Chapter 11. NON-LINEAR DYNAMICS OF KEY MINERAL PHASES IN AN ARCHAEAN HYDROTHERMAL AU SYSTEM

Mineral distribution framework at Sunrise Dam: regional metamorphic parageneses, alteration assemblages and primary vein/breccia-forming mineralogy

The basaltic to andesitic volcaniclastics and banded iron formation protoliths at Sunrise Dam record greenschist facies peak metamorphic conditions, reflected by both the regional metamorphic paragenesis and localised alteration assemblages associated with Au and sulphide mineralization. Chlorite is highly abundant throughout the system (e.g. Figure 11.1). Although constituting a minor component of veining and hydrothermal alteration assemblages proximal to Au mineralization, investigations suggest that chlorite concentration and distribution are dominantly reflective of regional-scale 'background' metamorphism. This is consistent with abundances commonly increasing away from alteration zones. Chlorite frequently forms penetrative schistosities in many of the host rocks, in addition to intense S-C fabrics in the prominent shear zones that characterize the system.

Figure 11.1 – Breccia zone with basalt host-rock clasts encased in calcite and quartz cement. Basalt clasts have been extensively replaced by chlorite during retrograde greenschist-facies metamorphism.

Metasomatic alteration of the host rocks in selvages proximate to mineralization and fluid conduits (veining, brecciation and shear zones) is dominantly sericitic. Sericite composition ranges from paragonite/muscovite (Al-rich) to phengite (Mg-bearing). Investigations of Sunrise Dam have demonstrated a spatial correlation between paragonite/muscovite-forming reactions and Au mineralization in GQ. Conversely, phengite-dominated zones correspond to those that are barren or poorly mineralized. Although sericite dominates, carbonates (calcite and dolomite/ankerite) and (minor) chlorite also participate in host rock alteration. In some of the Group I ore bodies (e.g. the Placer and Margie's lodes) carbonate wall rock alteration intensifies away from mineralization zones.

Dominant vein and breccia cement-forming phases associated with mineralization are calcite, ankerite/dolomite and quartz (e.g. figures 11.2, 11.3 and 11.4). Individual veins are composed either exclusively of one of these phases, or a combination thereof. Where quartz-only and carbonate-only veins co-exist they may display locally coherent relative timing chronologies at the mesoscale, but display mutual cross cutting relationships at the ore body scale. This mutual cross cutting between different vein orientations has been interpreted to record transient phases of seismicity within the established deformation chronology, outlined in Chapter 10. Sericite and chlorite may also be present in veining but are less frequent and of lower abundance.

Figure 11.2 – Folded ankerite-quartz veining in strongly sericite-metasomatised andesite from

GQ. Sericite in this section is dominantly paragonite/muscovite, and visible pyrite is locally associated with veining.

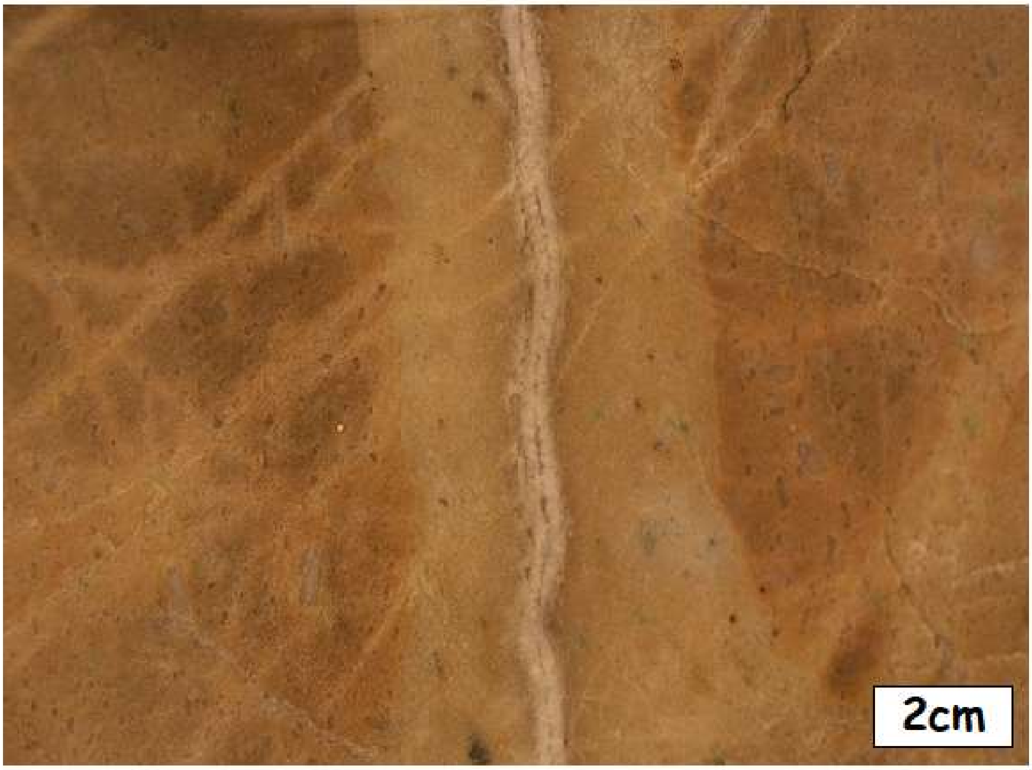


Figure 11.3 - Calcite±ankerite±quartz veining in a quartz-feldspar porphyry from Cosmo East. Phenocrysts are dominantly quartz. Feldspar in the groundmass of the host-rock surrounding the veins has been locally replaced by sericite. Chlorite is present in minor abundances.

Figure 11.4 – Brecciated of a similar quartz-feldspar porphyry host rock from Cosmo East. Angular clasts are encased in Calcite±ankerite±quartz cement.

Structural and petrological investigations suggest that carbonate-forming processes at Sunrise Dam (calcite and ankerite/dolomite) are entirely secondary – associated with vein/brecciation infill and host rock alteration. This is consistent with the basaltic to andesitic volcanics and volcaniclastics, and banded iron formation protoliths that host the deposit. Primary carbonates are present elsewhere in the Eastern Goldfields Superterrane of the Archaean Yilgarn craton in the form of minor lamprophyres and carbonatites (e.g. Mount Weld). Calcite and ankerite distributions in the system are therefore primarily structurally controlled, dependent upon the scales of deformation partitioning, spatial volumes of veining, fluid composition and pH.

Amphibole is another common phase throughout Sunrise Dam. Petrological investigations have concluded that while minor amounts of amphibole are vein-hosted, it is not an alteration phase spatially associated with mineralization. Amphibole abundances within Sunrise Dam are instead reflective of protolith distribution - with moderate to high abundances corresponding to andesite, basalt and ultramafic protoliths.

Hyperspectral infra-red reflectance spectroscopy

Hyperspectral reflectance analysis now plays an integral role in determining spatial distributions in the abundance, and composition, of key mineral phases in a range of ore deposits. Incident electromagnetic energy is applied to a rock volume; with reflectance measured as a ratio between the transmitted energy and that reflected by the surfaces of mineral phases. Wavelengths of electromagnetic energy relevant to hydrothermal systems are those in the visible to near-infrared (VNIR) and short wave infrared (SWIR) ranges (0.4 – 1.4µm and 1.4 – 3µm, respectively). The reflection response of key alteration phases such as sericite and chlorite are dependent upon cation-hydroxyl group configurations in their lattices. Hydroxyl groups bonded to specific cations (e.g. Mg^{2+}, Al^{3+} and Fe^{2+}) vibrate under exposure to specific wavelengths of electromagnetic energy, producing diagnostic absorption features that may be used to discriminate between mineral phases. Wavelength-specific absorption features under SWIR are present in paragonite (2190nm), muscovite (2200nm) and phengite (2220nm) compositional members.

SWIR reflectance can also discriminate between calcite ($CaCO_3$), and ankerite-dolomite series carbonates that also bear additional cations (Fe^{2+}, Mg^{2+} and Mn^{2+}). Calcite has a higher wavelength absorption feature (typically 2335nm) than ankerite and dolomite (2325nm and 2320nm, respectively). However, confident discrimination between the $CaFe(CO_3)_2$ (ankerite) and $CaMg(CO_3)_2$ (dolomite) series end-members under hyperspectral reflectance is problematic beacuse of their similar wavelengths. Therefore, following previous investigations of the Sunrise Dam deposit, the term “ankerite” is used here throughout to encompass all phases in the ankerite-dolomite series.

Hyperspectral images of drill core are sub-divided into pixels, each interrogated across a range of wavelengths spanning VNIR and SWIR to evaluate the presence or absence of individual mineral phases. Modern hyperspectral imaging techniques now permit analysis resolutions down to scales in the order of 10’s of microns. Acquired pixel data may be used either to quantify the down-hole concentrations of each mineral phase, or map down-hole variations in compositional end-members. Recent investigations have successfully utilised SWIR absorption features to map the distributions of sericite composition at Sunrise Dam and the Kanowna Belle gold deposit - also situated in the Eastern Goldfields Superterrane. In the GQ ore body at Sunrise Dam, this has demonstrated that zones of paragonite and muscovite-forming reactions spatially correspond with Au precipitation; phengite-forming reactions dominate within barren host rock (e.g. Figure 11.5).

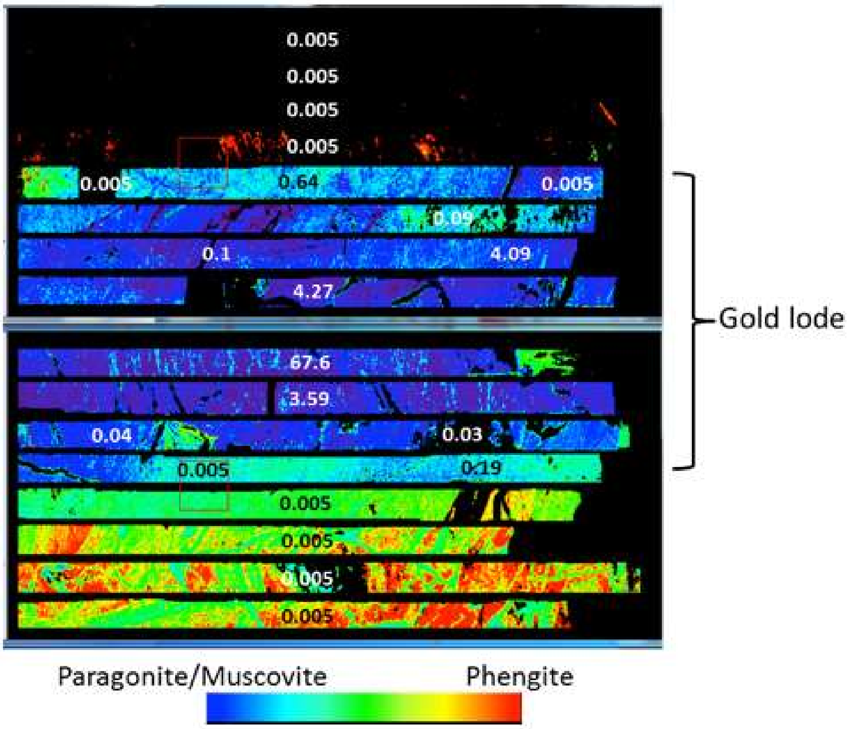


Figure 11.5 – Hyperspectral reflectance image of a 15m span of drill core from the GQ ore body showing how sericite (white mica) composition may be mapped. Blue (lower wavelength) end-members are paragonite/muscovite; red end-members are phengite; black represents an absence of sericite. Local Au grades (ppm) are indicated on the core. Here, paragonite/muscovite-forming reactions correlate with the Au mineralized zone, phengite or an absence of sericite correlate with barren zones.

Drill core analysis strategy

Chapter 10 presented a study of non-linear dynamics in Au from a number of Archaean hydrothermal systems using drill holes sectioned into uniform 100m increments at 1m-resolution. This chapter examines non-linear dynamics for down-hole mineral concentrations (sericite, chlorite, calcite, ankerite and amphibole) derived from hyperspectral analysis at

Sunrise Dam. Data were acquired for Vogue, GQ and Cosmo East - the textural differences between which are outlined in Chapter 10. Here, the entire length of each individual drill hole was analysed in order to maximize the amount of data used to produce the singularity spectra. As outlined above, hyperspectral data is acquired at high resolutions in the order of 10's of microns. However, Au assay data is routinely acquired at lower resolutions in the order of 0.5 – 1m. Therefore, 0.5m-resolution hyperspectral mineral concentration data were selected for this study to allow direct comparison with Au dynamics. Au and all phases were analysed over the same interval within each individual drill core.

Most drill cores from GQ range from 140 - 300m in length (90%) with some extending between 300-500m (10%). Most drill cores from Vogue range from 275 – 520m in length (85%) with some extending between 560 – 1070m (15%). Drill cores from Cosmo East range between 366 – 642m in length. All intervals analysed represent fresh rock; they are therefore representative of the primary (hypogene) sections of the system - unaffected by near-surface remobilization processes associated with oxidation and interaction with meteoric fluids.

The maximum size of wavelet that may be applied to a signal (i.e. the maximum length-scale of analysis) is pre-determined by the number of data points (its length). The greater the length of a drill core interval, the greater the range in wavelet scale that may be applied. Optimum singularity spectrum results are obtained when utilising octave values close to, or at, the maximum range permitted. Using too narrow a range in octaves results in a malformed singularity spectrum due to the dataset being analysed over an inadequate range of length scales to evaluate the organizational (multifractal) hierarchy of the system. Importantly, for any singularity spectra to be straightforwardly compared they must be derived from analyses utilising the same wavelet parameters (number of octaves and voices).

Consistent wavelet parameters were applied to all drill-cores within an individual ore body. The octave range for each ore body was selected to optimize the number of applicable drill-cores. A three octave, eight voice, setup was applied to drill-cores in GQ and Cosmo East. Most of the drill-cores intersecting the Vogue ore body are greater in length than those in GQ and Cosmo East; therefore, a four octave, eight voice, structure was applied. The absolute values of singularity spectrum metrics for Vogue therefore cannot be straightforwardly compared to those from GQ and Cosmo East. However, the behaviour of individual phases in Vogue relative to one another can be compared to their relative behaviour in counterparts in the other two ore bodies.

Comment [A1]: Have you ever compared the results of analyses using 1 octave 20 voices against 5 octaves 4 voices?

Wavelet analysis of hyperspectral data in individual ore bodies

The following sections present key singularity spectrum metrics ($D+\infty$, $D0(\alpha)$, $D1(\alpha)$, $D2(\alpha)$, spectrum range, left limb range, right limb range and spectrum asymmetry) for Au and each phase within an ore body. Definitions of each metric have been outlined in Chapter 9. Spectrum asymmetry is quantified using the same method presented in Chapter 10. A schematic illustration of different spectrum asymmetry values is included with the asymmetry histograms of each ore body for reference. Each individual metric is presented as a series of frequency normalized histograms of its distribution in each phase within an ore body. The relative behaviour of all phases within each ore body is compared, then relative to their counterparts in other ore bodies in following sections.

Comment [A2]: Not also D-∞?

GQ

Individual mineral phases and Au in GQ show distinct behaviour in many singularity spectrum metrics. Each displays considerable variation in singularity spectrum range (the strength of multifractality and hierarchical organization) between drill cores throughout the ore body (Figure 11.6). Chlorite spectrum ranges peak at ~1.75 and display the greatest variability, with individual spectra ranging from 0.5 - ~4.5. Chlorite also displays the greatest proportion of drill cores with spectrum ranges > 2.5. Calcite and ankerite display highly similar spectrum range behaviour both having end-members extending from 1 - 3.25 and peaking in the range 1.5 - 2.25. Au displays the highest modal spectrum range of all the phases/elements in GQ (~2.75). Sericite has the lowest modal spectrum range of all phases (0.75 – 1.25) and also the most restricted range profile (dominantly 0.25 – 2, with few > 2). Amphibole has a modal peak at ~1.5, similar to that in chlorite.

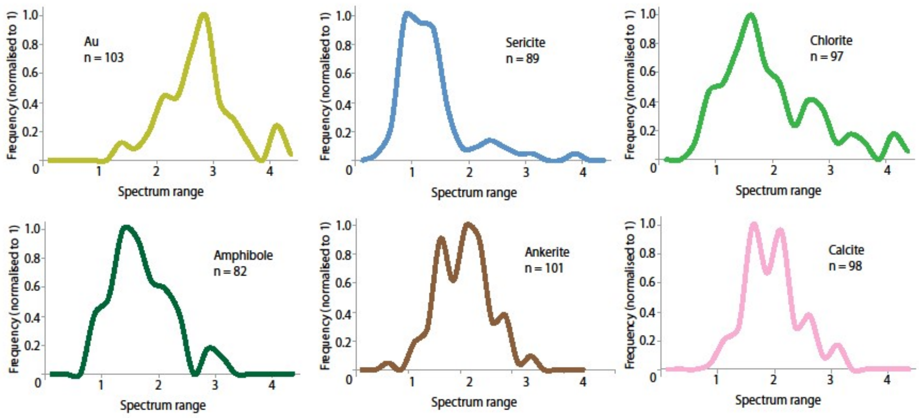


Figure 11.6. Frequency-normalized histograms of singularity spectrum range for Au and all mineral phases in GQ. Au has the highest mode in spectrum range; sericite has the lowest. Chlorite and amphibole also show low modes, slightly higher than sericite. Calcite and ankerite show intermediate modes. Bin width = 0.25.

Au has the greatest left limb ranges of any phase/element (Figure 11.7) peaking between 0.75 – 1.75. Sericite and chlorite have the narrowest left limb ranges, peaking between 0.25 – 0.5 and 0.25 – 0.75, respectively. Amphibole, ankerite and calcite have left limb ranges intermediate to those of Au (broad) and sericite and chlorite (narrow). Sericite and amphibole have the narrowest right limb ranges (Figure 11.8) both peaking between 0.5 – 0.75. Au also has the greatest modal peak in right limb range (1.25 – 1.5). Chlorite shows the most broadly distributed variation in right limb range of all phases (0.5 – 2).

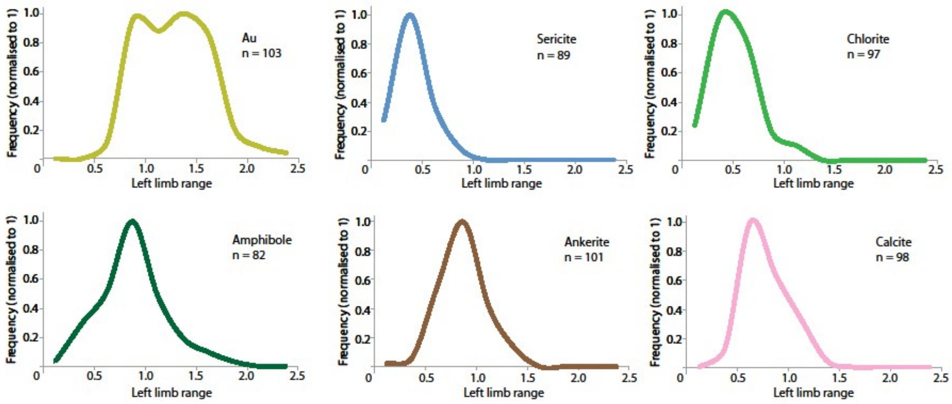


Figure 11.7. Frequency-normalized histograms of left limb range for Au and all mineral phases in GQ. Au has the broadest left hand limbs; chlorite and sericite have the narrowest. Calcite, ankerite and amphibole have intermediate left hand limb widths. Bin width = 0.25.

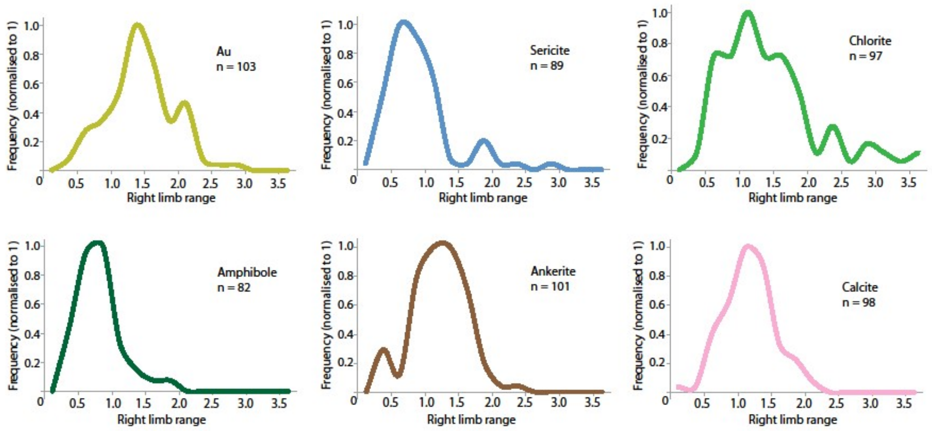
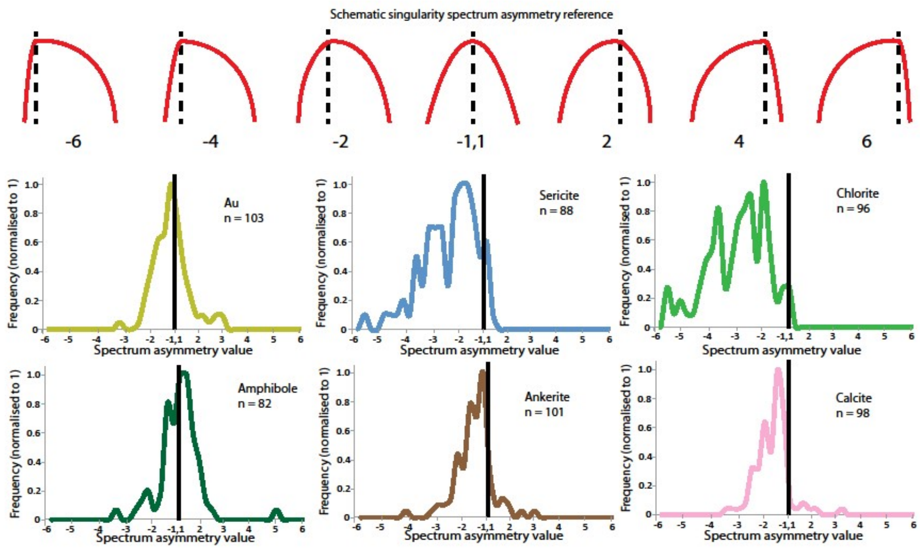


Figure 11.8. Frequency-normalized histograms of right hand limb range for Au and all mineral phases in GQ. Sericite and amphibole have the narrowest right limb ranges; Au and

chlorite show the greatest variability in right hand limb width. Calcite and ankerite have intermediate right hand limb widths, with less variation than Au and chlorite. Bin width = 0.25.

Mineral phases in GQ also display distinct singularity spectrum asymmetries (Figure 11.9). Au and amphibole have approximately equal proportions of left and right handed spectra, with end-member asymmetry values of -3 and 3. Both display modal peaks across the -1,1 marker (i.e. the majority are close to symmetric). Calcite and ankerite display highly similar distributions, characterized by almost exclusively (weak to moderate) left-handed asymmetries in the range -1 to -3. Chlorite and sericite also display almost exclusively left handed asymmetry. However, they display much broader profiles with substantial proportions of spectra characterized by extreme asymmetry values between -3 and -6. Chlorite has the greatest



proportion of spectra with extreme left handed asymmetry values between -6 and -3.

Figure 11.9. Frequency-normalized histograms of spectrum asymmetry values in Au and all mineral phases in GQ. Reference figure above shows schematic examples of different asymmetry values. Asymmetry values are the ratio of the broader of the two limbs to the narrower. Negative values express that the right limb is broader; positive values that the left is

broader. Au and amphibole have approximately equal proportions of left and right handed asymmetry. Calcite and ankerite have almost exclusively left handed asymmetry (weak to moderate). Chlorite and sericite are almost exclusively left handed, with the greatest proportions of extreme asymmetries. Bin width = 0.25.

D0(α), D1(α), D2(α) and D(+∞) positions for each phase/element are provided in Table 1:

Comment [A3]: On what did you base your decision to provide a table for these metrics rather than the figures as for the other metrics?

Table 1

	D0(α)	D1(α)	D2(α)	D(+∞)
Au	0.75 – 2.25 (1.25 – 1.5)	0 – 0.9 (0.25 – 0.5)	0 – 0.9 (0 – 0.25)	0 - 0.25
Sericite	0.75 – 1.75 (~0.5 – 1.75)	~0.6 – 1.4 (1)	0.4 – 1.4 (0.75 – 1)	0.75 – 1
Chlorite	0.75 - 2 (1 – 1.25)	~0.6 – 1.4 (1)	0.4 – 1.4 (0.75 – 1)	0.75 – 1
Calcite	0.75 – 1.5 (1 – 1.25)	0.2 – 1.2 (0.5 – 0.75)	(0.25 - 0.5)	(0.25 – 0.5)
Ankerite	0.75 – 1.75 (1 – 1.25)	0.2 – 1.2 (0.5 – 0.75)	(0.25 - 0.5)	0 - 0.25
Amphibole	0.75 – 2.25 (1 – 1.25)	0.2 to 1.4	0 – 1.4 (0.25 - 0.5)	0 - 0.25

Frequency distribution end-members for each phase/element are provided first; numbers enclosed in brackets are the modal peak on the frequency histogram.

In summary, calcite and ankerite in GQ display highly similar singularity spectrum signatures. Both have similar modal peaks and distributions in spectrum range, weak to moderate left handed asymmetry, the greatest D(+∞) values of any phase, and intermediate D1(α) and D2(α) values. Au displays the greatest singularity spectrum range (i.e. the strongest multifractal signature), the lowest values of D1(α), D2(α) and D(+∞), and both left and right handed asymmetry. Sericite and chlorite within GQ display similar behaviour in many spectrum metrics, having the highest D1(α), D2(α) and D(+∞) values, and the greatest spectrum asymmetry (almost exclusively left handed). However, sericite shows the lowest

Comment [A4]: surely sericite and chlorite have greater values according to this table?

Comment [A5]: yes

spectrum ranges of any phase, whereas chlorite shows the broadest spectrum range distribution. All phases with the exception of Au show highly similar distributions in D0(α).

Vogue

Mineral phases in Vogue also display distinguishing singularity spectrum characteristics. Sericite and chlorite display the broadest distributions in spectrum range (Figure 11.10). Chlorite is multi-modal with four modes of approximately equal strength at 1.5, 2.25, 3 and 3.75 (the last being marginally stronger). Sericite is bi-modal with a narrow peak at 0.75 and a broader one spanning ~2 – 3. Au displays a narrow distribution in spectrum range (the majority extending between ~2 – 3) and peaks at 2.25. Amphibole has the lowest modal peak of all phases (1.5) with a narrow distribution ranging from ~1 – 2.5. Calcite and ankerite show relatively similar spans in distribution and peak between 1.5 and 2.25.

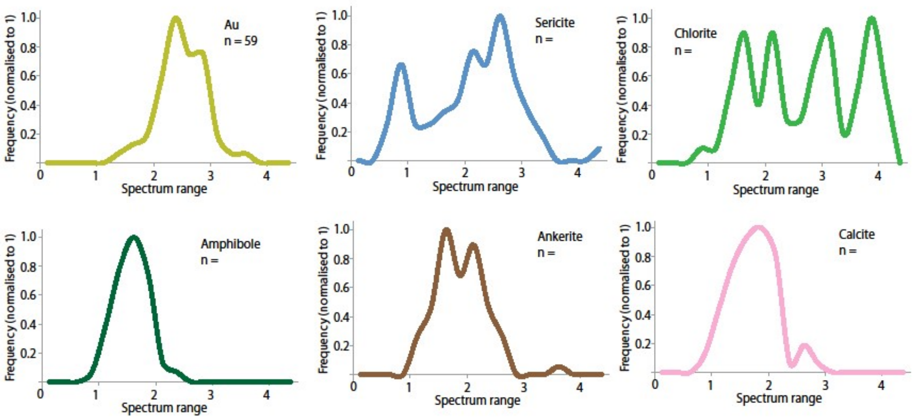


Figure 11.10. Frequency-normalized histograms of singularity spectrum range for Au and all mineral phases in Vogue. Chlorite and sericite have the broadest variation in spectrum range. Chlorite is multi-modal and has some of the broadest spectra of any phase/element. Broad spectra ranges in sericite are similar to those in Au. Amphibole has the lowest modal

peak in spectrum range. Calcite and ankerite have intermediate spectrum ranges. Bin width = 0.25.

Au has the broadest left limb ranges (peaking between 1 – 1.5); sericite has the narrowest (peaking between 0.25 – 0.75) (Figure 11.11). Calcite, ankerite, chlorite and amphibole have predominantly intermediate values between the peaks of Au and sericite. Chlorite and sericite have the broadest, and most diverse, right limb ranges (Figure 11.12). Sericite right hand limbs range from 0 – 2.75; chlorite ranges from 0.5 – 3.5. Amphibole has the narrowest right limb ranges, peaking between 0.5 – 0.75. Au, ankerite and calcite have similar right limb width peaks between 1 – 1.5.

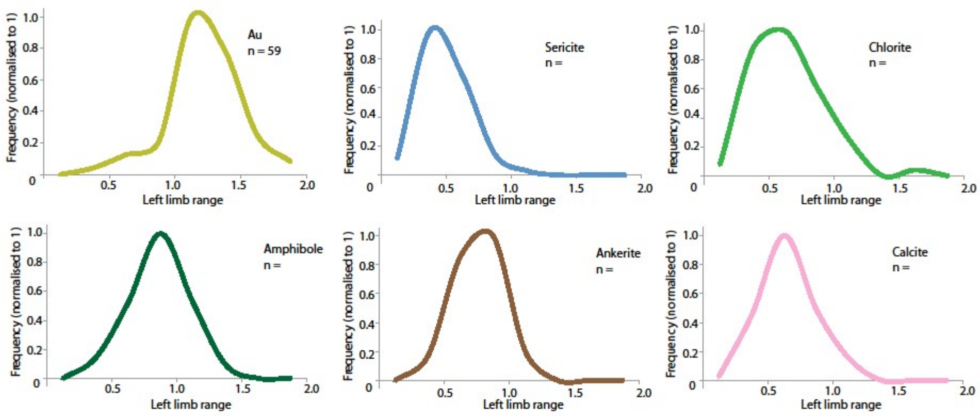


Figure 11.11. Frequency-normalized histograms of left limb range for Au and all mineral phases in Vogue. Au has the broadest left hand limbs, sericite the narrowest. Calcite, ankerite, amphibole and chlorite have intermediate left limb widths. Bin width = 0.25.

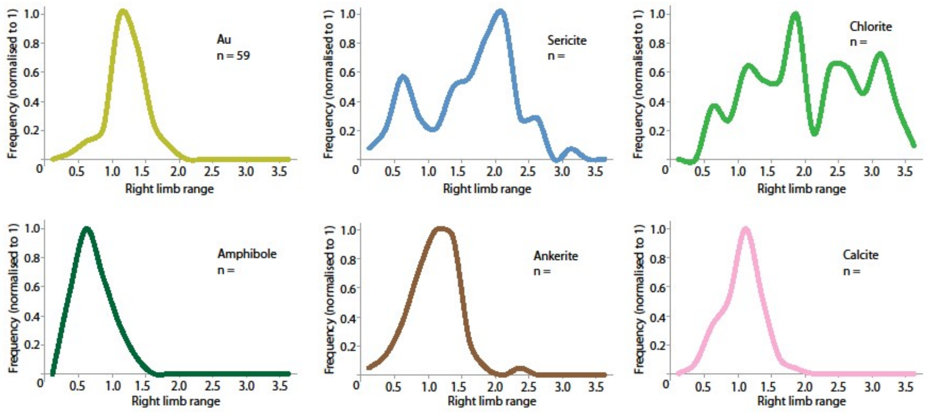


Figure 11.12. Frequency-normalized histograms of right hand limb ranges in Au and all mineral phases in Vogue. Chlorite and sericite have the broadest and most diverse right limb widths. Amphibole has the narrowest right hand limbs. Au, calcite and ankerite have similar, intermediate, right limb ranges. Bin width = 0.25.

Au singularity spectra in Vogue show relatively weak asymmetry (most between -2 and 2) with almost equal proportions of left handed and right handed (Figure 11.13). Calcite and ankerite show a strong predominance of left-handed asymmetry (weak to moderate). Ankerite dominantly extends from -1,1 to -3; calcite from -1,1 to -3.5. Sericite and chlorite display the broadest asymmetry profiles of all phases, and are almost exclusively left-handed. Both display a substantial proportion of spectra with strong asymmetries < -3. Rare end-members in chlorite extend to extreme values < -8. Strong left handed asymmetries in sericite and calcite are consistent with them having the broadest right limb ranges.

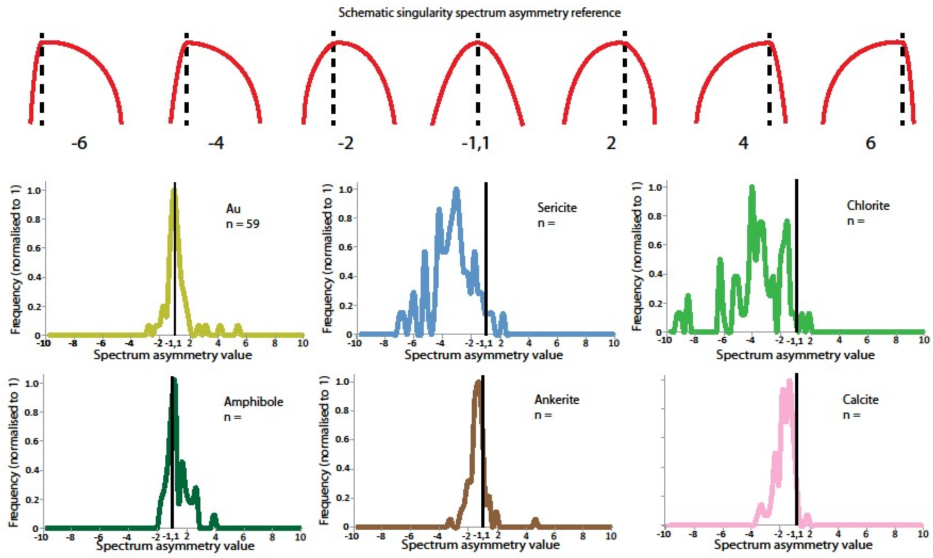


Figure 11.13. Frequency-normalized histograms of spectrum asymmetry values in Au and all mineral phases in Vogue. Reference figure above shows schematic examples of different asymmetry values. Au has approximately equal proportions of left and right handed asymmetry. Calcite and ankerite have a predominance of weak to moderate left handed asymmetry. Sericite and chlorite have weak to strong left handed asymmetry (almost exclusive). Bin width = 0.25.

D0(α), D1(α), D2(α) and D(+∞) positions for each phase/element are provided in Table 2:

Table 2

	D0(α)	**D1(α)**	**D2(α)**	**D(+∞)**
Au	0.75 - 2 (1.25 – 1.5)	0 – 1 (0.25 – 0.5)	0 – 0.5 (0 – 0.25)	0 – 0.5 (0 – 0.25)
Sericite	0.75 – 1.75 (1 – 1.25)	0.5 – 1.25 (0.75 – 1)	0.5 – 1.25 (0.75 – 1)	0.5 – 1 (0.75 – 1)
Chlorite	0.75 – 1.75 (1.25 – 1.5)	0.5 – 1.25 (0.75 – 1)	0.5 – 1.25 (0.75 – 1)	0.25 - 1 (0.5 – 0.75)
Calcite	0.75 – 1.5 (1 – 1.25)	0.25 – 1 (0.5 – 1)	0 – 1 (0.5 – 0.75)	0 – 0.75 (0.25 – 0.5)
Ankerite	0.75 – 1.5 (1 – 1.25)	0.25 – 1 (0.5 – 0.75)	0 – 1 (0.25 – 5)	0 – 1 (0 – 0.25)
Amphibole	1 – 1.75 (1.25 – 1.5)	0.25 – 1.25 (0.5 – 1)	0 – 1.25 (0.25 – 5)	0 – 1 (0.25 – 0.5)

Frequency distribution end-members for each phase/element are provided first; numbers enclosed in brackets are the modal peak on the frequency histogram.

In summary, chlorite and sericite in Vogue show relatively similar non-linear dynamics. Both phases display the greatest variations in singularity spectrum range. Many of their occurrences are the most strongly hierarchical structures in the ore body, with spectrum ranges ≥ 2.5. They also display the strongest asymmetry of all phases (both almost exclusively left handed) and have the highest $D(+\infty)$, $D1(\alpha)$ and $D2(\alpha)$ values. Au has the lowest $D(+\infty)$, $D1(\alpha)$ and $D2(\alpha)$ values, relatively low variation in spectrum range (peaking between 2 – 3) and relatively weak asymmetry (both left and right handed). Calcite and ankerite in Vogue display spectrum range modal peaks (~1.5 – 2.25), spectrum range end-members (~1 – 3), and spectrum asymmetry (a dominance of weak to moderately left handed). Calcite has higher modes in $D(+\infty)$, $D1(\alpha)$ and $D2(\alpha)$ values than ankerite. Amphibole has intermediate $D(+\infty)$, $D1(\alpha)$ and $D2(\alpha)$ values, the lowest mode in spectrum range and both weak left and right handed asymmetry.

Cosmo East

Chlorite in Cosmo East has the narrowest singularity spectrum ranges of all phases (Figure 11.14) with a strong peak in the range 1 – 1.25. Fewer occurrences have ranges between 1.5 - 3. Sericite also shows a strong peak in the range 1 – 1.25; however it is more strongly multi-modal than chlorite with a greater proportion of spectrum ranges between > 1.5. Au singularity spectrum ranges peak between 2.5 - 2.75, with end-members extending from ~1 – 4. Ankerite has a relatively narrow spectrum range profile between ~1.5 – 3, with two sub-peaks at 1.75 – 2 and 2.5 – 2.75. Calcite shows a broad peak between 1 – 2.75 (strongest in the range 2 – 2.5) and a narrower one between 3 – 3.25.

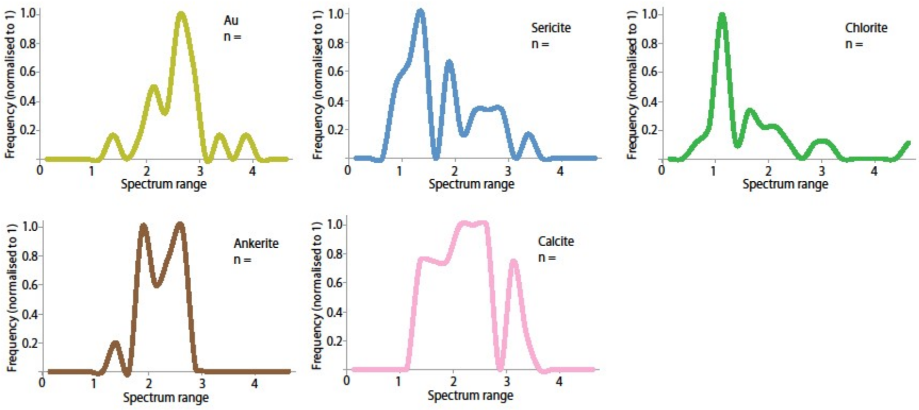


Figure 11.14. Frequency-normalized histograms of singularity spectrum range for Au and all mineral phases in Cosmo East. Chlorite has the narrowest singularity spectra of any phase. Sericite also has a lot of narrow spectra. Au has one of the highest modal peaks. Calcite and ankerite have dominantly intermediate spectrum widths. Bin width = 0.25.

Chlorite and sericite display the narrowest left limb ranges of all phases (Figure 11.15) peaking in the range 0.25 – 0.5. Au has the broadest left limb ranges, peaking between 1 – 1.5. Calcite and ankerite have intermediate left limb ranges, peaking between 0.5 – 0.75 and 0.75 – 1.25, respectively. Right limb widths in chlorite and sericite are generally the narrowest of all phases (Figure 11.16) peaking between 0.5 – 0.75 and 0.75 – 1, respectively. Sericite has an additional (lower strength) peak between 1.5 – 2. Right hand limbs in Au range between 0 – 1.75, peaking between 1 – 1.25. Ankerite right hand limbs range between 0.5 – 1.75, with two peaks at 0.75 – 1 and 1.25 – 1.5. Calcite right hand limbs range from 0.5 – 2.25, with the strongest peak between 1 – 1.5 and a second between 2 – 2.25.

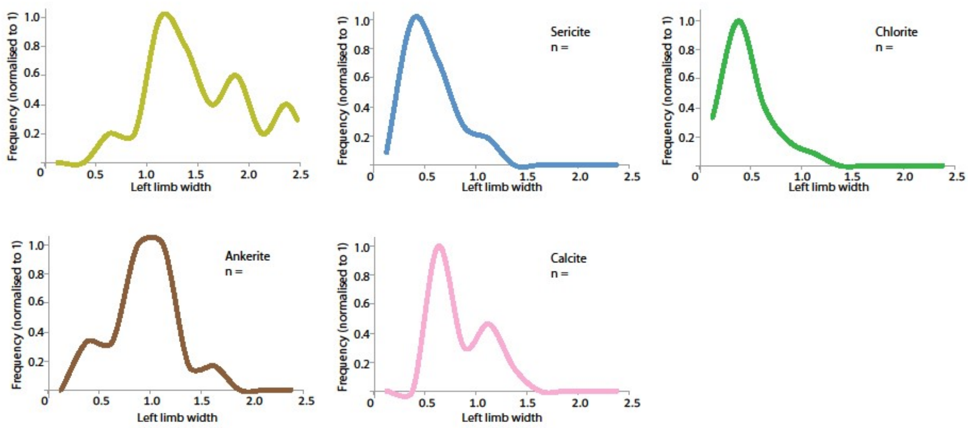


Figure 11.15. Frequency-normalized histograms of left limb range for Au and all mineral phases in Cosmo East. Sericite and chlorite have the narrowest left hand limbs; Au has the greatest proportion of broad left hand limbs. Calcite and ankerite have intermediate left limb widths, with ankerite slightly broader. Bin width = 0.25.

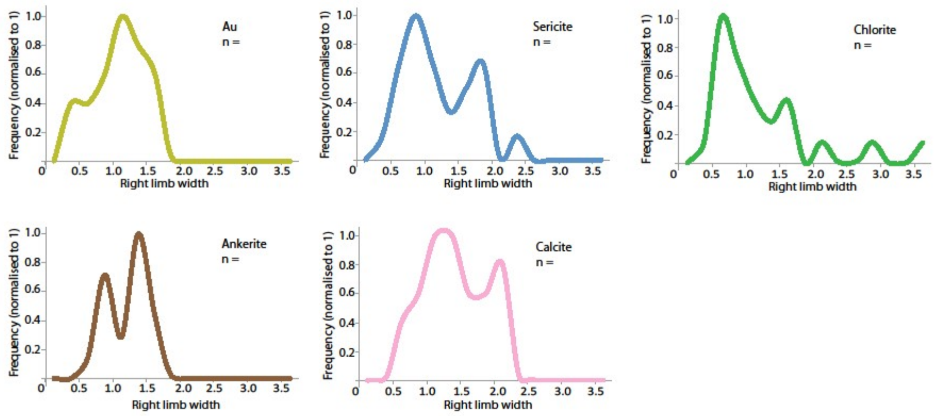


Figure 11.16. Frequency-normalized histograms of right limb ranges in Au and all mineral phases in Cosmo East. Sericite and chlorite typically have the narrowest right hand limbs. Au, calcite and ankerite have strong right hand limb peaks between 1 – 1.5. Bin width = 0.25.

Au singularity spectra display multi-modal asymmetry (Figure 11.17) extending from strongly left handed (4.5) to moderately right handed (-2.75). The majority (73%) are weakly to strongly left handed. Chlorite displays exclusively left handed asymmetry from weak (-1.36) to strong (-4.55). The greatest proportion of chlorite spectra are weak to moderate (≥ -3), peaking at ~2, however it also has a stronger asymmetry peak between -4 to -3.75. With one exception, sericite has exclusively left handed asymmetry – extending from weak (-1.29) to strong (-4). It has a strong narrow modal peak of relatively weak asymmetry at -2 to -1.75, similar to that in chlorite. The rest of the spectra are more evenly distributed between moderate (-2) to strong (-4) asymmetries. Ankerite shows both left and right hand asymmetry, with the strongest modal peak across the symmetry marker at -1,1. It also has two lower strength modal peaks at -2 to -1.75 and -3 to -2.75. With one exception, calcite also has exclusively left handed asymmetry, dominated by a strong modal peak of weak asymmetry at -1.75 to -1.25. Calcite shows similar, but slightly stronger, left handed asymmetry than ankerite.

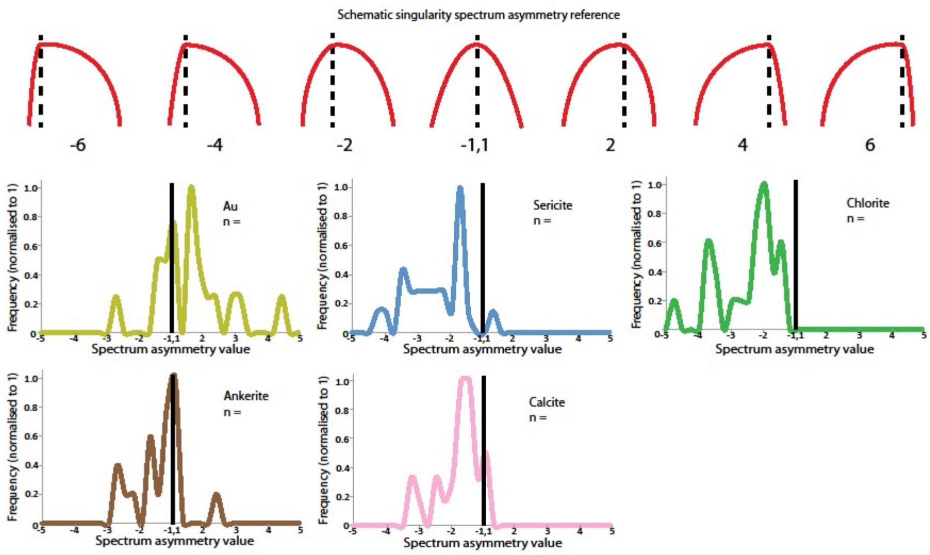


Figure 11.17. Frequency-normalized histograms of spectrum asymmetry values in Au and all mineral phases in Cosmo East. Reference figure above shows schematic examples of

different asymmetry values. Au shows both left and right handed asymmetry. Sericite, chlorite, calcite and ankerite all have almost exclusively left handed asymmetry. Chlorite and sericite have greater proportions of spectra with stronger asymmetry than calcite and ankerite. Bin width = 0.25.

D0(α), D1(α), D2(α) and D(+∞) positions for each phase/element are provided in Table 3:

Table 3

	D0(α)	D1(α)	D2(α)	D(+∞)
Au	1.25 – 2.25 (1.25 – 1.5)	Bi-modal (0 – 0.25; 0.75 – 1)	0 – 1 (0 – 0.25)	0 – 1 (0 – 0.25)
Sericite	1 – 1.75 (1.25 – 1.5)	0.75 – 1.5 (1 – 1.25)	0.75 – 1.5 (0.75 – 1)	0.25 – 1.25 (0.75 – 1)
Chlorite	0.75 – 1.75 (1 – 1.25)	0.75 – 1.25 (0.75 – 1)	0.75 – 1.25 (0.75 – 1)	0.5 – 1 (0.5 – 1)
Calcite	0.75 – 1.5 (1.25 – 1.5)	0.5 – 1 (0.5 – 0.75)	0 – 1 (0.25 – 0.5)	0 – 0.75 (0.25 – 0.5)
Ankerite	1 – 1.75 (1.25 – 1.5)	0.25 – 1.25 (0.5 – 0.75)	0 – 1 (0.25 – 0.75)	0 – 1 (0 – 0.25)

Frequency distribution end-members for each phase/element are provided first; numbers enclosed in brackets are the modal peak on the frequency histogram.

In summary, chlorite and sericite in Cosmo East show similar behaviour in many singularity spectrum metrics. Both show the lowest modal peak in spectrum range of all phases (1 – 1.25), have the most extreme asymmetries (both almost exclusively left handed), and the highest D(+∞), D1(α) and D2(α) values. Calcite and ankerite show relatively similar behaviour in spectrum asymmetry (a dominance of symmetry to weakly left handed asymmetry), D1(α), D2(α) and a dominant modal peak in spectrum range between 2 – 2.5. However, ankerite has a greater proportion of lower D(+∞) values than calcite and a narrower variation in spectrum range. Au has a narrow modal peak in spectrum range at 2.5 – 2.75, has the greatest proportion of left hand asymmetry, the lowest D(+∞) and D2(α) values, and a bimodal distribution in D1(α).

Characterization of the non-linear properties of common mineral phases in the Sunrise Dam hydrothermal system

Chlorite

Analysis of Au and five key mineral phases in three texturally distinct ore bodies (GQ, Vogue and Cosmo East) allows a characterization of their non-linear spatial dynamics within a model hydrothermal system. Chlorite in each of the three bodies shares a number of common features:

1) almost exclusively left handed asymmetries (98.5%)

2) some of the most extreme spectrum asymmetries of any phase (matched only by sericite)

3) the highest $D(+\infty)$, $D1(\alpha)$ and $D2(\alpha)$ values of any phase (matched only by sericite)

Chlorite in Vogue displays distinct behaviour in hierarchical organization (singularity spectrum range) to that in GQ and Cosmo East. Chlorite in GQ and Cosmo East is characterized by a dominance of relatively narrow singularity spectra (typically displaying ranges between 1 – 2), with a lower proportion of spectra with ranges > 2. The low modal peak in Cosmo East is narrower (more refined) than that present in GQ, which is more distributed. These narrow chlorite spectrum ranges in GQ and Cosmo East are lower than all other phases, with the exception of sericite. In contrast, chlorite in Vogue shows a strongly multi-modal distribution in singularity spectrum, with two peaks that are the highest of any phase within the ore body. Therefore, whereas chlorite in GQ and Cosmo East is one of the least hierarchically organized phases, in many parts of Vogue it is the strongest. In other words, chlorite is one of the most regularly distributed phases in GQ and Cosmo East, with relatively consistent amplitudes and wavelengths in both high and low concentrations. Conversely, in many parts of Vogue it is the most irregularly and intermittently distributed phase. Left handed asymmetry in chlorite from Sunrise Dam indicates that the processes responsible for the spatial distributions of low concentrations (right limb) were more heterogeneous and noisy than those responsible for the distributions of the low concentrations (left limb).

Importantly, common chlorite features (1), (2) and (3) above are further consistent with its behaviour in Salt Creek and also in 100m-scale data for Cosmo East (both presented in Chapter X). Additionally, the relationship between chlorite and Au in Cosmo East (narrower singularity spectra in the former) is consistent with their relationship in the 100m interval data (Chapter X).

Sericite

Sericite in each of the three bodies shares a number of common singularity spectrum attributes:

1) almost exclusively left handed asymmetries

2) some of the most extreme spectrum asymmetries of any phase (similar to those of chlorite)

3) the highest $D(+\infty)$, $D1(\alpha)$ and $D2(\alpha)$ values of the phases examined (similar to those of chlorite)

Sericite in GQ and Cosmo East show similar hierarchical organization (spectrum ranges) - defined by modal peaks of 0.75 – 1.25 and 1 – 1.25, respectively. In both cases these are the lowest modal peaks of any phase, indicating that sericite is the most regularly distributed phase in each ore body – with all concentrations showing relatively uniform spatial behaviour. Geological factors that produce stronger hierarchical organization (greater spectrum ranges) in sericite in a number of GQ and Cosmo East drill cores are discussed in following sections. Sericite in Vogue has one of the most strongly hierarchical organizations of any phase, showing dominantly broad singularity spectrum ranges similar to those of Au. Sericite therefore shows the lowest degree of hierarchical organization in Cosmo East and GQ, but some of the strongest hierarchical organization of any phase in Vogue. This contrast suggests that sericitic alteration cells in GQ and Cosmo East are more regular in intensity and spacing, but those in Vogue are more heterogeneous and patchy. Left handed asymmetry in sericite at Sunrise Dam indicates that the processes responsible for the distributions of the common high abundances (left limb) were more uniform than those responsible for the rarer low abundances (right limb).

Importantly, common sericite features (1), (2) and (3) are consistent with its behaviour in 100m-scale hyperspectral data for Cosmo East. Additionally, the relationship between sericite and Au in Cosmo East (broader singularity spectra in the latter) is consistent with their relationship in the 100m interval data.

Au

Au in all three ore bodies shows very similar behaviour in a number of singularity spectrum properties:

1) the lowest D1(α), D2(α) and D(+∞) values of any phase/element
2) highly similar spectrum ranges in each ore body (~2 – 3)
3) generally broader singularity spectra than mineral phases present (with the exception of sericite and chlorite in Vogue)
4) both left and right hand asymmetry (weak to moderate)

Examined as entire drill cores at 0.5-metre resolution, Au in the GQ, Cosmo East and Vogue ore bodies at Sunrise Dam are not significantly differentiated from one another via their hierarchical spatial organizations. Au spectra ranges in all three ore bodies mostly lie between 2 – 3, with end-members extending from ~1 – 4. Within this, Vogue is strongest between 2 – 2.5; Cosmo East and GQ are strongest between 2.5 – 3. These results are consistent with those acquired when the ore bodies are examined in standard 100m intervals at 1m-resolution (Chapter 10). In the narrower interval study, Vogue displays marginally narrower mean spectra ranges than GQ, and Cosmo East is distinguished as the most strongly hierarchical.

Calcite and ankerite

Calcite and ankerite in all three ore bodies show very similar behaviour in a number of singularity spectrum properties:

1) intermediate singularity spectrum ranges, typically between 1 – 3.
2) intermediate $D1(\alpha)$ and $D2(\alpha)$ values
3) almost exclusively left hand asymmetry (weak to moderate)

Calcite and ankerite in GQ and Cosmo East show stronger multifractal signatures (i.e. are more irregularly and intermittently distributed) than those associated with metasomatic alteration of the host rock (sericite) or regional ‘background’ greenschist-facies retrograde metamorphism of the system (chlorite). Conversely, calcite and ankerite in Vogue commonly display narrower multifractal signatures (i.e. are more regularly distributed) than sericite and chlorite. Carbonates throughout Sunrise Dam show relatively irregular and intermittent distributions, but are less irregularly distributed than Au.

Geological controls upon the non-linear dynamics of common mineral phases in hydrothermal systems

The hierarchical organization of a multifractal is sensitive to the range of *relative* concentrations in the signal, the relative amplitudes of fluctuations and the wavelengths over which these concentrations correlate. In geological systems, a number of factors control the distributions of mineralization and associated alteration (and hence their multifractal signatures) including:

1) scales of strain partitioning
2) deformation style (veining, brecciation, shear zone development)
3) pressure and temperature (P-T) conditions
4) fluid composition and pH
5) scales of fluid-rock interaction
6) spatial distribution of primary lithologies

Non-linear dynamics of mineral phases classified by dominant host rock lithology

Drill holes in GQ and Vogue were classified according to dominant host lithology to evaluate lithological control upon singularity spectra behaviour. Dominant host lithologies in GQ drill cores are andesite, polymictic conglomerate/breccia and volcaniclastic sandstone. Vogue drill cores are almost exclusively andesite-dominated (between 34.6 – 88%) with few exceptions. Vogue drill cores were sub-divided into two approximately equal proportions: those where andesite < 65% and those where andesite ≥ 65%. The 25 drill cores analysed from Cosmo East sub-divide into too many dominant lithologies to allow statistically valid comparison between them. The following section presents the non-linear dynamics of mineral phases in Vogue and GQ categorized by dominant host rock lithology. Au dynamics in these ore bodies were categorized by dominant host lithology in Chapter 10.

Sericite shows similar singularity spectrum ranges in andesite and conglomerate/breccia-dominated sections of GQ, and marginally broader spectra in volcaniclastic sandstone-dominated sections (figure 11.18). Sericite in sections of Vogue composed of lower and higher proportions of andesite both display high proportions of broad singularity spectra (figure 11.19). However, sericite from drill cores in Vogue composed of ≥ 65% andesite show a greater proportion of narrow spectra. Chlorite in andesite and conglomerate/breccia-dominated sections of GQ shows broad distributions in spectrum range, primarily between 0.5 – ~3 (figure 11.18). Of the two, andesite-dominated sections are more evenly distributed across this range. Andesite-dominated sections of GQ have a greater proportion of spectra > 3 than conglomerate/breccia-dominated. In contrast, chlorite in volcaniclastic sandstone-dominated sections of GQ shows a dominance of narrow singularity spectra. Chlorite in sections of Vogue dominated by lower and higher proportions of andesite both share two strong peaks at intermediate widths of ~2 and ~3 (figure 11.19). However, sections with < 65% andesite display a much greater proportion of broad spectra (≥ 3.5); those with ≥ 65% andesite display a much greater proportion of narrow spectra (≤ 1.5).

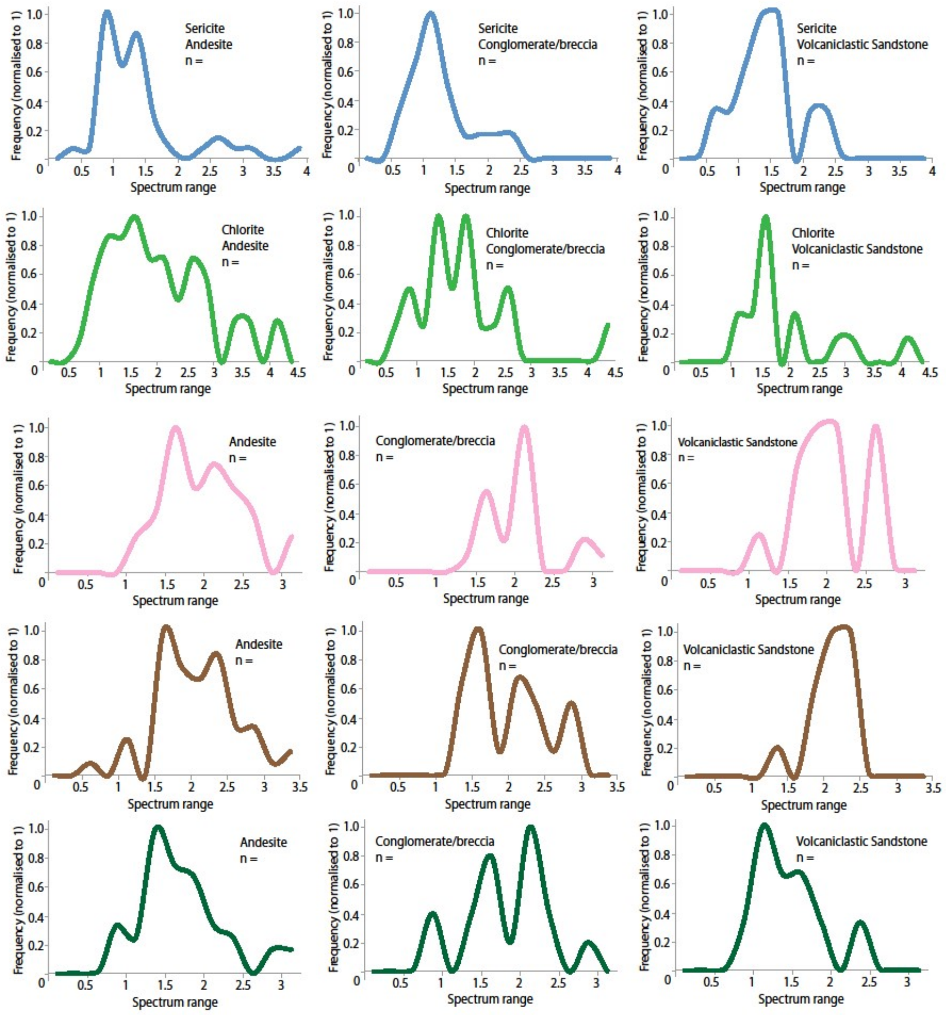


Figure 11.18. Singularity spectra widths for each phase in GQ classified by the dominant host rock lithology over the drill core interval.

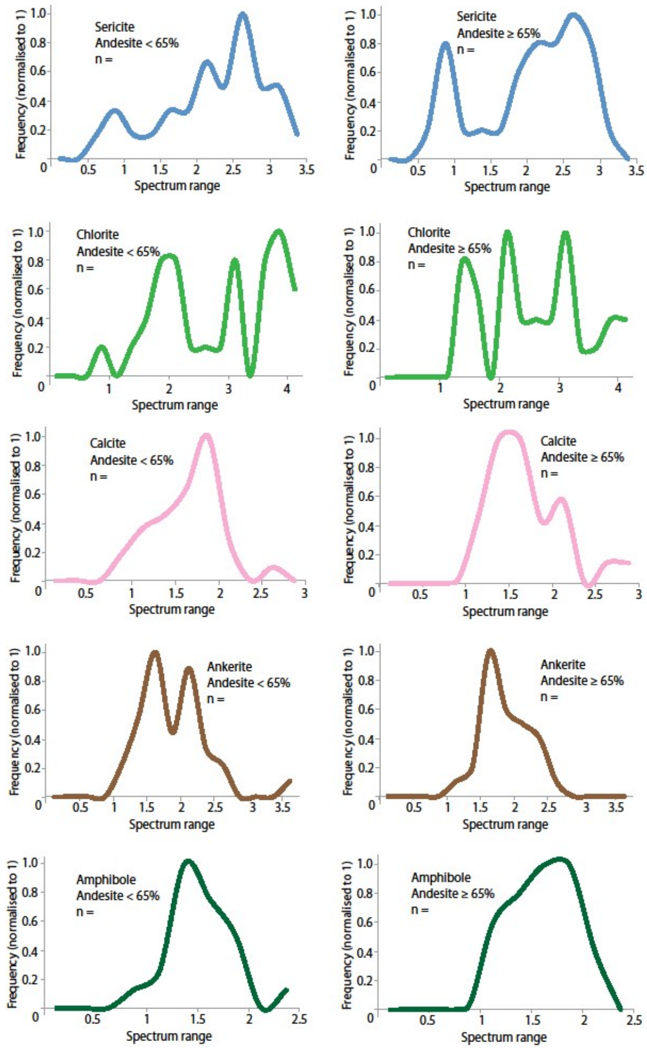


Figure 11.19. Singularity spectra widths for each phase in Vogue classified by the dominant host rock lithology over the drill core interval.

Calcite in andesite and volcaniclastic sandstone-dominated sections of GQ show strong variability in singularity spectrum width, between ~1 - 2.75 (figure 11.18). Volcaniclastic sandstone-dominated calcite shows stronger multi-modality than andesite-dominated. Calcite singularity spectra in conglomerate/breccia-dominated sections are more consistent (~1.25 – 2.25). Calcite singularity spectra in Vogue sections with < 65% andesite are marginally broader than in sections with ≥ 65% andesite (figure 11.19). Ankerite in andesite and conglomerate/breccia-dominated sections of GQ (figure 11.18) shows strong variability in singularity spectrum width (between ~1.5 – 3.5 and ~1 - 3, respectively). Conglomerate/breccia-dominant sections are more strongly multi-modal than the andesite-dominated. Ankerite singularity spectra in volcaniclastic sandstone-dominated sections of GQ are highly consistent, between ~1.5 – 2.5. Ankerite in Vogue sections with < 65% andesite and those with ≥ 65% andesite both show strong peaks at spectrum widths of ~1.5 (figure 11.19). However, sections with < 65% andesite show a greater proportion of broader spectra (an additional peak at 2 - 2.25.

Amphibole singularity spectra in andesite and volcaniclastic sandstone-dominated sections in GQ show relatively similar distributions with strong peaks between 1 – 1.5 (figure 11.18). Amphibole in conglomerate/breccia-hosted sections of GQ is strongly multi-modal, with three peaks at ~0.75, ~1.5 and ~2.25 of increasing strength. Conglomerate/breccia-hosted amphibole in GQ is therefore more strongly multifractal than andesite and volcaniclastic sandstone-dominated. Amphibole singularity spectra in Vogue sections with < 65% andesite are generally narrower than those in sections with ≥ 65% andesite (figure 11.19).

Chlorite spectra in volcaniclastic sandstone-dominated sections in GQ are much narrower than in those dominated by other lithologies. Narrow chlorite spectra end-members in Vogue (i.e. those in which chlorite is more regularly distributed) are more dominant in sections with ≥ 65% andesite; broad chlorite spectra end-members are more dominant in those with < 65% andesite. Chlorite in Sunrise Dam is primarily associated with regional greenschist-facies metamorphism. Therefore, different host lithologies may have dramatically different chlorite concentrations. Narrow spectra in drill cores with greater proportions of andesite may therefore reflect less down-hole variability in host lithology. A similar effect may explain a greater proportion of narrow sericite spectra in sections with ≥ 65% andesite.

Chlorite is more regularly distributed (has narrower singularity spectra) in volcaniclastic sandstone-dominated sections of GQ than in other host lithologies. On the other hand, sericite in GQ shows no appreciable variations in spatial dynamics between the three host lithologies. Sericite in Vogue displays similar, strong irregularity and intermittency in most of the sections composed of low and high proportions of andesite. However, sericite is more regularly distributed in a greater proportion of drill cores characterized by ≥ 65% andesite. Ankerite in volcaniclastic sandstone-dominated sections of GQ is typically more irregular and intermittent than in those dominated by andesite and conglomerate/breccia. Calcite is more intermittent and irregularly distributed in Vogue drill cores with < 65% andesite than in those with ≥ 65% andesite. A degree of variation in the spatial behaviour of certain phases can therefore be correlated with dominant host rock lithology. However, the following section uses key examples of sericite and chlorite to demonstrate that variations in the spatial dynamics of mineral phases is often strongly controlled by specific lithologies that compose *minor* proportions of a drill core interval.

Controls upon the non-linear dynamics of sericite and chlorite

Where sericite and chlorite display narrow singularity spectra the hyperspectral signals are generally relatively continuous and regular, and *self-similarity* can be intuitively recognised over confined ranges of amplitudes and spatial scales. Here, strain partitioning, fluid pathway distributions, fluid availability and scales of fluid-rock reaction have interacted to produce similar variations in the intensity and spatial wavelengths of sericitic metasomatism within the system. Similarly, narrow spectra in chlorite reflect that the spatial distributions of protoliths (host rock compositions), fluid availability and chlorite-forming reactions conspired to produce regular fluctuations and wavelengths in chlorite concentration during regional greenschist-facies metamorphism. A minor proportion of chlorite also occurs in alteration assemblages associated with mineralization. Sericite and chlorite in drill cores defined by narrow singularity spectra commonly show two dominant modal concentration ranges - either very high (on the order of 8000 – 10000 counts) or low (in the order of 0 – 2000) with relatively few intermediate values (e.g. figure 11.20a,b). The high concentration band often dominates and the intervals are characterized by high amplitude fluctuations between the two bands over wavelengths on the order of a few metres.

On the other hand, in sections of the ore bodies where sericite and chlorite are quantified by a broad singularity spectrum range, this is commonly associated with one of two signal features:

1) The presence of at least one strong, relatively sharp, discontinuity in phase concentration (e.g. Figure 11.20c), or
2) The signal is dominated by (atypically) low concentrations of the phase, punctuated by spatially localised zones of moderate or intense concentrations that correlate at greater wavelengths than the background concentrations (e.g. Figure 11.20d)

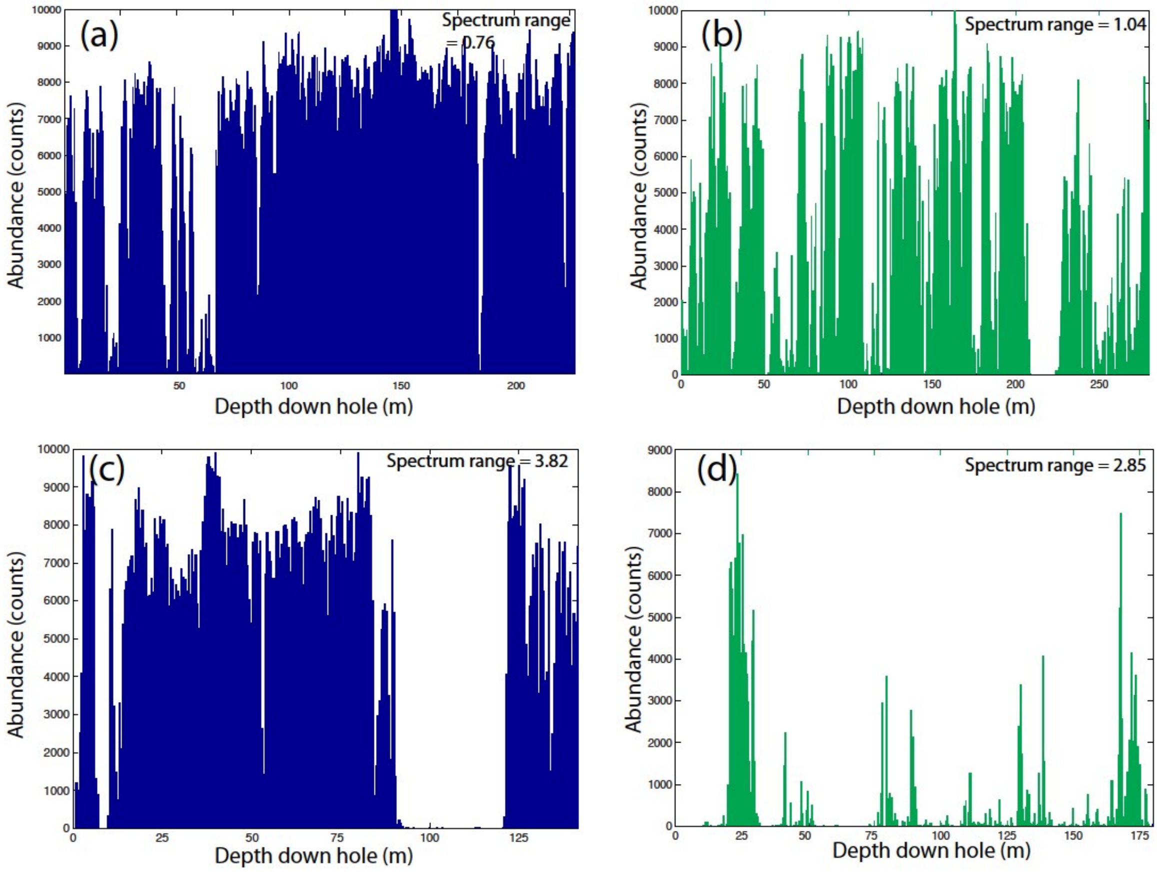


Figure 11.20. Common types of sericite and chlorite concentration signal at Sunrise Dam, determined by hyperspectral analysis. (a) Sericite signal showing a dominance of high concentrations along the drill core (~7000-9000 counts) with high amplitude fluctuations to less abundant low concentrations (~0 – 2000 counts). (b) Chlorite signal with large fluctuations between low and high concentrations over similar wavelengths of up to ~20m. Proportions of high and low concentrations are approximately equal. (c) Sericite signal with similar behaviour to (a), but with a strong sharp ~25m-wide discontinuity. Note that sericite concentrations across the discontinuity (here, basalt) are extremely low (0 – 30 counts). The detail of sericite concentration across the basalt unit is shown in Figure 11.21b. (d) Chlorite signal characterized by atypically low background concentrations of up to ~10000 counts, punctuated by narrow

zones of high abundances similar to the background levels in (a), (b), and (c). Variations of signal types (a) and (b) are associated with narrow singularity spectra in sericite and chlorite. The singularity spectrum width for each hole is noted next to the signal. Signal features such as those in (c) and (d) are commonly associated with broad singularity spectra. All four signal types are applicable to both phases.

Both of these types of feature increase the number of concentration 'tiers' - enhancing the signal's hierarchical organization. Strong discontinuities in sericite and chlorite concentration in GQ and Cosmo East are most commonly associated with a dramatic decrease in concentration relative to the rest of the signal. Importantly, sericite and chlorite concentrations in the discontinuities are severely reduced, not entirely eliminated. The significance of this is illustrated later on.

In a number of GQ drill cores (e.g. Figure 11.20c) low sericite concentration discontinuities correspond to basalt host rocks. In others it corresponds to volcaniclastic sandstone. Strong concentrations of calcite and ankerite in many of these basalt intervals record fluid pathway generation and fluid availability. This indicates that the basalt exerted a lithological (chemical) control upon sericite-forming reactions, not a rheological control resulting in a lack of fracturing and brecciation (fluid pathway development). Strong sericite concentration discontinuities in other drill cores do not correspond with lithological boundaries. Instead, they may reflect differential fluid pathway generation and scales of fluid-rock interaction.

Deconstruction of the sericite discontinuity example in Figure 11.20c into component intervals for independent analysis (Figure 11.21) demonstrates how each component contributes to the singularity spectrum. Figure 11.21b shows the detail of the sericite signal across the 30 metre-wide basalt interval (90-120 m), where concentrations are ≤ 25 counts. Reducing all concentrations in the basalt interval to 0 and reanalyzing the entire drill core (0-140 m) reduces

Comment [A6]: On figure 11.21c, for the pale blue title, I'd put Entire interval with basalt unit devoid of sericite. I find this a confusing figure so am adding details to help me read and understand it.

the singularity spectrum range from 3.82 to 0.99 (Figure 11.21c). The reduction in spectrum range is almost entirely from the right hand limb, from 2.91 to 0.43. The left limb remains largely intact (0.91 to 0.56) and maintains its position on the spectrum plot. Following removal of the low sericite concentrations in the basalt, a small range of fractal dimensions characterizes the rest of the signal. The spectrum limbs are now close together because the high and low probability grades in the remaining signal now scale similarly over a restricted range of amplitudes and wavelengths. The basalt discontinuity therefore strongly influences the multifractal signature of the drill core. The low concentrations removed from the basalt interval represent the less frequent (low-probability) concentrations in the signal. This example demonstrates that the right limb of the spectrum describes the low end-member concentrations in sericite. Here, the left limb describes the (high-probability) high concentrations. This contrasts with typical Au assay signals, in which the rare high Au grades are the lowest probability and occupy the right limb of the spectrum. These high and low probability classifications apply to most of the sericite and chlorite signals in Sunrise Dam, unless they are similar to that in Figure 11.20d. Here, the probabilities shown by high and low concentrations of sericite/chlorite are inverted relative to Au because low concentrations dominate.

Comment [A7]: 1.56?

Comment [A8]: not high?

Comment [A9]: What would happen to the spectrum of the entire interval if instead of the sericite signal being low within the basalt section it was high? & if you then removed that signal? Would this not provide similar signals to Au? e.g. make the maximum abundance for sericite within the basalt section 60000 rather than 10000 (or whatever you think would work).

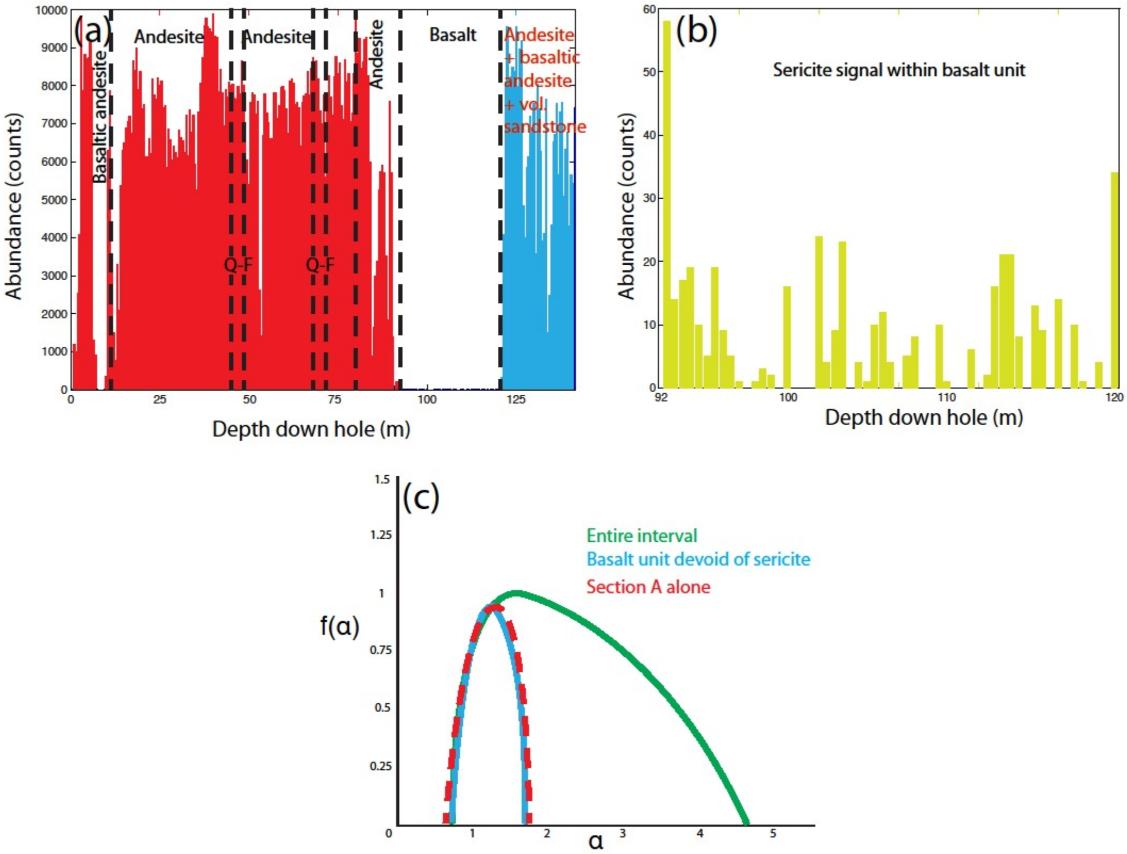


Figure 11.21. Modification of the sericite signal in Figure 11.18c to demonstrate the effects of lithological and structural discontinuities upon the singularity spectrum. (a) Sericite signal from Figure 11.18c with lithological boundaries marked. Q-F = Quartz-Feldspar porphyry. The basalt unit corresponds with substantially lower sericite concentrations, the detail of which is shown in (b). Importantly, the sericite concentration in the basalt is dramatically lower, not absent. The portion of the signal to the left of the basalt unit (red) is “section A”; the portion to the right of the basalt (blue) is “section B”. The entire original drill core interval shows a broad singularity spectrum (c). All low sericite concentrations across the basalt unit were reduced to “0” and the signal re-analysed (maintaining the rest of the signal). When the basalt is devoid of sericite, the singularity spectrum for the drill core narrows dramatically, demonstrating the strong control of lithological discontinuities upon sericite singularity spectra. This reduction in span is almost entirely from the right hand limb. When analysed independently (maintaining signal length) “section A” shows an almost identical singularity spectrum to that when the basalt is devoid of sericite. Therefore, discontinuities

with reduced concentrations of a phase will increase spectrum width; those entirely devoid of a phase may not influence the spectrum.

Analysed independently, sections A and B in Figure 11.21 each produce singularity spectra identical to that when the two form a composite signal separated by the 30-metre discontinuity devoid of sericite. Importantly, this illustrates that when two multi-fractals described by the same range of fractal dimensions are amalgamated the resultant singularity spectrum may remain the same. Geologically, this signifies that structural or lithological discontinuities in which a phase is entirely absent may exert no impact upon the singularity spectrum.

Low chlorite concentration discontinuities in a number of drill cores from GQ correspond with Quartz-Feldspar porphyries. Figure 11.22 demonstrates the influence of one of these quartz-feldspar porphyry intrusions upon the multifractal signature of chlorite across the drill core. The initial chlorite signal in the entire drill core interval is characterized by a broad singularity spectrum width of 4.15. Removal of low chlorite concentrations across the quartz-feldspar porphyry in Figure 11.22a results in a dramatic narrowing of the singularity spectrum width to 1.04. The reduction in singularity spectrum is almost entirely from the right limb (low probability low values) in a similar manner to the sericite example in Figure 11.21. Intrusion of the Quartz-feldspar porphyry has imposed a strong control upon the spatial distribution of chlorite-forming reactions during retrograde metamorphism under greenschist-facies conditions, increasing the *intermittency* and irregularity of the signal. Protolith distribution in Sunrise Dam is therefore a first-order control upon chlorite multifractality (and also sericite). When sections 'A' (green) and 'B' (blue) to either side of the quartz-feldspar porphyry are analysed independently (maintaining drill hole length) they also display narrow spectrum ranges (0.73 and 1.74, respectively). A low range of fractal dimensions therefore characterizes the scaling dynamics of each individual section. However, the singularity spectrum that describes section

Comment [A10]: you mean - green only - 0 to 210 m; and blue only - 0 to 210 m; ?

'B' alone is almost twice the breadth of both 'A' and 'B'' combined when sericite concentrations are removed from the basalt. Importantly, scales of correlation across barren discontinuities may therefore be described by fewer fractal dimensions than that of the sections to either side independently.

Comment [A11]: that's good.

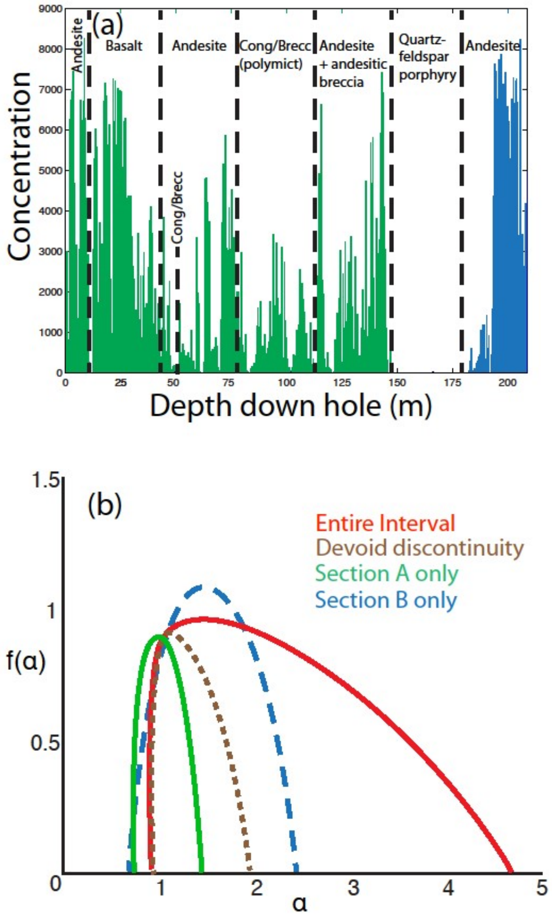


Figure 11.22. Analysis of different components of a chlorite concentration signal to demonstrate the effects of discontinuities upon the singularity spectrum. (a) Chlorite signal with lithological boundaries marked. Chlorite concentrations within the quartz-feldspar porphyry unit are sparse and dramatically lower than the surrounding signal (≤ 22 counts). The portion of the signal to the left of the quartz-feldspar porphyry (green) is "section A"; the

portion to the right of the quartz-feldspar porphyry (blue) is "section B". The entire original drill core interval shows a broad singularity spectrum (b). All low chlorite concentrations across the quartz-feldspar porphyry unit were reduced to "0" and the signal re-analysed (maintaining the rest of the signal). The left limb position of the spectrum is constant. When the quartz-feldspar porphyry is devoid of chlorite, the singularity spectrum for the drill core narrows dramatically. This demonstrates that the low concentration quartz-feldspar discontinuity strongly controls the singularity spectrum. Independently, "section A" shows a narrow spectrum; "section B" a spectrum of moderate width. Importantly, discontinuities defined by an absence of a phase may produce narrower singularity spectra than those of the intervals to either side.

Controls upon the non-linear dynamics of carbonate-forming processes (calcite and ankerite)

Carbonates at Sunrise Dam have been interpreted to be entirely secondary – associated with vein and breccia infill, and wall rock alteration. Their hyperspectral spatial distributions therefore present an uncontaminated record of carbonate-forming processes associated with alteration in the system. Calcite and ankerite in GQ and Cosmo East have stronger hierarchical spatial organization than sericite and chlorite, correlating over a large range of wavelengths and amplitudes. Conversely, calcite and ankerite in Vogue are more regular than sericite and chlorite, correlating over a more restricted range of wavelengths and amplitudes.

Calcite and ankerite signatures are most commonly composed of low background concentrations that have low wavelength, high frequency, correlations, punctuated locally by medium to high concentrations that correlate over greater wavelengths. Calcite and ankerite signals therefore share a number of similar characteristics with typical Au assay signals. Lower concentrations in calcite and ankerite are the most abundant (i.e. are higher probability) and are therefore quantified by the left limb of the singularity spectrum. Conversely, the relatively rare medium to high concentrations are lower probability, quantified by the right limb of the spectrum. Low background concentrations in carbonate phases will correspond either with low volumes of veining, veining dominated by a greater proportion of quartz than carbonate, or minor carbonate involved in host rock alteration. Broader singularity spectra in ankerite and calcite generally correspond to signals with greater contrasts between the common ‘background’ concentrations and the less frequent medium to high concentrations (higher amplitude fluctuations). Strong contrasts in carbonate concentration in hydrothermal systems such as Sunrise Dam are associated with locally high volumes of veining or intense brecciation (e.g. Figure 11.23a,b). These localised zones of high concentration infill influence the singularity spectrum (Figure 11.23 c,d) in the same manner as the high-grade Au nuggets that were examined in Chapter 10.

Comment [A12]: I have not yet found any reference to 11.23 c and d.

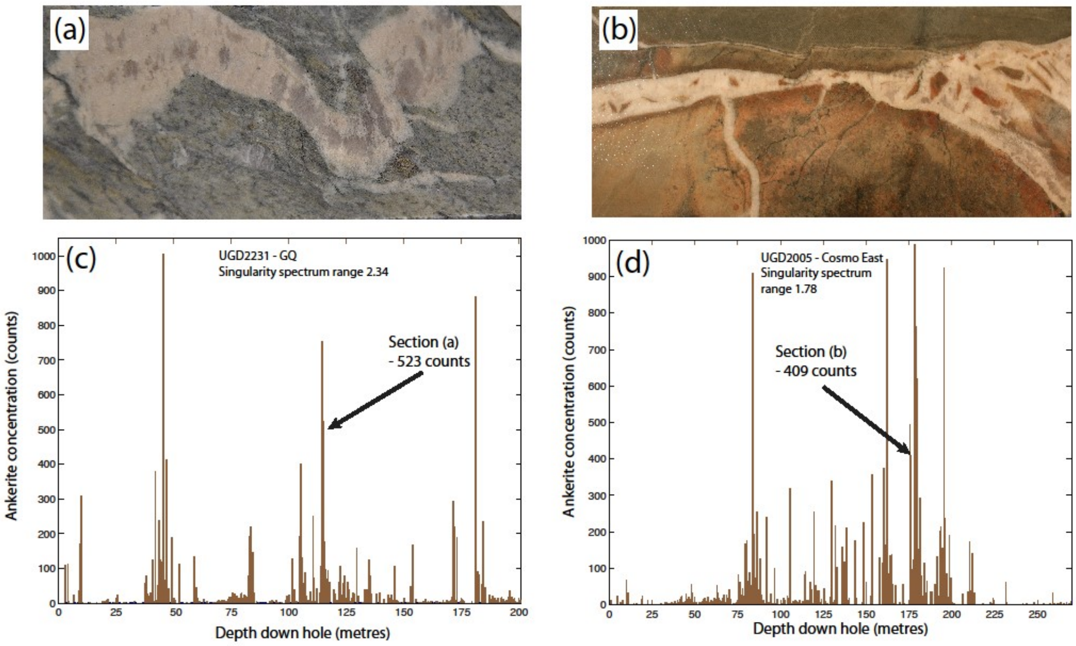


Figure 11.23. (a,b) Examples of carbonate vein and breccia cement infill textures associated with strongly elevated concentrations of ankerite well above background levels. (a) folded ankerite-quartz veining in extensively sericite-altered andesite from GQ. (b) brecciation

in sericite-altered siltstone from Cosmo East in-filled with ankerite+quartz cement. (c) down hole ankerite concentration in drill hole UGD2231 from GQ with the position of sample (a) indicated. (d) down hole ankerite concentration in drill hole UGD2005 from Cosmo East showing the position of sample (b) indicated. The singularity spectrum range for each drill core is presented on the down-hole ankerite concentration plots. Ankerite in UGD2231 has one of the strongest hierarchical organizations in GQ. Carbonate infill textures shown are ankerite+quartz, but are also commonly observed in calcite.

Conversely, narrow singularity spectra in calcite and ankerite generally correspond to lower amplitude fluctuations between the low and high concentrations present (i.e. the phase is more regularly distributed throughout the drill hole). More regular amplitudes of fluctuation generally correspond either to drill holes with atypically high background concentrations across the board (e.g. where medium carbonate-concentration veining is pervasive throughout) or where rare high concentrations (intense veining and/or brecciation) are not developed.

Comparisons of the non-linear dynamics of different phases within individual drill holes

Figures 11.24 and 11.25 display the singularity spectrum range for each mineral phase against those of other phases over the same drill core intervals. Au singularity spectrum ranges in GQ show no correlation with those of chlorite, sericite or calcite (Figure 11.24). However, Au singularity spectrum ranges in GQ do show a positive correlation with ankerite. Vein-forming phases in GQ (calcite and ankerite) show no correlation in singularity spectrum range. Sericite and chlorite in GQ also show no correlation in singularity spectrum range. Calcite and ankerite (vein-forming) show weak positive correlations with host-rock alteration (sericite) in most of the drill holes.

Comment [A13]: Insert, and refer to, a, b, c, d, e, f, g, and h.

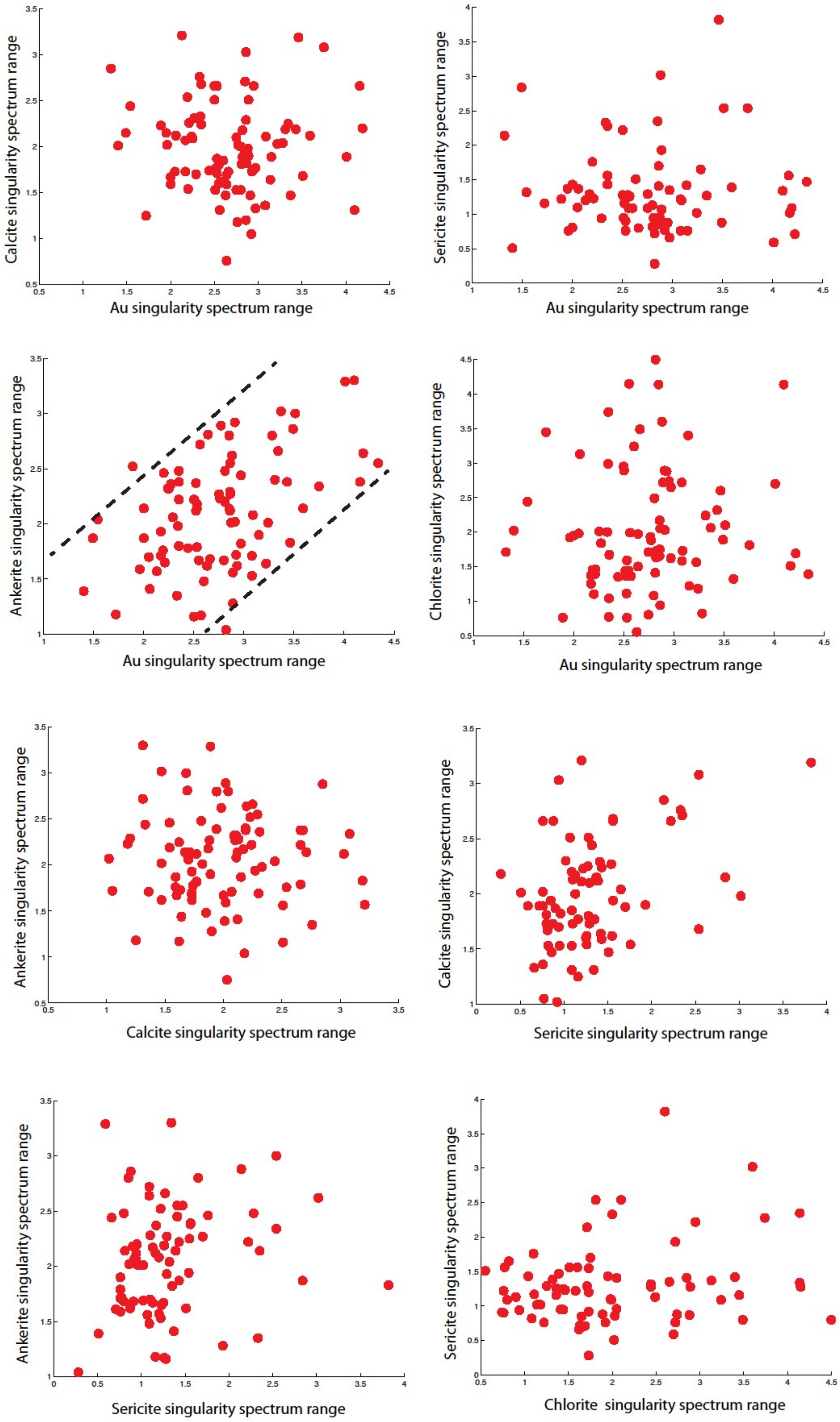

Calcite singularity spectrum range
Au singularity spectrum range
Sericite singularity spectrum range
Au singularity spectrum range
Ankerite singularity spectrum range
Au singularity spectrum range
Chlorite singularity spectrum range
Au singularity spectrum range
Ankerite singularity spectrum range
Calcite singularity spectrum range
Calcite singularity spectrum range
Sericite singularity spectrum range
Ankerite singularity spectrum range
Sericite singularity spectrum range
Sericite singularity spectrum range
Chlorite singularity spectrum range

Figure 11.24. Scatter plots comparing the widths of singularity spectra between different phases over the same drill core intervals in the GQ ore body. Au shows a lack of correlation with calcite, sericite and chlorite. However, it shows a 'corridor' of positive correlation in spectrum width with ankerite (marked) indicating that the multiplicative processes responsible for their spatial distributions are linked. The correlation between Au and ankerite in GQ is stronger than that between them in Vogue (Figure 11.25). The vein and breccia cement-forming carbonates (calcite and ankerite) show a lack of correlation.

Au singularity spectrum range in Vogue shows no correlation with chlorite, amphibole, ankerite and sericite (Figure 11.25). Au singularity spectrum range does however show a moderate positive correlation with calcite. Sericite (host rock alteration) in Vogue shows a weak positive correlation with calcite. Ankerite and calcite in Vogue show a positive correlation in singularity spectrum range.

Comment [A14]: Insert, and refer to, a, b, c, d, e, f, g, and h.

The lack of correlation in singularity spectrum width between Au and chlorite in both ore bodies is an important benchmark. This is because petrological interpretations indicate that chlorite at Sunrise Dam is dominantly (almost entirely) the product of regional-scale greenschist-facies metamorphism, not mineralization-associated alteration assemblages. Chlorite abundance commonly increases in rocks more distal to mineralization.

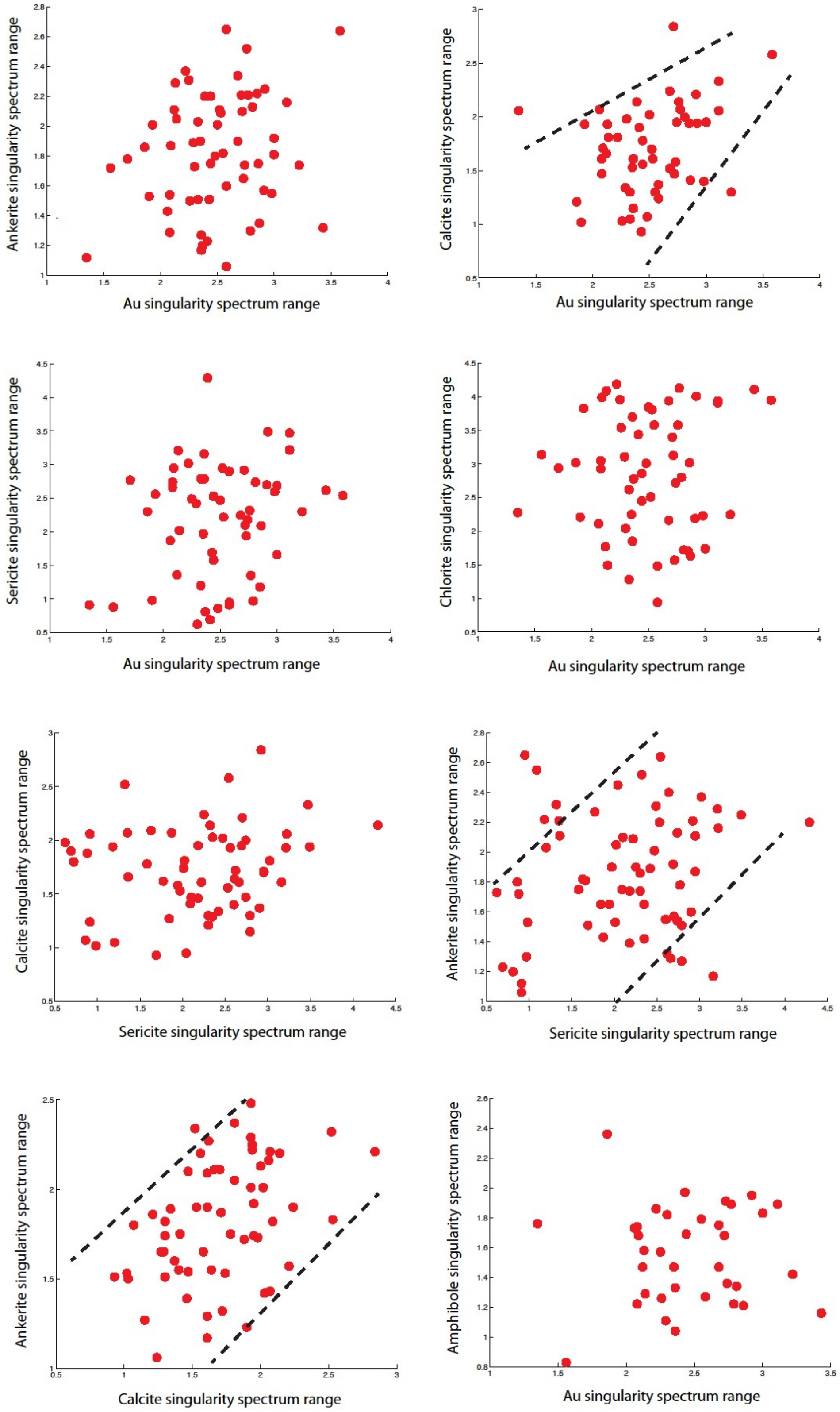

Ankerite singularity spectrum range
Au singularity spectrum range
Calcite singularity spectrum range
Au singularity spectrum range
Sericite singularity spectrum range
Au singularity spectrum range
Chlorite singularity spectrum range
Au singularity spectrum range
Calcite singularity spectrum range
Sericite singularity spectrum range
Ankerite singularity spectrum range
Sericite singularity spectrum range
Ankerite singularity spectrum range
Calcite singularity spectrum range
Amphibole singularity spectrum range
Au singularity spectrum range

Figure 11.25. Scatter plots comparing the widths of singularity spectra between different phases over the same drill core intervals in the Vogue ore body. Au shows a lack of correlation with ankerite, sericite and chlorite. However, the majority of Au versus calcite data show a moderate positive correlation. The relationship between Au and ankerite in Vogue is weaker than that in GQ (Figure 11.24). Calcite and ankerite in Vogue show a 'corridor' of positive correlation in singularity spectrum width. This relationship is stronger than that between them in GQ. Dashed lines indicate 'corridors' of correlation defined by the majority of points in a plot.

Au and ankerite display a strong positive correlation in singularity spectrum range in GQ, but no correlation in Vogue. Therefore, Au precipitation is more strongly linked to ankerite-forming reactions in GQ than in Vogue. This suggests that Au distribution in GQ is more intermittent or 'nuggety' in areas where ankerite precipitation is more irregular and less uniform. The lack of correlation in singularity spectrum ranges between Au and ankerite in Vogue is comparable to that between Au and chlorite. Conversely, Au and calcite singularity spectrum ranges display a moderate correlation in Vogue but a lack of correlation in GQ. Au-precipitation is therefore more strongly linked to the distribution of calcite-forming reactions in Vogue than in GQ. The lack of correlation between Au and calcite in GQ is comparable to that between Au and chlorite over the same intervals (which are functions of largely unrelated processes).

Calcite and ankerite show highly similar singularity spectrum metric distributions to one another in both GQ and Vogue. If interpreted on the strength of histogram distributions alone, the two may be naively considered as genetically associated in both ore bodies. However, the differences in spatial dynamics between the two phases are revealed when their spectrum widths for each individual drill core are compared. This allows distinction of the positive correlation between them in Vogue, and a lack of correlation in GQ. The lack of correlation in GQ is consistent with their relative highs and lows commonly being out of phase along drill cores. Phase comparisons within individual drill cores should therefore be integral in the wavelet-based analysis of ore deposits.

Weak to no correlations exist in singularity spectrum ranges between the vein-forming mineralogy (calcite and ankerite) and surrounding host rock alteration (dominantly sericite) in both GQ and Vogue. Texturally, this is a function of the different scales over which each process manifests locally. As is common in many hydrothermal systems, veining and brecciation at Sunrise Dam are more spatially confined than the host rock alteration selvages associated with them. Drill cores typically have diameters of ~5cm. Therefore, a drill core may intersect a strongly sericitized alteration cell but miss the proximate fluid conduits in which calcite and ankerite may have crystallized. Alternatively, veining may develop in the absence of host rock alteration – generating a local carbonate peak that does not correspond with sericitic alteration. All of the fluid-rock textures outlined above are manifest at Sunrise Dam. In short, the volume and/or abundance of veining (indicated by relative carbonate abundance) is not necessarily proportionate to the spatial extent of local host rock replacement.

The singularity spectrum that quantifies a mineral phase or element is sensitive to 1) its down-hole spatial organization in peaks and troughs, and 2) the *relative* concentration at each down-hole increment. Therefore, if the signals of two mineral phases are identical with respect to *both* of these criteria they will produce identical singularity spectra. However, the relative proportions of two phases produced at a given site is dependent upon the relative volumes of each reaction product, reaction kinetics, and the availability of reactants. This is further compounded where the two product phases are locally produced via different reactions. The relative concentrations of two or more chemically affine phases in a geological system are never absolutely consistent along a drill-core. Consequently, two phases with a strong spatial association may start to diverge in spectrum behaviour if the relative strengths of highs and lows vary between the two (e.g. Figure 11.26). This type of relationship may explain why the positive correlations in spectrum range between Au and ankerite in GQ, and calcite and ankerite in Vogue, form 'corridors' with a degree of freedom (figures 11.24 and 11.25).

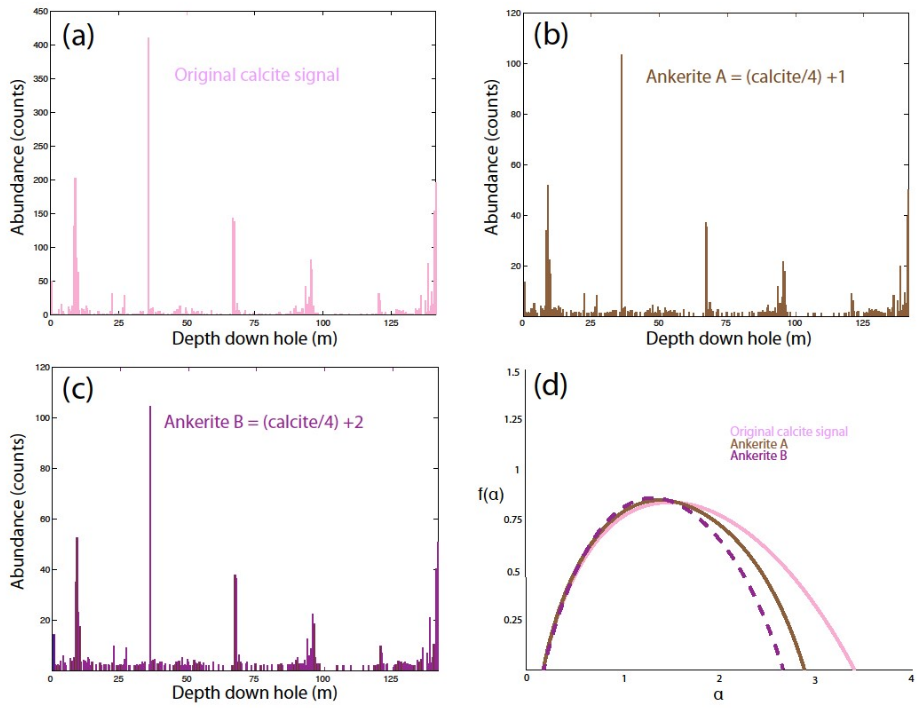


Figure 11.26. Demonstration of how two spatially correlated mineral phases may show different singularity spectra using manipulation of a calcite signal from GQ. (a) original calcite signal. (b) synthetic ankerite signal, where ankerite = (calcite/4) +1. (c) synthetic ankerite signal, where ankerite = (calcite/4) +2. In both cases, increments of calcite absence are maintained. This conserves the wavelengths of down-hole correlation, but modifies the relative strength of the maximum and minimum concentrations. Note that ankerite in signals (b) and (c) have a strong genetic association with calcite, but their relative concentrations are now slightly different. Ankerite now has slightly narrower singularity spectra than the calcite it is genetically associated with. The closer the maximum and minimum concentrations converge in

value, the more the spectrum narrows. These effects may account for the 'corridors' of positive correlation between Au and ankerite in GQ, and calcite and ankerite in Vogue.

Divergence in singularity spectrum behaviour between two genetically associated phases or elements may also indicate that one of the two is associated with processes out-with those responsible for the formation of the other. For example, every occurrence of Au in a drill hole, or ore body, may be hosted in ankerite veining. However, a proportion of ankerite veins in the system may also be devoid of Au - producing different spatial organization in ankerite and Au. Therefore, while Au is genetically associated with ankerite, they may have somewhat different spectra. This may be further complicated when Au mineralization is associated with more than one generation of veining. The first episode of Au mineralization may show a strong association with ankerite-only veins. A second phase of Au mineralization may be associated with calcite-only or quartz-only veins, diluting the initial spatial association with ankerite.

Au precipitation may also be preferentially associated with reactions producing one specific compositional end-member of a phase. However, these correlations may be masked where phase abundances are determined from the sum of all compositional end-members (i.e. the entire spectral range displayed by the phase). Au and associated phases would not be expected to display perfectly linear (1:1) correlations in singularity spectrum metrics because the relative strength of concentration maxima between their signals will always show a degree of variation.

Chapter Summary

Hyperspectral reflectance imaging is a fundamental exploration tool routinely utilised to evaluate spatial distributions in the abundance and composition of mineralogy in a wide range of ore deposits. This research has demonstrated that common vein-hosted mineralogy (calcite and ankerite), host-rock alteration mineralogy (sericite), regional-scale metamorphic assemblages (chlorite and amphibole) and Au in hydrothermal systems organize spatially as multifractals.

The degree to which the multifractal signatures (spectrum range) of two mineral phases or elements in an ore body align with one another may be utilised as a measure of the degree to which the processes responsible for their spatial organization are linked. At Sunrise Dam this is demonstrated by contrasting the relative behaviour of Au to chlorite or amphibole in both GQ and Vogue (dominantly reflective of regional-scale metamorphism and primary protolith mineralogy, respectively) to that between Au and vein-hosted ankerite in Vogue. The former show a random dispersion (lack of correlation) in singularity spectrum range, whereas Au and ankerite in Vogue show a moderate to strong positive correlation. A stronger causal link exists between ankerite abundance and Au in Vogue than in GQ. Vein and breccia cement-forming phases (calcite and ankerite) show a stronger link in dynamics in Vogue than in GQ.

Stronger multifractality (greater spectrum ranges) in sericite and chlorite are commonly a function of the presence of lithological or structural boundaries that produce sharp discontinuities in their concentration. Such discontinuities strengthen the hierarchical structure of the signal by producing low concentrations that contrast with the more common (high) concentrations that dominate. Conversely, discontinuities that result in a complete absence of a phase may reduce singularity spectrum range. Wavelet-based quantification of hyperspectral reflectance signals is a fundamental tool in ore deposit analysis that complements core and thin section-based petrology and structural investigations. While the scales of analysis in this study have been 50cm resolution, the maximum resolution to which it is applicable is restricted only by the resolution of hyperspectral analysis. Future research should focus upon quantifying the spatial dynamics of individual compositional end-members in common alteration phases such as sericite, chlorite and carbonates.

Recommended Reading for Chapter 11

Baker, T., Bertelli, M., Blenkinsop, T., Cleverley, J., McLellan, J., Nugus, M. & Gillen, D., 2010. P-T-X Conditions of Fluids in the Sunrise Dam Gold Deposit, Western Australia, and Implications for the Interplay between Deformation and Fluids. Economic Geology, **105**, 873-894.

Blenkinsop, T., Baker, T., McLellan, J., Cleverley, J. & Nugus, M., 2007. Sunrise Dam Gold Mine Geological Study Project. Project G15, pmdCRC.

Graham, S., Lambert, D. & Shee, S., 2004. The petrogenesis of carbonatite, melnoite and kimberlite from the Eastern Goldfields Province, Yilgarn Craton. Lithos, 76, 519-533.

Hill, E. J., Oliver, N. H. S., Cleverley, J. S., Nugus, M. J., Carswell, J. & Clark, F., 2014. Characterisation and 3D modelling of a nuggety, vein-hosted gold ore body, Sunrise Dam, Western Australia. Journal of Structural Geology, **67**, 222-234.

Müller, D. & Groves, D. I., 1997. Potassic Igneous Rocks and Associated Gold-Copper Mineralization. Lecture notes in Earth Science, vol. 56. Springer-Verlag.

Roache, T. J., Walshe, J. L. & Huntington, J. F., 2000. On-Site Validation and Implementation of New Hylogging Technologies – Technology Transfer and Re-Skilling. Minerals and Energy Research Institute of Western Australia, M400 Final project report.

Wang, R., Cudahy, T., Laukamp, C., Walshe, J., Young, C., Roache, T. & Jenkins, A., 2015. White mica as a hyperspectral tool in exploration for Sunrise Dam and Kanowna Belle gold deposits, Western Australia. In: SEG 2015: World-Class Ore Deposits: Discovery to Recovery; 27-30 September 2015; Hobart, Tasmania, Australia. Society of Economic Geologists (SEG); 2015. Poster P255.

Wang, X., 2015. Understanding vein-hosted mineralization at the Sunrise Dam gold deposit through coupled mechanical-fluid flow modeling. Unpublished Masters Thesis, the University of Western Australia.