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Mechanical Regimes of Hydrothermal Gold Mineralization

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Abstract

Pore fluid pressure and differential stress are among the most important controls on the mechanical behavior of mineralizing systems. Their separate influences can be readily identified on failure mode diagrams, which show failure envelopes for pore fluid factor, or pore fluid pressure at failure, against differential stress. The effect of the intermediate principal stress can be shown on such diagrams by using a failure criterion that includes all three principal stresses, such as the Murrell extension to the Griffith criterion. The effect is apparent from the significant variation of the position of the failure envelope as a function of the ratio between the three principal stresses, which is therefore another important control on failure. Characteristic regimes for different gold deposit types occur as distinctive fields on failure mode diagrams. Carlin, Epithermal and Volcanogenic Massive Sulfide deposit types have low absolute pore fluid pressures. Iron Oxide Copper Gold, Intrusion Related Gold and Porphyry deposits encompass low to intermediate values of pore fluid pressure, while the field of Lode Gold deposits may extend to the highest pore fluid pressures. Lode Gold, IOCG and Epithermal deposit types may have the largest values of differential stress. Carlin and VMS deposits are associated with normal stress regimes: the other deposit types may have structures that formed in either normal or reverse stress regimes. Exploring the effects of the stress ratio, and refining these currently broadly-defined regimes for the mechanics of mineralization, are important future directions for research.

Introduction

A thorough understanding of hydrothermal ore formation requires a mineral systems approach that considers energy, fluid, and metal sources, deformation, permeability and fluid flow, and precipitation mechanisms, and the interactions between them (e.g. Wyborn et al., 1994; McCuaig and Hronsky, 2016; Ord et al., 2016; Wyman et al., 2016). This is a formidable task, for which some basic parameters remain unknown, and for which only a few of the numerous feedback loops are quantified (Ord and Hobbs, 2018). Hence there is still a need to study components of mineral systems, such as the mechanical controls on hydrothermal fluid flow and ore formation, in order to build up to the system scale analysis.

The mechanics of hydrothermal systems can be understood inductively by analysis of structures and structural controls on ore bodies. Indeed, a primary focus of the applied structural geologist is to acquire, synthesize and interpret a range of primary data (structural, stratigraphic, geochemical and geophysical) to understand structural and tectonic controls on the paleo-hydrothermal 'plumbing system' across scale and time. We are now twenty years on from the last SEG Reviews Volume that addressed applied structural geology (Vol. 14: Structural Controls on Ore Genesis, 2001), and conceptual ore mineralization models have become increasingly sophisticated, reflecting a significant advance in our qualitative understanding of 'tectonofluid' interactions (e.g. Chen et al., 2019; Jensen et al., 2019; Zoheir et al., 2019; Vollgger et al., 2020; Cox, Rhys et al., Stenhouse et al., Tosdal and Dilles, this volume;). For practical reasons, such models generally are identified by deposit style, or 'class' (e.g. VMS – Volcanogenic Massive Sulphide, Carlin type, Epithermal etc.: Table 1).

The next frontier for enhancing our predictive capability likely rests on quantification of the effects of tectonofluid interactions (Cox, this volume), which requires cross-disciplinary collaboration between applied structural geologists and computational geoscientists, and a nuanced understanding of the limitations of knowledge. Relevant here, one of the key parameters impacting the mechanics of hydrothermal systems, the full stress state, is not widely known. Yet this parameter, which includes the intermediate principal stress and pore

fluid pressures, has a profound impact on tectonofluid interactions and their effect (Nádai, 1950; Sibson, 2000; Faye et al., 2018; Cox, this volume).

The aim of this paper is to evaluate and compare the mechanical regimes, including a consideration of the full stress state, of different hydrothermal gold mineralizing systems, or classes. Focusing on fracture and fault-controlled mineralization, and using results from contributions to this volume where applicable, we develop a mechanical facies model for gold mineralization that emphasizes the overlap and contrast between different classes of mineralization. We start by graphically illustrating the most important mechanical parameters affecting hydrothermal mineralization: stress, fluid pressure and temperature (e.g. Cox et al., 1987; Sibson, 1987; Ord et al., 2016).

Failure Mode Diagrams

Failure mode diagrams ("Brittle Failure Mode Plots"; Sibson, 1998) show failure criteria in terms of pore fluid factor vs. differential stress (e.g. Sibson, 1998; Cox, 2010; this volume) or differential stress vs. least effective principal stress (Sibson, 2000). In this section, some new approaches to failure mode diagrams are introduced as a prelude to understanding how stress and fluid pressure influence various classes of Au deposits.

The pore fluid factor λ_v is defined as:

$$\lambda_v = P_f / \sigma_v$$

Where P_f is pore fluid pressure and σ_v is the vertical stress (compression positive).

Published failure mode diagrams have typically used a composite Griffith-Coulomb failure criterion with three modes of failure of intact rock:

- 1) Extension failure is given by (e.g. Cox, 2010):

$$\lambda_v = \frac{\sigma_3 + T}{\sigma_v}$$

where T is the tensile strength.

2) Extensional-shear failure conditions are given by (e.g. Cox 2010):

$$\lambda_v = \frac{8T(\sigma_1 + T\sigma_3) - \Delta\sigma^2}{16T\sigma_v}$$

where $\Delta\sigma$ is the differential stress.

3) Shear failure on optimally orientated faults is described by Cox (2010):

$$\lambda_v = \frac{1}{2\sigma_v} \left[2C \frac{1}{\mu} - \left(\frac{1 - \cos\left(\tan^{-1}\frac{1}{\mu}\right)}{\cos\left(\tan^{-1}\frac{1}{\mu}\right)} \right) \sigma_1 + \left(\frac{1 + \cos\left(\tan^{-1}\frac{1}{\mu}\right)}{\cos\left(\tan^{-1}\frac{1}{\mu}\right)} \right) \sigma_3 \right]$$

Where μ is the coefficient of internal friction and C is the cohesion.

Figure 1a shows failure mode diagrams for intact rock failure based on these relationships for $\mu = 0.75$, $C = 10 \text{ MPa} = 2T$ for normal faulting ($\sigma_v = \sigma_1$) and reverse faulting conditions ($\sigma_v = \sigma_3$) and assuming a vertical stress gradient of 27 MPa/km. The failure envelopes for a range of depths from 1 to 20 km are shown: any depth has a unique failure envelope.

Fig. 1 here

Conditions for reactivation of faults in different orientations also can be shown on these diagrams. The case for reactivation of incohesive, optimally orientated faults is shown in dashed lines. The diagrams show an inverse relationship between pore fluid factor and differential stress, indicating a trade-off between these two influences on failure.

Failure mode diagrams have two advantages over Mohr diagrams: the distinct roles of pore fluid pressure and differential stress can be clearly visualized, and a sequence of stress states is more readily shown as a stress path (e.g. Cox, this volume). A failure mode diagram of pore fluid pressure at failure against differential stress has a simpler geometry than when

pore fluid factor is used, as illustrated in Fig. 1b for the same parameters as Fig. 1a. The failure envelopes for different depths do not cross over in this graph.

A limitation of these diagrams is that the shear failure envelope for intact failure is generally non-linear (e.g. Paterson and Wong, 2006, p. 156), contrary to the Coulomb criterion. Byerlee's Law for frictional sliding requires two linear expressions depending on normal stress (Byerlee, 1978), showing that a single linear law also does not apply to frictional reactivation. There is debate about the status of extensional-shear as a mode of intact failure. Extensional-shear failure is widely accepted as a theoretical possibility, but there is no substantive body of experiments for extensional-shear, and the field evidence for this mode of failure is equivocal (Engelder, 1999). Extensional-shear failure on segments of a normal fault that were steeper than adjacent shear failure surfaces was suggested by Ferrill et al. (2012), but their conclusion was based on calcite crystal morphologies that represent a finite displacement. Hence, while extensional-shear displacements occurred, it is not completely clear that this type of movement ("mode 1.5": Ferrill et al., 2012) was the primary failure mode, rather than reactivation with displacements on the extensional-shear segments controlled by adjacent shear mode segments. The very limited experimental evidence of extensional-shear failure is not consistent with the Griffith extensional-shear failure criterion (Ramsey and Chester, 2004).

The influence of the intermediate stress and the stress ratio

Another limitation of failure mode diagrams such as those in Fig. 1 may be that they do not allow for the influence of the intermediate principal stress σ_2 . The effect of σ_2 on failure has been known at least since Nádai (1950), and is a subject of active research (Chang and Haimson, 2000; Colmenares and Zoback, 2002; Haimson and Rudnicki, 2010; Kleidon, 2010; Haimson and Bobet, 2012; Schöpfer et al., 2013; Hackston and Rutter, 2016; Ma et al., 2017; Rudnicki, 2017). Morris and Ferrill (2009) have shown how σ_2 has a profound effect on slip tendency, the direction of maximum resolved shear stress, and therefore slip direction. Failure criteria are reviewed in the context of their ability to predict borehole shear failure

by Rahimi and Nygaard (2015), with the conclusion that the criteria accounting for the effect of σ_2 are superior. Colmenares and Zoback (2002) have shown that failure criteria in some rock types are very sensitive to σ_2 . The effect of σ_2 on failure criteria is commonly embedded through the stress ratio $\phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$, where $0 \leq \phi \leq 1$.

The extension of the Griffith criterion by Murrell (Murrell, 1963) is an obvious place to start investigating the effect of σ_2 since it uses the same single material property (tensile strength) as the Griffith criterion, so that it can be compared with the plots in Fig. 1. The extended Griffith criterion for shear failure is (Murrell, 1963):

$$(\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 + (\sigma_1 - \sigma_2)^2 = 24T(\sigma_1 + \sigma_2 + \sigma_3)$$

Using the ratio ϕ gives:

$$\lambda_v = \frac{1}{3\sigma_v} \left[\Delta\sigma\phi + \sigma_1 + 2\sigma_3 - \frac{\Delta\sigma^2(1 - \phi + \phi^2)}{12T} \right]$$

This criterion leads to continuous, curved λ_v vs $\Delta\sigma$ relationships, which depend considerably on σ_2 via the ratio of the principal stresses ϕ (Fig. 2). Higher values of ϕ (i.e. when σ_2 approaches σ_3) generally have failure envelopes that require higher $\Delta\sigma$ at a given λ_v or P_f .

Fig. 2 here

However, the maximum value of $\Delta\sigma$ at any given λ_v or P_f occurs at a value of ϕ which is generally less than 1. This complex relationship between λ_v , $\Delta\sigma$ and ϕ is illustrated in Fig. 3, which shows $\Delta\sigma$ at failure as a function of ϕ for three different values of λ_v . The maximum value of $\Delta\sigma$ occurs at $0.6 < \phi < 1$, depending on λ_v . Variations in ϕ therefore affect shear failure in a non-linear manner.

Fig. 3 here

Hydrothermal mineral systems and failure mode diagrams

Failure mode is an indication of the roles of pore fluid pressure and differential stress: for most common stress states, extensional failure indicates supra-hydrostatic to supra-lithostatic pore fluid pressure (since most crustal stresses are compressive), and shear failure indicates a significant differential stress (Fig. 1). Therefore, delineating fields for hydrothermal mineral systems on failure mode diagrams may enable comparison of the mechanics of different ore systems.

The data required for showing hydrothermal mineral systems on failure mode diagrams can be obtained by summarizing data from hydrothermal ore deposit classes, acknowledging that this procedure has limitations. Ore deposit classes are not defined primarily by their mechanics, so that some ore deposit classes (e.g. Iron Oxide Copper Gold, IOCG deposits) may encompass a variety of mechanical systems, ranging from fault or breccia dominated systems (e.g. Olympic Dam; Oreskes and Einaudi, 1990) to replacement style systems (e.g. E1 deposit near Ernest Henry mine in Queensland, Australia; Case et al., 2017). A simple grouping of the major classes of hydrothermal gold deposits is used here (Table 1): Volcanogenic Massive Sulfide (VMS), Carlin type, Epithermal, Intrusion Related Gold Deposits (IRGD), Porphyry, Lode Gold (including orogenic gold deposits: Groves et al., 1998) and Iron Oxide Copper Gold (IOCG). This classification is deliberately broad and inclusive, because limited mechanical data does not justify further subdivision. One example of how the approach could be refined in future would be to distinguish between intermediate/high and low sulfidation epithermal deposits, which may have different tectonic settings, structural controls and fluid pressure regimes (e.g. Sillitoe, 2008; Rhys et al. this volume). The Witwatersrand ores, which may have formed by two separate processes (sedimentary and hydrothermal: Frimmel et al., 2005; Frimmel and Hennigh, 2015) are not included because of this complication.

Absolute values of pore fluid pressures can be directly constrained by fluid inclusion studies (e.g. Baker et al., 2010). However, ore deposit studies do not usually specify $\Delta\sigma$, which can at present only be evaluated in a relative sense by failure mode. Many deposits may contain examples of extension, extensional-shear and shear failure, commonly with evidence for repeated movements that indicate reactivation (e.g. Sibson, 1987; Cox et al., 1991; Tunks et al., 2004). These modes may not all necessarily be linked to mineralization, but predominant types of failure can be associated with some gold mineralizing systems (Table 1).

A key aspect of many hydrothermal mineral systems is that fluid pressures and differential stresses fluctuate (Sibson et al., 1988; Cox et al., 1991; Micklethwaite, 2009). Hence ore deposits will encompass a range of values on failure mode diagrams. The amount of this variation may itself be a characteristic feature of the hydrothermal system. Fluid pressures and differential stresses also will vary in different parts of the hydrothermal system. A logical restriction would be to focus on $P_f - \Delta\sigma$ relationships at the ore depositional site, since that is where most data can be gathered, and it is the focus of economic interest.

Stress regime is a critical boundary condition for hydrothermal systems. Stress regimes can be characterized by the fault type associated with them as Normal: $\sigma_v \geq \sigma_H \geq \sigma_h$; Strike-slip: $\sigma_H \geq \sigma_v \geq \sigma_h$; and Reverse $\sigma_H \geq \sigma_h \geq \sigma_v$, where σ_H and σ_h are the maximum and minimum horizontal stresses respectively. The stress regime is considered at the scale of the deposit, and does not refer to the larger, plate scale configuration which might imply quite different regional patterns (cf. Rhys et al. this volume; Blenkinsop this volume). Some deposit types, for example VHMS and Carlin Type, are exclusively associated with normal stress regimes, while other deposit types seem to form in more than one stress regime (Table 1).

The $P_f - \Delta\sigma$ ranges implied from the data in Table 1 and a Griffith-Coulomb failure criterion are shown in Fig. 4 for the seven types of hydrothermal gold classes. Some interesting observations and inferences from this figure are discussed below.

Fig. 4 here

Discussion

Stress Ratios and Mineral Deposits

A general variability of ϕ in the crust is shown by Lisle et al. (2006), with slight but systematic variations in ϕ with stress regime. The value of ϕ and its variations have several important consequences for mineral deposit studies. Firstly, the value of ϕ influences slip directions on faults. For a fault with a normal \mathbf{n} , the slip direction may be located anywhere on the fault between the $\mathbf{n}-\sigma_1$ plane and the $\mathbf{n}-\sigma_3$ plane (Ramsay and Lisle, 2000) depending on the value of ϕ , potentially causing variations of slip direction on the same fault of up to 90°. Studies of gold deposits show that ϕ has influenced displacement directions, and that ϕ may vary during tectonic events. For example, ϕ varied from 0.5 (D3) to 0.95 (D4/D5) in mineralizing deformation events at Sunrise Dam Gold mine (Blenkinsop et al., this volume). Variations in ϕ between 0 and 0.5 determined pre-ore displacements on the Scotchman's Fault and the South Fault system at the Stawell deposit in the Lachlan fold belt, Australia (Miller and Wilson, 2004). Post ore displacements which affected the ore involved $\phi = 0.15$. This study illustrates how important it is to consider the three-dimensional geometry of structures (cf. Stenhouse et al., this volume) in relation to the orientation and relative magnitudes of the three principal stresses. Accurately predicting syn- or post-ore displacements on faults, and therefore the locations and shapes of ore bodies, requires the value of ϕ and its variations to be known.

Another consequence of considering the value of ϕ in mineral deposit studies is for numerical modelling of the mechanics of mineralizing systems (e.g. Wilson et al., 2016). The stress tensor, including the relative stress magnitudes embodied through ϕ , may be an important boundary condition for numerical models. In addition, as shown in Figs. 2 and 3, shear failure criteria depend on ϕ , so that an accurate prediction of locations where shear failure occurs, and permeability is created, depends on knowing ϕ . The stress ratio can be determined through several modern methods of paleostress analysis using fault slip and

vein orientation data (e.g. Žalohar and Vrabec, 2007; Yamaji et al., 2010; Yamaji and Sato, 2011; Delvaux, 2012; Hansen, 2013; Faye et al., 2019).

The value of ϕ affects the position of the shear failure envelope (Fig. 2), and is therefore a factor that governs paths to failure in addition to λ_p and $\Delta\sigma$. Cycling between failure and stability during mineralization may involve changes in all three parameters, which could interact in a dynamic way (Fig. 5).

Fig. 5 here

Mechanical Regimes and Mineral Deposits

Perhaps the most obvious difference in the regimes of hydrothermal gold mineralization shown in Fig. 4 is the separation of Carlin, Epithermal and VMS deposits from the IRGD, IOCG, Porphyry and Lode Gold deposits. The first group all have pore fluid pressure limited to tens of MPa at failure by their shallow depths. Intrusion Related Gold Deposits, IOCG and Porphyry deposits have potential for intermediate P_f values at failure, while Lode Gold deposits, which may form at a range of crustal levels (Groves, 1993), even if the extent of this range is more limited than previously considered (Phillips and Powell, 2009), could have very high P_f .

Also revealed on Fig. 4, but less intuitive, is the distinction between deposits that may have experienced large $\Delta\sigma$ values (Lode Gold, IOCG, Epithermal) compared to those in which the dominant mode of failure is extensional and therefore differential stresses are probably limited to the domain of extension and extension-shear failure ($\Delta\sigma < 25$ MPa for the rock properties used in Fig. 4). These include the Porphyry, IRGD, and VHMS deposits. Carlin type deposits are associated with shear failure, but $\Delta\sigma$ is still limited because of their shallow depths. Cox (this volume) suggests that much of the deformation history for some lode gold deposits lies in the low $\Delta\sigma$ part of the diagram.

There is no straightforward correlation between mineralization class and tectonic setting, except for Carlin type and VMS deposits. These types of deposit are the only ones that are

restricted to normal stress regimes. Stress regimes are variable for all the other deposit types. Deposits such as Porphyries, associated with plate margins, are not distinguished by stress regime from IOCG deposits, which may form away from plate margins (Groves et al., 2010).

Fluctuating pore fluid pressures between hydrostatic and at least lithostatic are common to all types except for Carlin and VMS, which are generally considered to have hydrostatic P_f . It is clear that other gold deposit classes do not form in strong, permeable, critically stressed crust with only hydrostatic pore fluid pressures as documented by Townend and Zoback (2000). Instead, pore fluid pressures can fluctuate from hydrostatic to lithostatic or above during the formation of these ore deposits. This key difference from the Townend and Zoback case is caused by the inherent ability of these hydrothermal systems to form hydrological seals, perhaps rather rapidly (Tenthorey et al., 2003; Kay et al., 2006; Tenthorey and Fitzgerald, 2006). The mechanics of such hydrothermal mineralizing systems may depend on the chemical reactions that occlude permeability in order to obtain near lithostatic P_f values. The special nature of the mechanical conditions is clear from the contrast between near hydrostatic pressures in many geothermal systems compared to the suprahydrostatic fluid pressures evident in mineralizing systems that are pervaded by fractures (Rowland and Simmons, 2012).

Figure 4 has some limitations that mainly reflect lack of detailed knowledge about the mechanics of mineralizing systems. The diagram deals only with failure by fracture ("fracture-controlled"; Cox this volume), although some orogenic and IOCG deposits formed at temperatures in which dislocation and diffusional processes have operated. Although the mechanical fields depicted on the figure encompass large ranges in $P_f - \Delta\sigma$, the figure does not convey the dynamic nature of mineralizing systems. In addition, it would be desirable to include the effects of variations in rock properties (e.g. tensile strength; Hronsky, 2019) and zonation in mechanical conditions within deposits on such a diagram. At present, diagrams such as Fig. 4 are more useful to explore concepts than to accurately describe mechanics. It may be possible in future to reduce the ranges of $P_f - \Delta\sigma$ that are characteristic of different mineralizing systems, which would be most useful for mechanical modelling.

Another more general limitation with the approach embodied by Fig. 4 that considers only a limited range of mechanical parameters, is that it does not take into account interactions between physical and chemical processes. For example, fluctuations between permeability creating mechanisms and permeability destruction is viewed as a stage in the chemical reactor model of mineralizing systems by Ord et al. (2012). The model suggests that such a stage is necessary to maintain flow in the ore system, and that it is a stationary state that follows from an initial exothermic stage of carbonate/hydrous silicate alteration. An important difference between the chemical reactor model applied to gold mineralizing systems by Hobbs and Ord (2018) and Ord and Hobbs (2018) and previous models such as the fault valve model, is that open flow chemical reactors produce internal fluctuations in temperature and pressure, without relying on externally imposed changes in stress or fluid pressure. This model predicts that temperature variations are more likely to be critical for gold precipitation in some conditions.

The possibility of phase separation in a mixed H₂O–CO₂–NaCl fluid is a further example of how the mechanics of hydrothermal systems may be linked to chemistry. Such fluids are common in Lode Gold systems (Ridley and Diamond, 2000; Baker, 2003), and phase separation has been invoked as a mechanism for gold precipitation (e.g. Sibson et al., 1988). Phase separation can result in very large increases in fluid volume (Micklethwaite et al., 2010) which could drive extensional or extensional-shear failure due to increasing fluid pressure when flow occurs across a hydrologic boundary from an overpressured regime into a hydrostatic regime (c.f. Oliver et al., 2006).

Concluding Remarks

The intermediate principal stress σ_2 is a significant factor in determining relevant failure criterion for gold mineralization. Values of σ_2 close to σ_3 (i.e. low values of the stress ratio ϕ) require lower differential stresses for shear failure at a given pore fluid pressure or pore fluid factor than when the value of σ_2 is close to σ_1 . Therefore stress state changes that lower ϕ may promote failure. The specific value of ϕ is also important for predicting slip

directions of syn or post mineralization faults that may affect ore bodies, and for obtaining correct results from mechanical modelling of mineralization. The stress ratio can be estimated from fault slip analyses; limited current observations show that ϕ does change during and after mineralizing events. Variations in values of ϕ can contribute to dynamic changes in the mechanics of mineralization. An important future goal for mineralization studies is to document and predict the effects of changes in ϕ through mineralization cycles.

Different classes of hydrothermal gold mineralization have characteristic mechanical regimes, identified by the range of pore fluid pressures and differential stresses that occurred during mineralization. These regimes can be delineated on failure mode diagrams. Failure mode diagrams that show pore fluid pressure at failure are geometrically simpler than diagrams that show the pore fluid factor.

Carlin, Epithermal and Volcanogenic Massive Sulfide deposit types have low absolute pore fluid pressures (to a maximum of a few tens of MPa). Iron Oxide Copper Gold, Intrusion Related Gold and Porphyry deposits encompass low to intermediate values of absolute pore fluid pressure, while Lode Gold deposits may experience the highest pore fluid pressures. Lode Gold, IOCG and Epithermal deposit types have the largest ranges and possible values of differential stress, which is limited in the other types to stresses appropriate to extensional-shear failure. Carlin and VMS deposits are the only ones associated with a specific stress regime (normal).

The regimes identified for these deposit classes consolidate, and are a useful expression of, current knowledge about their mechanics, with some useful implications for exploration. Carlin and VMS deposits should be identified with extensional failure and normal faults formed in normal stress regimes, but none of the other types appear to be restricted in this respect. The full range of failure modes (extension, extensional-shear, shear and reactivation) may be expected in Lode Gold, IOCG and Epithermal deposits, while Porphyry and IRGD deposits are dominantly hosted in extensional and extensional-shear structures. Given these general mechanical constraints, the applied structural geologists should maintain a flexible mindset when interpreting primary data. An expedient direction for

research may be further refinement and quantification of mechanical regimes for hydrothermal gold mineralization.

Physical processes (including thermal changes) interact with chemical and mineralogical changes to form hydrothermal deposits. A mineral systems approach, of which the mechanical regimes described here are one component, is needed to understand the evolution of the whole system. Coupled numerical simulations will provide increasingly relevant insights into this complex system in the future. Field-based studies will be all the more critical to provide constraints, such as stress ratios, on such models, and to provide the whole of the geological history, including pre-, syn- and post mineralization events.

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Figure Captions

Fig. 1. Failure mode diagrams for intact failure (solid lines) and optimal reshear (dashed lines), for Normal and Reverse stress regimes, using a Griffith-Coulomb failure criterion, a tensile strength of 5 MPa and a coefficient of sliding friction of 0.75. Dashed vertical lines separate extensional-shear from shear failure.

Failure conditions for depths of 1, 2, 3, 7, 10 and 20 km are shown in different colors as labelled.

- a) Pore fluid factor $\lambda_v = P_f/\sigma_v$ vs. $\Delta\sigma$ in MPa. $\lambda_v = P_f/\sigma_v$.
- b) Pore fluid pressure at failure, P_f , vs. $\Delta\sigma$.

Fig. 2. Failure mode diagrams for shear failure plotted using a Griffith Murrell failure criterion that accounts for the effect of σ_2 . Each set of curves shows the variation expected from $\phi = 0$ to $\phi = 1$ (black), *i. e.* ($\sigma_1 = \sigma_2$) to ($\sigma_2 = \sigma_3$), in increments of 0.2. Normal and Reverse stress regimes are shown for depths of 1, 5 and 10 km as labelled.

Fig. 3. The effect of ϕ on $\Delta\sigma$ at failure from the Griffith Murrell failure criterion at three values of λ_v as labelled. The maximum value of $\Delta\sigma$ occurs in the range of ϕ values between 0.6 and 1.

Fig. 4. Mechanics of Hydrothermal gold mineralization displayed on a graph of pore fluid pressure P_f at failure vs differential stress. Abbreviations as in Table 1, with V = VMS. The large areas of P_f - $\Delta\sigma$ space occupied by different styles of mineral deposits reflect: i) the range in depth at which they may form ii) fluctuations in pore fluid pressure of the mineralizing system iii) the possibilities of intact failure as well as reactivation. A Griffith-Coulomb failure criterion is used to allow comparison with Fig. 1.

Fig. 5. Pathways to shear failure illustrated on a failure mode diagram for the Griffith Murrell failure criterion with the same parameters as Fig. 2, showing only the reverse stress regime at 5 km. Arrows show the effect of changing the variables as labelled. Dashed line indicates that the failure criteria changes, rather than P_f or $\Delta\sigma$.

Table Captions

Table 1. Key aspects of the mechanics of hydrothermal gold mineralization.

VMS = Volcanogenic massive sulfide deposits, IRGD = Intrusion Related Gold Deposits, IOCG = Iron Oxide Copper Gold deposits. λ is the pore fluid pressure factor, Mode is the failure mode: E – extension (including extensional-shear), S shear.

Deposit style	Deformation Styles of Mineralization	λ	Mode	Fluid T °C	Depth km	Stress regime
VMS ¹	Stockwork Massive sulfide	0.4		300-400	0-1	Normal
Carlin Type ²	Disseminated	0.4	E	180-240	1-3	Normal
Epithermal ³	Veins, stockwork Massive sulfide	0.4-1	E, S	100->500	0.05-2	All
IRGD ⁴	Sheeted veins (pegmatites), Disseminated, Breccia, Replacement	0.4-1	E	200-600	1 -7	All
Porphyry ⁵	Veins: tectonic, radial, concentric, stockwork. sheeted Dykes, plutons	0.4->1	E	300-700	1-10	All
Lode Gold ⁶	Veins: shear, extension, stockwork, Shear zone	0.4->1	E, S	300-600	2-20	All
IOCG ⁷	Breccia, Replacement Shear zone Veins	0.4->1	E, S	200-700	1-10	All

¹Franklin et al., (2005); Lafrance, (this volume)

²Cline et al., (2005)

³White and Hedenquist, (1995); Simmons et al., (2005); Rowland and Simmons (2012); (Henley and Berger, 2011); Rhys et al. this volume

⁴Sillitoe, (1991); Thompson et al., (1999); Lang and Baker, (2001); Baker, (2002); Hart, (2007)

⁵Seedorff et al., (2005); Rusk et al., (2008); Sillitoe (2010); Tosdal and Dilles (this volume)

⁶Sibson et al., (1988); Cox et al., (1995); Groves et al., (1998); Goldfarb et al., (2005); Witt et al., (2005); Blenkinsop (this volume); Cox (this volume)

⁷Hitzman et al., (1992); Hitzman (2000); Pollard, (2000); Williams et al., (2005); Hunt et al. (2007); Groves and Bierlein, (2010); Case et al., (2017)