these processes and specific observables that can be acted upon from a practical exploration sense.

Table 13.1. Scale dependent processes and concepts and their significance with resulting exploration indicators.

Scale	Process/concept	Significance	Exploration indicators
Continental: 1000 km	Rapid (1 – 5 my) processes of simultaneous decarbonation and dehydration	Rock mass is advected through isotherms rapidly (≈ cm y^{-1}) so that devolatilisation is rapid (< 1 my)	• Extension associated with slab roll-back • Extension associated with rifting of previously metasomatised lithosphere • Alkaline igneous complexes • Contact metamorphism of altered mafics and sediments in the crust.
Camp scale: 100 km	Crustal plumbing systems sub-critical but close to critical	Flow rates in crust are optimal	• "Bifractal" distribution of alteration patches as in Nevada, Zambezi
Deposit scale: 10 to 1 km	A chemical reactor that has operated in an unstable manner with coupled exothermic/endothermic processes	Equilibrium solubility of gold is enhanced	• Multifractal spectra for alteration and mineralisation • Long range correlations in alteration/mineralisation spectra begin at short length scales. • Large width for multifractal singularity spectrum. Multifractal spectrum asymmetrical to the right.
Drill-hole	Processes that lead to	Large amplitude	• Early exothermic

scale: to Outcrop-thin/ section scale: 1km to 1 mm	high equilibrium solubility of gold	fluctuations in temperature leading to large amplitude fluctuations in fluid pressure. Fluid release reactions increase amplitude of fluid pressure fluctuations even further	hydration/carbonation reactions overprinted episodically by deformation (brecciation, fracturing) synchronous with endothermic fluid releasing reactions such as • Coupling of pyrite forming reactions with gold deposition.

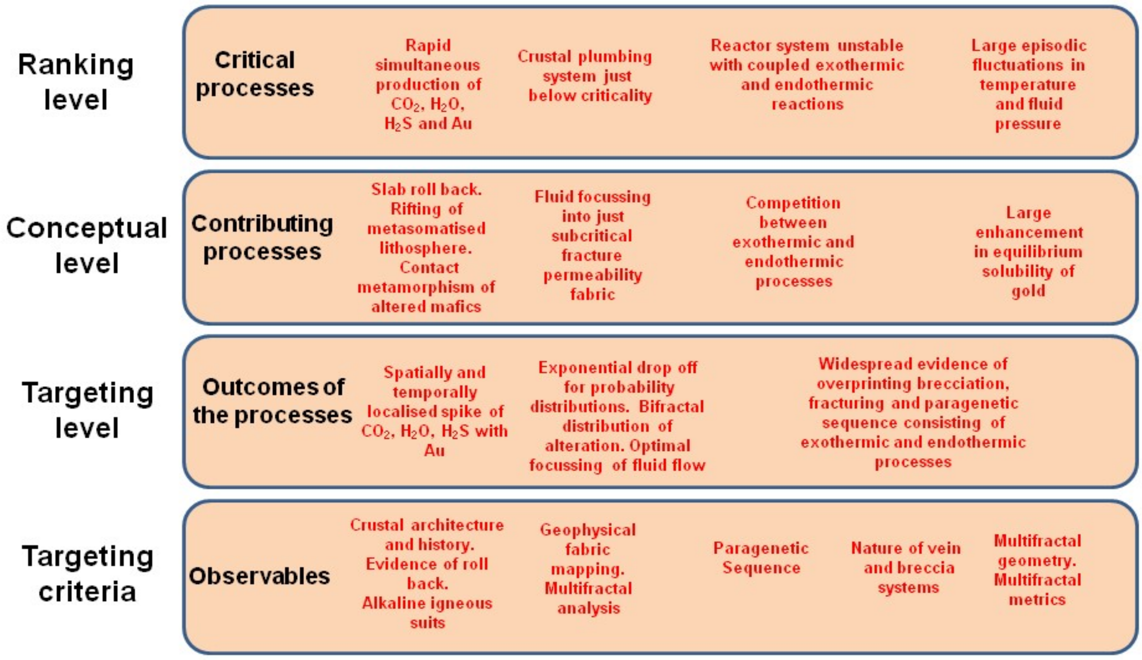


Figure 13.18. Critical processes and the exploration ranking model for orogenic gold based on the mineralising process being a nonlinear dynamic process. The figure is based on concepts introduced by McCuaig, Beresford and Hronsky (2010).

13.8. The way forward.

Similar to developments in other scientific disciplines, the rapid acquisition, processing and accessibility of data poses challenges and provides opportunities to the solid Earth Sciences. The temptation is to collect data at finer and finer detail simply because it is possible and easily processed in the hope that the increased detail will reveal new understanding. Such data collecting exercise are best done with a rigorous theoretical background that enables only relevant data to be collected and provides a basis for interpretation and testing of theoretical models. The last 100 years of detailed deposit based investigations with a basis in equilibrium chemical thermodynamics and a view of deposits as linear, non-dynamic entities has not provided the insight necessary. We have proposed in this book that viewing orogenic gold systems as nonlinear open flow chemical reactors is a rigorous approach grounded in the thermodynamics of chaotic systems that provides considerable insight into the behaviour and evolution of these systems. In order to analyse dynamical systems very large data sets are required. The common procedure of sampling every meter or half meter of drill core does not provide enough data to construct meaningful attractors and recurrence plots. The hope is that technology will be developed to routinely sample at much closer intervals.

To date the approach in mineral exploration has been essentially an empirical pattern recognition procedure with great sophistication developed in methodologies such as weights of evidence, liner regression of relationships between multi-element data bases, fuzzy logic, processing of geophysical and geochemical images and pattern search algorithms. The approach is to attempt to find patterns without knowing the rules by searching through vast amounts of data. The paradigm shift we propose is a shift to a thermodynamic framework where the system is viewed as resulting from the dynamic competition, at all spatial scales, from continental- to nanometre-scales, between the supply of mass and energy and the dissipation of energy through alteration, deformation and metal deposition processes. The exploration procedures and techniques then follow from this view as indicated in Table 13.1 and Figure 13.8.

Some of the future research areas that are highlighted by discussions in this book and that are fundamental to increasing our understanding of hydrothermal systems are:

- *Multifractal fabric mapping and mapping of alteration patches with reference to critical plumbing systems*. The wavelet analytical methods used in this book need to be extended to two dimensions and applied to geophysical data sets to search for alteration patches. The results need analysis using multifractal methods and recurrence plots. This work is aimed at establishing the characteristics of regional alteration patterns that correlate with highly mineralised terrains.
- *Recurrence plots and methods aimed at establishing the dynamics of hydrothermal systems*. We need access to much larger data sets to enable recurrence plots to be constructed for different styles of mineralisation. Such plots enable the attractors to be established for different systems and allow constraints on the differential equations that describe the dynamics to be defined. Emphasis needs to be placed on characterising big, well-endowed systems from small, poorly-endowed systems.
- *Details of chemical reactions*. To advance the theoretical understanding of hydrothermal systems a complete nonlinear model needs to be established including the derivation of stable non-equilibrium mineralogical states. This will require the development of a catalogue of activation energies, Gibbs energies and chemical potentials for all important chemical reactions together with a classification into fluid producing and fluid absent reactions and estimations of temperature evolution within natural systems.
- *Better integration of structural histories with paragenesis and gold deposition mechanisms*. At present there is little attempt to integrate mineral paragenesis with deformation histories. We need better observational constraints on the mineralogical and deformation histories of hydrothermal systems and characterisation of such histories in terms of the energy balance for the system

The study of the nonlinear dynamics of hydrothermal systems is in its infancy with many approaches and analytical procedures yet to be explored. It is hoped that this book might inspire researchers and mineral explorers, particularly the younger ones that may have had exposure to aspects of nonlinear dynamics in undergraduate mathematics, physics, chemistry and/or biology classes, to investigate these systems in greater detail. Since hydrothermal systems are the epitome of large nonlinear systems with large numbers of non-equilibrium chaotic states, they provide a natural laboratory to explore and add to what we know about the behaviour of large systems with many degrees of freedom, operating far from equilibrium. Instead of regarding the complexity of hydrothermal systems as a hindrance to understanding, one should regard such complexity as a deep source of knowledge that reflects the quite wondrous behaviour of nonlinear geological, chemical and physical interactions.

Recommended reading.

McCuaig, T.C., Beresford, S. and Hronsky, J. 2010. Translating the mineral systems approach into an effective exploration targeting system. Ore Geology Reviews 38, 128-138.

Webber, C. L. Jr., Ioana, C., and Marwan, N. 2016. Recurrence Plots and Their Quantifications: Expanding Horizons. Proceedings of the 6th International Symposium on Recurrence Plots, Grenoble, France, 17–19 June 201. Springer Proceedings in Physics, Springer.