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SELF-ORDERING AND COMPLEXITY IN EPIZONAL MINERAL DEPOSITS[1]

Richard W. Henley[2] and Byron R. Berger[3]
[2]131 Poppet Road, Wamboin, NSW 2620, Australia and Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia,
[3]U.S. Geological Survey, MS 964, Federal Center, Denver, Colorado

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■ **Abstract** Epizonal base and precious metal deposits makeup a range of familiar deposit styles including porphyry copper-gold, epithermal veins and stockworks, carbonate-replacement deposits, and polymetallic volcanic rock-hosted (VHMS) deposits. They occur along convergent plate margins and are invariably associated directly with active faults and volcanism. They are complex in form, variable in their characteristics at all scales, and highly localized in the earth's crust.

More than a century of detailed research has provided an extensive base of observational data characterizing these deposits, from their regional setting to the fluid and isotope chemistry of mineral deposition. This has led to a broad understanding of the large-scale hydrothermal systems within which they form. Low salinity vapor, released by magma crystallization and dispersed into vigorously convecting groundwater systems, is recognized as a principal source of metals and the gases that control redox conditions within systems. The temperature and pressure of the ambient fluid anywhere within these systems is close to its vapor-liquid phase boundary, and mineral deposition is a consequence of short timescale perturbations generated by localized release of crustal stress.

However, a review of occurrence data raises questions about ore formation that are not addressed by traditional genetic models. For example, what are the origins of banding in epithermal veins, and what controls the frequency of oscillatory lamination? What controls where the phenomenon of mineralization occurs, and why are some porphyry deposits, for example, so much larger than others?

The distinctive, self-organized characteristics of epizonal deposits are shown to be the result of repetitive coupling of fracture dilation consequent on brittle failure, phase separation ("boiling"), and heat transfer between fluid and host rock. Process coupling substantially increases solute concentrations and triggers fast, far-from-equilibrium depositional processes. Since these coupled processes lead to localized transient changes in fluid characteristics, paragenetic, isotope, and fluid inclusion data relate to conditions at the site of deposition and only indirectly to the characteristics of the larger-scale hydrothermal system and its longer-term behavior. The metal concentra-

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tions (i.e. grade) of deposits and their internal variation is directly related to the geometry of the fracture array at the deposit scale, whereas finer-scale oscillatory fabrics in ores may be a result of molecular scale processes.

Giant deposits are relatively rare and develop where efficient metal deposition is spatially focused by repetitive brittle failure in active fault arrays. Some brief case histories are provided for epithermal, replacement, and porphyry mineralization. These highlight how rock competency contrasts and feedback between processes, rather than any single component of a hydrothermal system, govern the size of individual deposits. In turn, the recognition of the probabilistic nature of mineralization provides a firmer foundation through which exploration investment and risk management decisions can be made.

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INTRODUCTION

Epizonal base and precious metal deposits underpin much of our modern industrial economy. They make up a range of familiar deposit styles including porphyry deposits, epithermal veins and stockworks, carbonate replacement bodies, and marine volcanic rock-hosted massive sulfide (VHMS) style deposits. All develop from magma-related hydrothermal systems in the upper levels (4–5 km) of the crust. These deposits occur along active, convergent tectonic plate margins and in continental rift environments, and are commonly spatially and temporally associated with volcanism and epizonal intrusions.[4] But while a century of dedicated research has achieved an excellent framework for understanding the nature of epizonal deposits, we still cannot say with confidence what ultimately determines where a given mineral deposit forms, how grade is controlled within deposits, and why some deposits are so much larger than others.

The essence of epizonal deposits is their intrinsic variability from the deposit (e.g. tonnage and grade statistics) to the mesoscopic (e.g. alteration zonation, banded veins) and microscopic (e.g. compositionally zoned minerals, fluid-inclusion and isotopic attributes) scales. Subsets may be distinguished that share characteristics and contexts, but each deposit remains unique. While reviews of epizonal deposits have focused previously on these shared characteristics, in this paper we focus on variability, and ask questions about its cause. For example—how do the rich textural patterns, oscillatory banding (Figure 1, see color insert; Figures 2 and 3; Figure 4, see color insert), and the heterogeneity within mineral grains actually come about in vein deposits? If deposits are individually distinc-

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[4] The term epizonal logically extends to metal deposits formed on and below the sea floor at active spreading centers such as the TAG Field. In order to focus on key processes, we have elected to confine this paper to deposits formed at convergent plate margins; however, we emphasize that the processes and concepts explored here are applicable in a much wider range of hydrothermal deposit settings—from oceanic spreading centers to shear zones associated with mountain building.

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(a)

Figure 2 Photographs of fracture and replacement styles of polymetallic mineralization in carbonate rocks from the Bingham Canyon, Utah mining district. Replacement of the carbonate rock appears to be best developed when the fluid flow-controlling fractures are subparallel to the laminations. Figure 2*a* is a view of thinly bedded, partially marmarized carbonate rock cut by Pb-Zn-Cu-Ag mineralized fractures on the No. 6 level of the Highland Boy mine, Bingham Canyon, Utah. The mineralized fractures are parallel to the drift (dark area on bottom left of slide) and subparallel to bedding in the host rock, and these fractures are linked by narrow, mineralized fractures. Mineralization adjacent to the fractures extends laterally by replacing individual laminations in the limestone (JM Boutwell, photograph #15, U.S. Geological Survey photographic archives library; no scale given, but width of view estimated as ∼3 m).

tive, why can they be usefully categorized by certain spatial information such as alteration patterns? And since the products of hydrothermal systems are determined by atomic scale interactions (mineral and rock properties, fluid speciation, etc), how does order and self-similarity arise from them at much larger scales?

We first provide a very brief overview of the characteristics of epizonal deposits and examine the system-scale context within which hydrothermal deposits form. We then examine hydrothermal processes within them and pay particular attention to data on the consequences of short timescale perturbations and the coupling of brittle failure of rocks, heat transfer, and heterogeneous chemical processes in ore formation. Mineral parageneses and textures are then seen as the consequence of transient coupled processes within hydrothermal systems over a range of length and timescales. This foundation enables us to understand the

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(b)

Figure 2 Figure 2*b* is a view of carbonate replacement ore on the 5.5-level of the Highland Boy mine, Bingham Canyon, Utah. Unreplaced zones are white. The dark area in the upper left of the photograph is massive Pb-Zn-Cu-Ag carbonate-replacement ore. In the center and right parts of the photograph, the feeding, ore-bearing fractures are clearly delineated as linear dark zones with selvages of lamination replacement. The fractures are separated by gray, pyritic carbonate-replacement mineralization. Numerous cross-linking, mineralized fractures are also evident in the central part of the photograph. How do the localized zones of massive polymetallic replacement along the feeding fractures form? Why are some laminations replaced with alternating mineralogies while others are monomineralic? (JM Boutwell, photograph #18, U.S. Geological Survey photographic archives library; no scale given, but width of view is approximately 2–3 m).

dynamics of epizonal environments and the wide spectrum and intricacy of their deposits.

Epizonal deposits occur throughout the crust and throughout geologic time. They are integral to the geochemical evolution of the lithophere and worthy of study in their own right regardless of any economic utility; however, detailed understanding opens opportunities to strengthen traditional approaches to their exploration by helping us comprehend, for example, how simple processes become amplified to form giant ore deposits and where in the crust this is most likely to have occurred.

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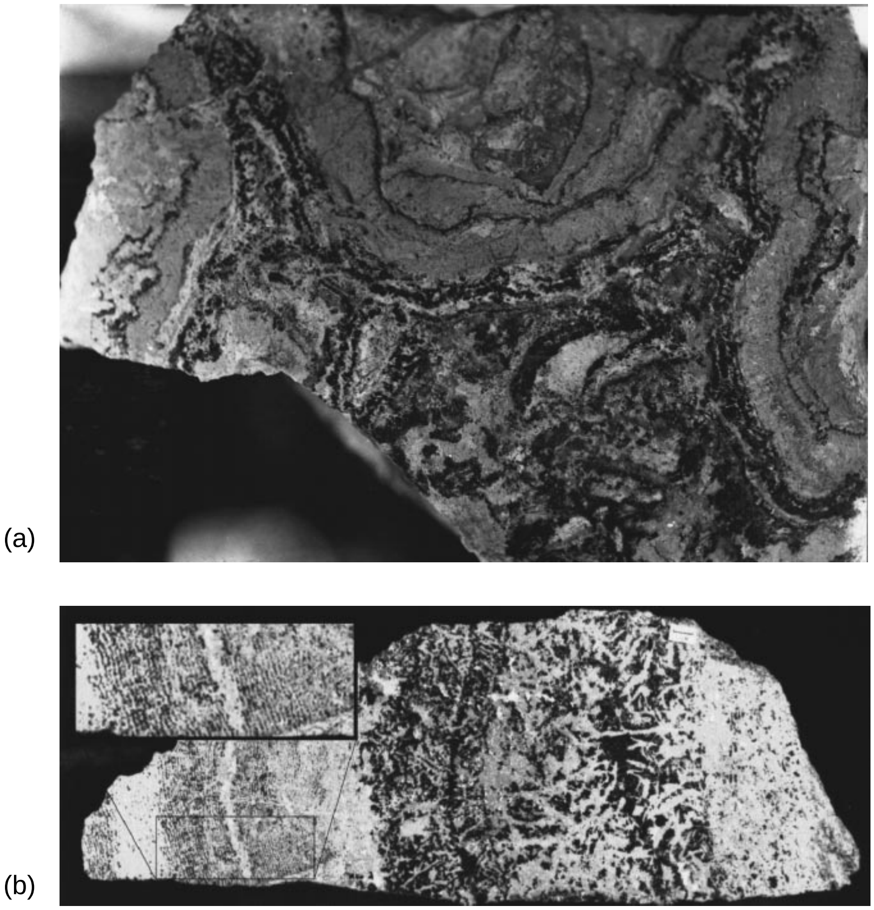

Figure 3 Examples of complex lamination, banding, and brecciation from the epithermal Tonopah, Nevada, and replacement-style Ten Mile (Kokomo), Colorado deposits. Figure 3*a* is of hypogene silver-gold ore hosted by Miocene, non-marine volcanic rocks from the Murray vein 950-level Tonopah-Extension mine, Tonopah mining district. Bands of alternating sulfides and rhodochrosite and sulfides and quartz rim quartz-sulfide-cemented breccia and, in turn, the banded material make up the clasts in a cockade-structure matrix. What varying conditions and mechanisms are indicated by such complex textural features? The pictured specimen is approximately 34 cm in width (ES Bastin, photograph #257, U.S. Geological Survey photographic archives library). Figure 3*b* illustrates the very fine-scale replacement of laminations in carbonate rock by pyrite and sphalerite in the Wilfley mine, Kokomo mining district, Colorado. The thin, alternating pyrite and sphalerite replacement of the laminae is evident on the left side of the photograph. Bladed and dendritic pyrite are evident in the center and right parts of the photograph. Through what mechanisms does such alternating mineralogy occur, and why in only part of the replacement ore, whereas bladed and dendritic structures develop in adjacent laminations while still preserving the lamellar banding at a coarser scale? The pictured specimen is approximately 37 cm in width (MH Bergendahl, photograph #10, U.S. Geological Survey photographic archives library).

THE NATURE OF EPIZONAL MINERAL DEPOSITS

Posepny (1893) and Lindgren (1913) were among the first to try to identify the underlying principles governing the form and occurrence of epizonal deposits. In parallel with the contemporary development of metamorphic facies concepts, Lindgren proposed that hydrothermal deposits developed along simple pressure-temperature gradients related to intrusions. Emmons (1924), Bateman (1950), and others further developed Lindgren's paradigm with the progressive emergence of the concept of a continuum of deposit styles. Such a continuum is implicit in a number of syntheses (e.g. Sillitoe 1973) wherein the spatial contexts of deposits are compared. While some porphyry deposits may be associated with epithermal veins, however, epithermal veins may be less commonly associated with porphyry mineralization; the continuum concept is therefore inherently probabilistic.

The crustal context of epizonal deposits has been further defined by White (1955, 1981), Henley & Ellis (1983), Hayba et al (1985) and others (Table 1). New techniques, such as fluid inclusion and isotope analyses, together with a much broader knowledge of mineral deposit occurrences in the crust, hydrothermal experiments, and data from hydrothermal systems active in today's crust, all provide additional information to underpin our understanding. As shown in Figure 5, these data indicate broad or fuzzy temperature-depth relations between different epizonal deposit styles rather than simple linear relations or depth continuity between styles.

Variability and complexity are characteristics of all epizonal vein, replacement, and porphyry deposits and occur from the deposit through the grain scales. Sets of deposits share common characteristics reflecting similar environments of formation, yet vary widely in their size and metal content. Individual deposits are characterized by their heterogeneity, but despite seeming randomness in detail, a level of ordering also occurs throughout and introduces an air of simplicity. Within individual ore bodies, for example, grades are not uniformly distributed, nor are the relative proportions of the ore minerals consistent. Link et al (1964) and Koch & Link (1967), for example, studied metal distributions in the Fresnillo district, Mexico, and found that the variance in metal values changed radically between individual sample sites and from place to place along a vein.[5] In many mining districts there are numerous individual veins, some of which may be of considerable length (>1 km), but seldom does an entire vein constitute ore, even though the overall mesoscopic vein textures may appear the same throughout.

At the microscopic scale, mineralogical compositions vary widely within deposits. In high-temperature porphyry deposits, complex relations are evident between sulfide minerals. However, the variation in composition within minerals has not been well documented—although the preservation of exsolution textures

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[5] Studies of other styles of hydrothermal mineralization have also shown that grade distribution is fractal and therefore shows power law behavior (Kentwell et al 1999a,b; Turcotte 1986).

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TABLE 1 Selected references for epizonal deposit styles

	Commodities	Selected references
Porphyry-style		
Subvolcanic, within and adjacent to intrusions	Cu-Mo (general) Cu-Au	Beane & Titley (1981), Titley & Beane (1981), Titley (1982, 1995), Williams & Forrester (1995), Sillitoe & Gappe (1984), Sillitoe (1979, 1991)
Polymetallic vein/ replacement-styles		
Zoned around and within epizonal intrusive centres	Pb-Zn-Ag	Titley(1982)
Epithermal-style		
Near-surface (<500 m) in volcanic terranes	Au-Ag (general) Adularia-sericite/Acid-sulfate Au-Ag High-sulfidation/ low-sulfidation Au-Ag Hot-spring Au-Ag	Berger & Bethke (1985), Berger & Henley (1989), Henley (1991), Hayba et al (1985), Heald et al (1987) Hedenquist (1987), Sillitoe (1993) Berger (1985), Nelson (1988)
Submarine Volcanogenic		
Massive sulfide deposits Near-surface and sea-floor submarine volcanic terranes	Cu-Zn, Zn-Pb-Cu, Au-Ag	Ohmoto & Skinner (1983), Franklin (1993)

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is common. Such internal variations demonstrate the unstable nature of these environments. For example, oscillation between structural states in alteration biotite crystals in the Bingham Canyon, Utah, porphyry-style deposit has been interpreted as a consequence of non-equilibrium crystallization in the Bingham Canyon, Utah, deposit (Xu & Veblen 1995). Nonperiodic layer stacking occurs in biotite topotaxically replacing actinolite. At the temperature of formation, 450°C (Bowman et al 1987), Xu & Veblen (1995) propose that because neither the biotite nor the andalusite was deformed, periodic fluctuations in the fluid composition affected the rate of formation of biotite and the chaotic crystal-stacking structure that is observed.

Compositional variations within minerals are more common in lower-temperature epizonal environments (cf Craig et al 1998, Halden 1996). Sector zoning is, for example, frequently observed in epithermal vein minerals. Domain-

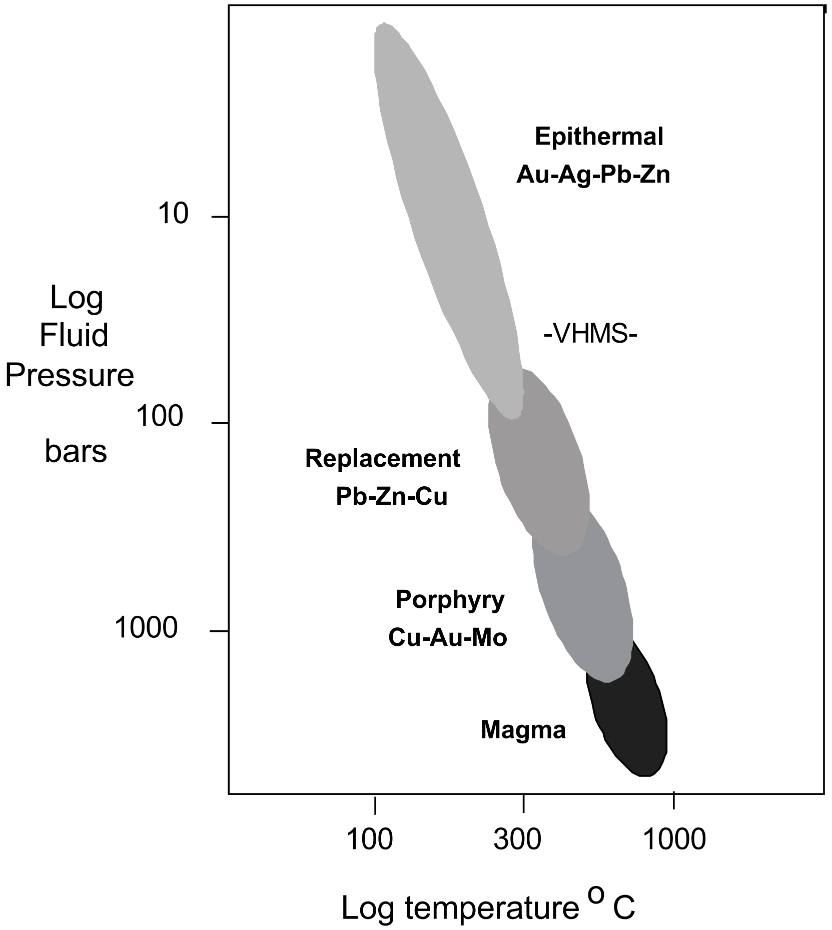

Figure 5 The relative temperature-pressure contexts for the formation of the major styles of epizonal mineral deposits. Note that there is no implied continuum in this diagram: some porphyry deposits may be genetically related to epithermal veins, but the occurrence of epithermal veins does not imply the presence of a porphyry deposit at depth. Volcanic rock-hosted massive sulfides (synonymous with Kuroko deposits) develop at the ocean-sediment interface so that their formation temperatures are commensurate with the presence of an overlying head (cold water pressure) of seawater but may otherwise be regarded as submarine epithermal deposits.

sectored colloform and spherical growth forms of vein silica have been found to be intergrowths of tridymite-cristobalite (cf Stein & Kirkpatrick 1976, Hunahashi 1973), and domain-sectored texture has also been observed in adularia. At the Seikoshi mine, Japan, Akizuki & Sunagawa (1975) interpreted domain-sectored, aggregated adularia crystals to be a result of differential growth rates. In poly-

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metallic veins, pyrite and occasionally sphalerite show columnar growth layers. For example, in the carbonate replacement-style Kokomo-Tenmile (cf Bergendahl & Koschmann 1971) and Leadville (cf Thompson & Arehart 1990) districts, Colorado, the columns of pyrite actually consist of blade-like composites of individual pyrite grains (cf Craig et al 1998) with satellite nodes and (or) dendrite-like structures. Sphalerite, or sometimes quartz, occurs interstitial to the pyrite, and eutectic intergrowth textures are also found. The latter are most commonly observed in galena with sulfosalts such as pearceite. At the Knob Hill mine, Republic, Washington, Taylor (1968) found that the iron content in sphalerite varied from 0.1 to 6.1 wt%, with heterogeneous grains common and homogeneity in electrum at Republic rare; one grain varied from 20 to 65 wt% gold. At Creede, Colorado, Barton et al (1977) measured rhythmic compositional variations in iron concentration across banded sphalerite crystals, as did Loucks (1984) at Topia, Mexico.[4] These patterns are commonly ascribed to indicate time-variant concentrations of metals in solution at the deposition site as the sequences of bands form.

At the mesoscopic scale, epizonal vein deposits show a remarkable similarity in the progression of vein stages, each with its own distinctive mineral content and paragenesis (Table 2), banding, and lamination We define bands as composed of distinctive sets of laminae, whereas stages constitute distinctive sets of bands. In base-metal deficient, silver-gold epithermal deposits, there may be several stages, but the bulk of the ore minerals are generally deposited during the earliest

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[4] Fowler & L'Heureux (1996) also documented systematic banding in sphalerite from Pine Point, Northwest Territories.

TABLE 2 Characteristic features of epithermal- and polymetallic rhythmic-style laminae and banding in veins and replacements. Polymetallic-replacement lamination and banding generally occur in either mantos or chimneys

Epithermal-style	Polymetallic rhythmic-style
Episodically formed with ore minerals in seams, clots, and(or) aggregates	Episodically formed with massive sulfide or dispersed grains; dendritic forms common
Distinct stages recognizable	Distinct stages recognizable
Sharp boundaries between bands	Common alternation of essentially monomineralic layers
Grooved layer surfaces; fan shape pattern common	Sharp and transitional boundaries between bands
Repetitive banding cycles; bands commonly wavy	Bands commonly form ellipsoidal masses
Colloform mineral growth and open-space filling textures	Common intramineral microfaulting with stepped layer boundaries and offsets between bands
Quartz predominant mineral	

stages. Very high-grade gold-silver ores (e.g. Sleeper, Nevada) almost ubiquitously are characterized by fine-scale interlayering of gold-pyrite and quartz laminae. In polymetallic vein and replacement deposits there is commonly an early barren stage followed by the base-metal mineralization stage, when sphalerite is often the earliest ore mineral. In many of these deposits, there is a subsequent base-metal-deficient, precious-metal stage with more complex epithermal-style banding and lamination, and most deposits also have a final, barren stage. In all of the epizonal styles, the progression of stages is unidirectional—i.e. there is no reversibility in the development of vein fabrics. Such systematics are well documented for a number of deposits, including the silver-base metal epithermal veins at Fresnillo, Mexico (Simmons 1991). Henley et al (1997) have examined banding and lamination in ore-bearing, typical epithermal vein material from Golden Cross, New Zealand (Figure 4, see color insert; Figure 6). They demonstrated that lamination thicknesses were not random and that a systematic spatial frequency occurred in the sample.

The wide range of complex banding and lamination fabrics and mineral compositions observed suggest that oscillating chemical conditions occur within vein systems. The oscillations switch rapidly between a limited number of mineral phases to form biminerallic, sharply to transitionally interfaced laminae (Table 2). Are these oscillations systematic or random? Do perturbations at the hydrothermal system scale trigger a sequence of oscillations at the deposit scale, as is commonly assumed, or are they the consequence of localized chemical processes intrinsic to the vein array? How are metal concentrations in veins related to oscillatory fabrics in time and space?

By contrast, at the fracture-filling scale in porphyry copper-gold systems there is less obvious internal variation, and therefore detailed descriptions of vein textures are rare. At El Salvador, Chile, Gustafson & Hunt (1975) noted banding of K-feldspar in early veins and more common banding in later veins. Meyer et al (1968) also described banding particularly in molybdenite-quartz veins at Butte,

▶

Figure 6 Analysis of oscillating fabric in an auriferous epithermal vein, Golden Cross, New Zealand. The sample and the scanned section are shown in Figure 4, color insert. High-resolution (5-μm beam diameter) laser-ablation ICP microprobe traverses (Henley et al 1997) clearly define (*a*) the discrete occurrence of gold alloyed with silver as electrum or associated with iron and silver as pyrargyrite, while iron also occurs discretely as pyrite without precious metals. (*b*) Fine-scale banding and lamination of silica (81 laminae) and adularia (80 laminae) are also well defined. Fast Fourier analysis (*c*) of the latter data comprising 411 analyses shows 3 distinct peaks at 11, 15, and 19 points, which correspond to 2, 3, and 4 laminae subsets, and finer-scale peaks may occur at the background noise level. Artifacts in the data may account for the 3 and 4 laminae sets, but we suggest that the 2 laminae spatial frequency, which may be directly related to time, indicates that lamination is not random. More detailed interpretation of the frequency relationship currently requires assumptions about relative deposition rates for silica and adularia.

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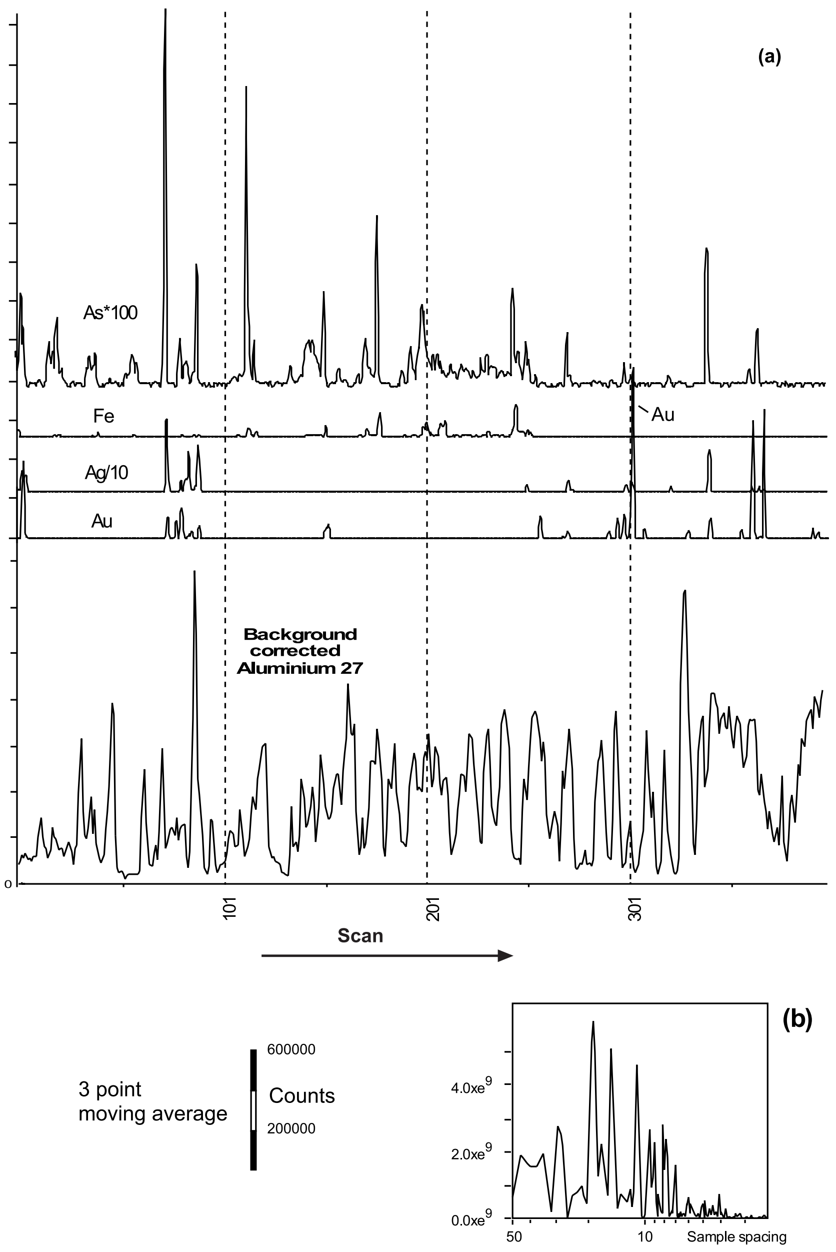

Figure 6

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Montana. However, quartz textures in generally discontinuous veinlets are frequently reported as mosaic type—a texture that here we interpret as a result of post-depositional annealing in the high-temperature environment, as is also seen for hypothermal vein deposits (Matthai et al 1995). In some cases, disseminated sulfides are associated with the traces of healed fractures, but are isolated from dilated veinlet segments of the fracture.

Variability also occurs between the magnitudes of deposits of similar style, regardless of age or province. Singer 1993, Singer et al 1993, and Crovelli et al (1995) have shown that for economic and near-economic porphyry copper deposits, total contained copper in individual deposits is log normally distributed. Similar behavior is evident for both epithermal- and Kuroko-style deposits based on other substantial data sets (e.g. Cox & Singer 1986, Shoji & Kaneda 1998). However, the log normal data sets are subsets of natural occurrences that have been filtered out by economic considerations. It is permissible then to suggest that the total contained metal of all similar occurrences follows some form of homogenous power law distribution (Figure 7), implying similarity in the processes of formation but chance in magnitude. Are epizonal deposits and their distinctive individual characteristics the consequence of simple crustal processes, or are we seeing the results of strong interactions between processes with outcomes influenced by some set of initial crustal or mantle conditions? Are their stages and finer-scale fabrics the expression of far-from-equilibrium chemical ordering triggered by stress release, but superimposed on larger-scale, longer-period compositional changes? Attempting to find answers to these deposit-scale questions requires that we first describe the larger-scale architecture, characteristics, and dynamics of the hydrothermal systems within which ore deposits form.

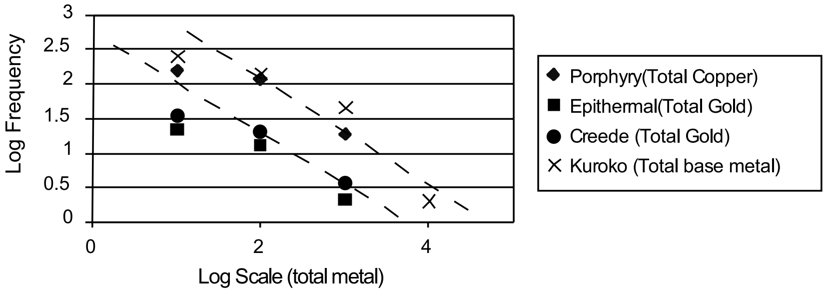

Figure 7 Relative frequency of occurrence of different scales (i.e. tonnage total metals) of epizonal deposits, plotted from the data of Singer (personal communication). Economically mineable deposits have a log normal distribution, but uneconomic natural occurrences are under-represented in the data. As a result, it is likely that the relative frequencies of different scales of natural occurrences of mineralization may be assumed to approximate power law distributions.

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THE CONTEXT FOR EPIZONAL MINERALIZATION

Mass and Energy Flux in Hydrothermal Systems

Epizonal ore deposits evolve within the large convective fluid-flow systems that are common in tectonically active, volcanic terranes. Analysis of fluid samples from active geothermal and volcanic hydrothermal systems and of fluid inclusions from epizonal mineral deposits indicates an interplay of fluids from a range of crustal regimes. These fluids have evolved primarily from surface waters within the upper crust by reaction with rock, and mixing with fluids from within the thermal and chemical regime of crystallizing bodies of magma (Figure 8), so that two end-member fluid flow models can be identified for the epizonal environment. One is simple convection of ground and formation waters, and the other is the dispersion of fluid derived from magma crystallization. The specifics of any real epizonal system, past or present, are then a combination of these two. Such systems may vary in time in the balance of fluid and heat inputs and may involve a range of shallow groundwater sources. Is such time variation simply due to the rates of cooling of heat sources?

Mass flows through convective hydrothermal systems are on the order of 100–400 kg/s, and systems may operate over timescales of >1 million years; however, ore deposition occurs within 1–2 orders of magnitude shorter time intervals. For example, Hedenquist & Henley (1985) estimated that localized gold deposition below the active Champagne Pool alone was occurring at a rate of 1.3 million ounces per 10,000 years at Waiotapu, New Zealand. Estimates of the time for ore deposition in the >42 million ounce Ladolam Gold deposit (Lihir Island, PNG) are fewer than 8,000 years (Henley & Etheridge 1995).

Textural and fluid inclusion evidence from the full range of epizonal deposits is consistent in showing that the ambient state of the system fluid is close to its vapor-liquid phase boundary; it can be argued that this is a logical consequence of the high heat flux in these systems. Temperature-depth (fluid pressure) relations in active geothermal systems are constrained by the vapor-liquid phase boundary of the system fluid (Haas 1971, Sutton & McNabb 1977) and are largely determined by salinity and carbon dioxide concentration (Hedenquist & Henley 1985). Data from the undeveloped Wairakei geothermal field prior to exploration are provided as an example in Figure 9. By contrast, magmatic fluid is generated at higher, near-lithostatic fluid pressures; its explosive release or less violent expansion into the lower pressure convective regime determines in large part the nature of the magmatic-hydrothermal system and of deposits that form within it (Figure 5).

Hydrothermal systems and magmatic intrusions commonly occur together, but it is important to distinguish each in terms of cause and effect. Both are consequences of tectonically induced elevation of heat flow and mass transfer within and between the mantle and crustal reservoirs. Both are localized by the co-evolution of fault systems and particular suites of intrusions, and associated rocks

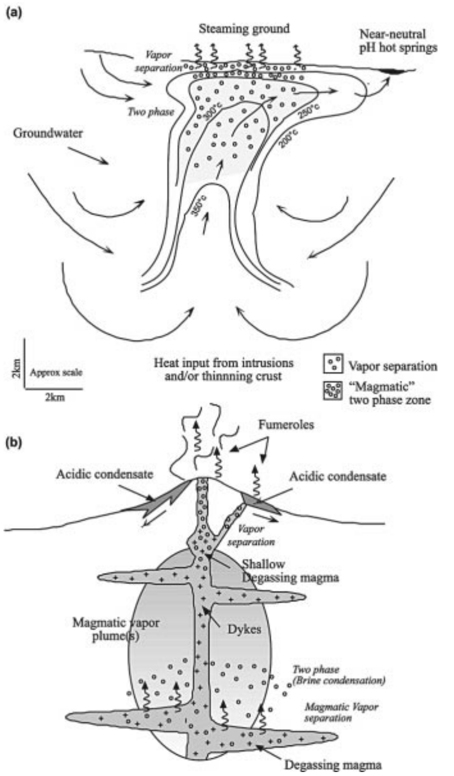

Figure 8 Schemas of the large-scale structure of epizonal hydrothermal systems. In any particular system, the chemistry of fluids within and at any point or time is dependent on the balance of these two end members and how that balance changes with time, as well as alteration and mineralization progress. Schema (*a*) focuses on convection of groundwater in response to crustal extension and intrusive activity. Schema (*b*) focuses on magma degassing to provide low-salinity vapor. Depending on intrusion depth, the latter may condense to provide metalliferous fluid and the development of acid sulfate-style deposits at shallow depths, or porphyry-style deposits at higher pressure and where confined by groundwater convection (i.e. schema *a*). Epithermal precious metal and VHMS deposits (at the seawater-sediment interface) develop primarily from convective systems coupled with magma degassing (schema *b*). It is important to recognize that the mass of metals we observe in any given deposit is only a small fraction of the total metal transported through the system during its lifetime. For reference, the upflow volume of a typical hydrothermal system is on the order of 20 km^3, so ore deposits developed within them represent $<1\%$ of the volume of the host system. (Modified from Henley 1996a)

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reflect elevated crustal heat flow and particular stages in the evolution of associated fault systems. The majority of porphyry Cu-Au deposits are localized along strike-slip fault systems and occur most frequently at inflections or step-overs (BR Berger, unpublished data, 1999). This suggests that magma flow through an active fracture array is passive with respect to the incremental growth of fractures (cf Ròman-Berdiel et al 1997, Castro & Fernandez 1998, Benn et al 1998, Hogan

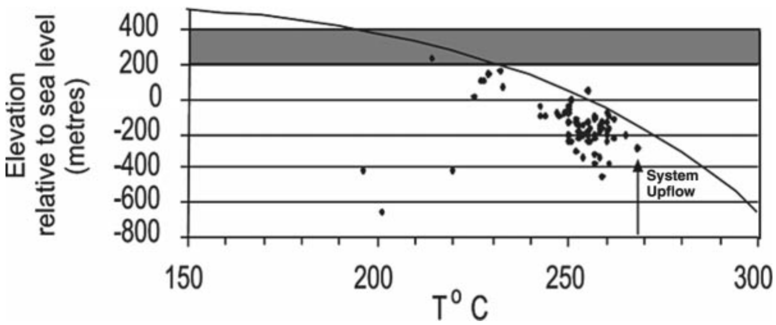

Figure 9 Maximum bottom hole temperatures for production wells drilled into the undisturbed Wairakei geothermal field (Grindley 1965) relative to a boiling point-depth curve for pure water. These data show that a broad band of t-depth data occur below the vapor-liquid phase boundary as a result of localized dilution with cold groundwater at the margins and surface of the system. The maximum upflow temperature of the convective system is identified as ~268°C. Heat loss along the boiling point-depth curve occurs through vapor loss—by escape either via available connected fractures to the surface, or into overlying cooler groundwater aquifers to form acidic steam-heated waters and associated solfatara (Henley & Stewart 1983) or distinctive sulfate-bicarbonate waters (Hedenquist & Stewart 1985). Fluid pressure in convective flows in the brittle crust is hydrodynamic; buoyancy upflow is combined with any available external head. In the active systems in the Taupo Volcanic Zone, New Zealand, the head adds about 7 to 10% of the systems' fluid pressure. In the undisturbed state of a system, low-permeability rock units (such as the Huka Falls lacustrine sediments at Wairakei) do not provide a capping effect that results in elevation of fluid pressure (McNabb & Dickinson 1995). However, as discussed in the text, the distinctive mechanical properties of such units may localize transient effects such as fluid draw-down in geothermal fields and ore formation in mineralizing systems.

et al 1998). Buoyancy drive through active fault arrays determines the relative level in the crust to which magma may rise, but the subsequent form of the intrusion is then a balance of magma pressure and external crustal stress regimes (cf Yoshinobu et al 1998, Hogan et al 1998, Petford & Koenders 1998). This coupling of crustal failure and buoyancy-driven processes may potentially develop system scale feedback and oscillation over timescales of 10^5–10^6 years. Although intrusions themselves are not necessarily the principal cause of hydrothermal activity, they may provide some spatial control on upflow and consequent mineralization, as a result of their differential response to cooling and external stresses as well as their distinctive internal brecciation and fracturing.

Fracture Arrays and Hydrothermal Systems

At the system scale, fluid-flow behavior may be modeled assuming steady-state heat transfer and using simple permeability-porosity flow equations without specification of the nature of the permeable paths or the porosity (e.g. Elder 1981;

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Cathles 1977, 1981; Norton 1984). Given that mineral deposition progressively reduces the permeability of a hydrothermal system, ongoing fault activity and fault systematics are important because of their controlling relation on fluid flux through maintenance of fracture-related permeability. Not surprisingly, active geothermal systems are commonly associated with regional-scale transcurrent fault systems, such as the Philippines Fault; also, the geothermal systems of the active Taupo Volcanic Zone, New Zealand, occur within a zone of extension between the transcurrent North Island shear zone and the Thames fault (see Figure 10).

Epizonal deposits commonly occur within transcurrent fault systems (Nishiwaki 1981, Henley & Etheridge 1995, Henley 1996b), but may be localized by individual faults in the system. Transcurrent fault zones commonly consist of subparallel sets of anastomosing faults that may interact elastically, resulting in the propagation of linking faults between them (Segall & Pollard 1980). If the linkage acts to inhibit shear, then a restraining bend develops, where displacement on the en échelon strike-slip systems is accommodated in the bend by reverse faults associated with gently dipping veining. Conversely, if shear is enhanced between the sets, then displacement on the interacting, en échelon faults will be accom-

Figure 10 The Taupo Volcanic Zone (North Island, New Zealand) is an actively extending step-over basin between two regional-scale transcurrent faults sub-parallel to a convergent margin. It contains extensive felsic volcanism, localized andesitic centers, and infrequent basalt dykes. There are a number of well-developed geothermal fields from which a range of multidisciplinary data is available for both the undisturbed and exploited systems. Of particular interest has been the demonstration that several of these systems are actively developing epithermal precious metal mineralization (Weissberg 1969, Hedenquist & Henley 1985, Krupp & Seward 1987). The chemical dynamics of a number of fields can be considered at a single instant in time, whereas reconstruction of the comparative chemistry of ore deposits in a given epizonal district necessarily requires analysis of data relating to the entire history of systems smeared over time periods of a minimum of a million years. Chloride ion and certain gas ratios are excellent tracers for these processes. Plotting the chloride concentration and fluid enthalpy (i.e. highest reservoir temperature) for the least diluted sampled fluid in each active system shows low salinity for the systems along the eastern margin of the Zone, and simple dilution systematics for systems farther to the west (Henley 1986). The eastern systems also have a distinctively higher level of contained gas, and noble gas signatures indicate the presence of a fraction of magmatic gas similar to that sampled directly from high-temperature fumeroles on White Island to the north (Giggenbach & Sheppard 1982). This pattern may be interpreted in terms of groundwater dispersion of a low-salinity magmatic fluid (cf Figure 11). The distribution of hydrothermal system fluid compositions is then particularly significant as an example of the coupling of hydrothermal chemistry with structural controls on magmatism and fluid flow in the region. The geothermal fields located on the map have all been extensively drilled to depths of the order of 2 km. (MK = Mokai, WR = Wairakei-Tauhara, RK = Rotokawa, Br = Broadlands, WT = Waiotapu, KA = Kawerau)

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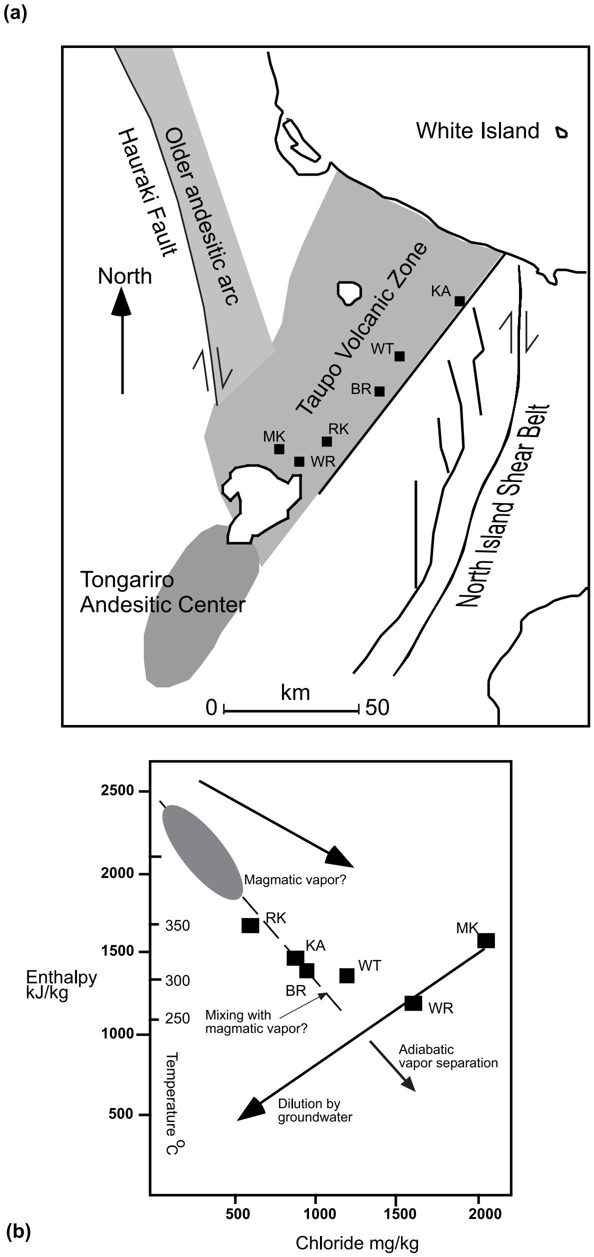

Figure 10

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modated between them by a zone of faults that make up a pull-apart structure. We shall return to the interactive processes triggered by contemporaneous evolution of such fracture systems when discussing the shorter-term phenomena that occur within hydrothermal systems and the formation of ore deposits.

The bulk permeability, k_p, of a hydrothermal system is primarily determined by the presence of linked fracture arrays related to such active faults, and the fluid flux is a power law function of fracture density,

$$q = a(d - d_c)^p, \tag{1}$$

where q is the mean flux; a is a constant; d is the fracture density; d_c is the percolation threshold, $d > d_c$; and p is an exponent (Zhang & Sanderson 1995; see also Cox & Knackstedt 1999). The equation presumes an existing fracture array (d-$d_c > 0$) rather than a dynamical array involving an interplay of stress fracturing and closure through mineral deposition. However, it highlights the dramatic exponential increase in fluid flow as the percolation threshold is exceeded. The Wairakei geothermal system has a gross system permeability of 10^{-14}–10^{-15} m^2 (1–10 millidarcies), which reflects the dominance of fracture-controlled fluid flow rather than homogenous porous medium flow (Henley & Ellis 1983). Its behavior consequent on exploitation indicates the connectedness of fractures.

Chemical Systematics of Epizonal Fluids

Reviews of the chemistry and water-rock interactions that occur in active geothermal systems (Henley & Ellis 1983; Giggenbach 1981, 1984, 1992) show that at the system scale, the major element compositions of fluids are constrained by reactions involving the predominant alteration minerals in the system. The potassium and calcium concentrations, for example, appear to be determined by illite-K-feldspar-epidote/zeolite-quartz-calcite reactions, such that fluid salinity is coupled to fluid pH (Henley et al 1984). However, the long term, open-system flow of reactive fluid through any body of rock progressively changes the composition of both, through solute precipitation and leaching. As noted by Giggenbach (1984), the instantaneous chemistry of any fluid plus rock package is therefore a consequence of the kinetics of a suite of alteration reactions rather than necessarily an equilibrium state of the system. Quasi-equilibria also occur between carbonate, iron-bearing silicates (e.g. chlorite and epidote) and pyrite, and control the relative (but not the absolute) concentrations of H_2S and H_2 and the ratios of the principal carbon species in solution (CO_2 and CH_4). These, in turn, determine the redox state (fH_2) of the fluid.

Carefully conducted sampling and analysis of active systems, including high-temperature volcanic gas vents, show relative simplicity in the range of major-element compositions of such fluids. The compositional variability reflects the extent of mixing of end-member fluids, reaction with host rocks, and heat loss (Giggenbach 1992, 1997). The dominant controlling variables are the redox state

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of the magmatic end-member and the salinity of the crustal fluid. In turn, these variables constrain the concentrations of the minor components, such as the ore metals (Au, Ag, Hg, Zn, etc), but do not necessarily determine their concentration in any given fluid. For the latter, including the ore metals of interest here, numerous attempts have been made to reconcile the observed chemistry of geothermal fluids with their thermodynamically calculated saturation states. These attempts are respectively limited by inherent errors in sampling, analysis, and the availability of fluid complexing and solubility data. However, Brown et al (1996) determined a range of gold contents (0.5 to 1.2 mg/kg) for fluid at Ohaaki-Broadlands (New Zealand) and demonstrated that the fluids were undersaturated with gold by a factor of about ten. Rae et al (1998) obtained a similar result for the Palinpinon geothermal field in the Philippines. We suggest, therefore, that while the concentrations of major components may be reliably related at the bulk sampling scale to quasi-fluid mineral equilibria, no such limiting assumption can be placed on the relative saturations of the minor elements because of their lower crustal abundances and erratic distribution in rocks. It follows that modeling of metal transport and deposition must commence from the premise of undersaturation. This is of fundamental importance because it places an important constraint on determining the chemical mechanisms for metal deposition—i.e. how do the metals attain supersaturation at the depositional site? Moreover, it permits long path length metal transport across thermal gradients without deposition en route (as would be required by setting initial saturation equal to 1) and the formation of dispersion trails the like of which have not been observed.

Fluid inclusion data from porphyry copper-gold deposits, as well as from some phenocrysts in unmineralized magmas, suggest the presence of a high-salinity liquid often consanguinous with low-salinity vapor. Paradoxically, the fluids actually sampled in active volcanoes are not such liquids. If porphyry deposits are formed in the roots of volcanos (Sillitoe 1973), why should there be such a difference in what we observe of fluid chemistry? To resolve this paradox, Henley & McNabb (1978) and Hedenquist & Lowenstern (1994) suggested that the systematics of the transport chemistry of epizonal systems could be reviewed in the context of progressive decompression of high-temperature, low-salinity magmatic vapor containing trace metals (Figure 11). [A pressure-dependent control on magmatic fluid salinity may also occur through the partitioning of chlorine between orthomagmatic biotite and melt (Cline & Bodnar 1991)]. Ulrich et al (1999), following earlier work by Heinrich et al (1992) have substantiated the partitioning of metals between liquid and vapor based on detailed laser ablation analyses of fluid inclusion populations in porphyry systems. Heterogeneity in the mantle lithosphere, perhaps associated with thermal and tectonic instabilities, is likely to be an important control on the trace metal content of magmas, and therefore magmatic gases (McInnes et al 1999).

Low-salinity metalliferous vapor migrates in response to fracturing processes as well as influencing crack failure through contribution of fluid pressure to the ambient effective stress field (cf Cox 1995) as well as chemical weakening. Mag-

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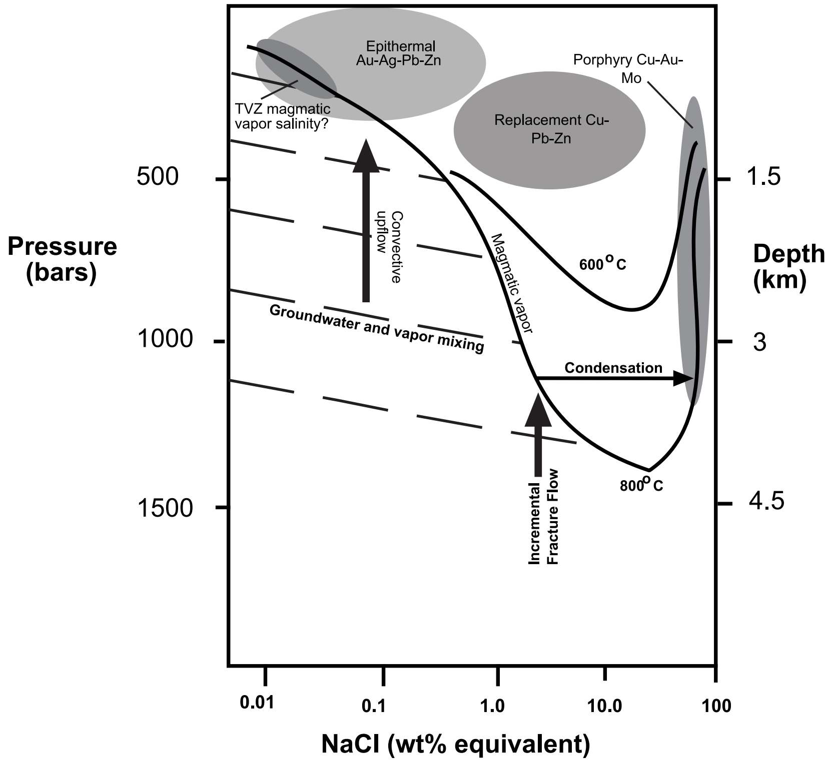

Figure 11 Generalized phase relations in the system XCl-H_2O where X is primarily sodium and potassium. CO_2 steepens the isotherms and increases critical pressures. As discussed elsewhere (Henley & McNabb 1978, Hedenquist & Lowenstern 1994), if there is upflow of low-salinity magmatic vapor, condensation occurs to form high-salinity, metal-enriched brines typical of the porphyry Cu-Au environment. Shallower degassing and condensation may produce high-level solfatara and acid-sulfate style deposits. Dispersion of vapor into convecting groundwater systems enables epithermal deposit formation at higher crustal levels, and such processes are indicated by fluid compositions in the Taupo Volcanic Zone geothermal systems (Figure 10*b*). Chemical scenarios for these fluid interactions are outlined by Giggenbach (1992, 1997). Singularly absent from lumped parameter models of porphyry systems is the recognition of the dynamical structural setting of hydrothermal deposits. For example, at mineralization scale in a porphyry copper deposit, the record of fluid flow is typically represented by a complex mesh of micro fractures and veins indicating that dilation is critical to the rapid, localized depressurization of magmatic vapor and subsequent condensation.

matic fluid migration, therefore, occurs through intermittent fracture dilation and transient phase separation. Later in this article, we describe a mechanism whereby heat transfer consequent on fracture dilation leads to further enhancement of salinity and metal concentration. Eventually, such magmatic vapor penetrates contemporary groundwater flow systems and becomes dispersed into the convective flow regime (Figure 11). Giggenbach (1992, 1997) has made suggestions for how redox conditions evolve in these dispersive processes and what their potential effects may be on metal transport and deposition.

The Systems Context

Hydrothermal systems are thermodynamic systems. The processes that govern their behavior are simple. Fluids flow through pressure gradients. They mix with vapors that are expelled from magmas as crystallization proceeds, they adsorb and release heat, and react with host rocks. While hydrothermal systems may be similar in style, however, their products (mineral deposits) are highly diverse. Structural and chemical effects, such as host rock reactivity, are self-evident as controls on deposit localization, but are each in turn dependent on the prior character of the rock sequences in which they operated. The region in space within which these processes occur serves to initially define the spatial boundaries of a hydrothermal system.

However, just as thermodynamic systems are open to external variables, hydrothermal systems are not isolated from the crust that contains them. They are open to inflow of groundwater and addition of thermal and stress energy. Any given system is therefore defined both by its internal variables and boundary constraints, as well as by external variables. Thus regional stress transforms into evolving fault systems, which in turn constrain the localization of hydrothermal and lithothermal (i.e. magmatic) systems and consequent processes within them. The compositional range of geothermal fluids encountered in different parts of the active Taupo Volcanic Zone, for example, is illustrative of the strong coupling of regional scale tectonics, magmatism, and system chemistry (Figure 10).

It is also important to recognize that systems inevitably evolve through time because bulk system changes occur, as well as changes in external stress and thermal fields. Because heat loss is relatively slow, the reorientation of crustal stress regimes influences the rate of devolution of hydrothermal systems and related internal perturbations by changing the brittle response behavior and reactivation characteristics of fault systems (Etheridge 1986).

The common tendency in mineral deposit studies is to focus on the time-integrated evolution of systems and ignore the variance in the data collected, and this turns attention away from the shorter time-scale interactions between crustal processes, which incrementally lead to alteration and mineralization patterns. Field data for active hydrothermal systems, such as Yellowstone, indicate that they may exist for 10^5 to 10^6 years. The lifetimes of volcanos are similar. As we have seen, by contrast, mineral deposit formation and alteration occur on a shorter timescale. Arguably, each increment or stage of mineralization may be of duration 10^2 to 10^3 years. Each deposit represents the cumulative unidirectional changes brought about by rapid processes such as rock failure or fluid phase reactions at timescales of 10^{-5} to 10^{-7} years. It follows that, while the assumption of an

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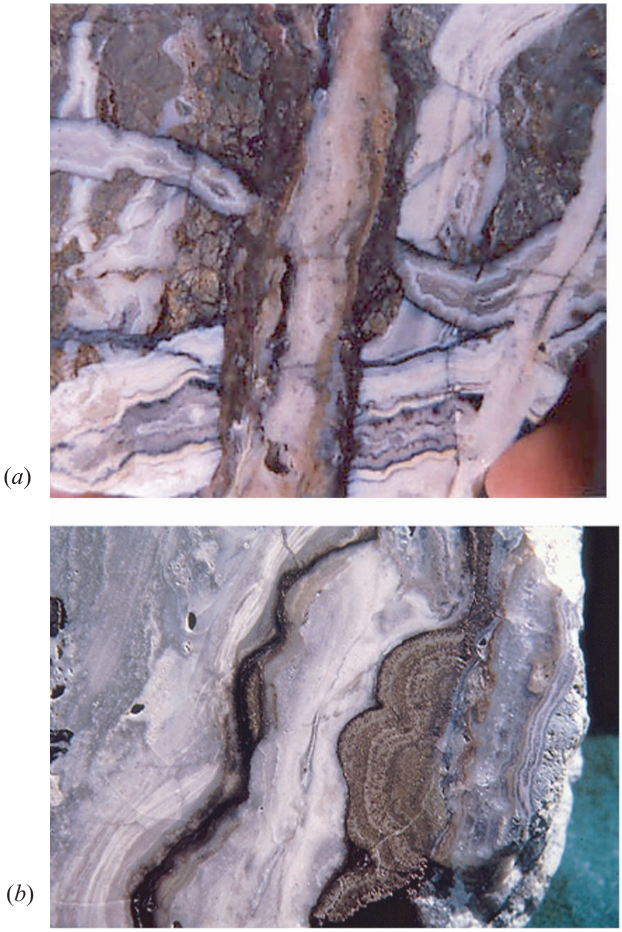

Figure 1 (*a*) Oscillatory laminations in complex cross-cutting veins in the Pliocene McLaughlin gold-silver deposit (California) which is hosted by Cretaceous sedimentary rocks (Sherlock et al 1995). The coloration differences between laminae reflect mineralogical differences involving recrystallized silica polymorphs and adularia. Vein stages and banding are well developed, and the veins are hosted by hydrothermally brecciated altered sediment. Prior to mining there was excellent preservation of the original silica sinter and other surface discharge features from the hydrothermal system, and extensive mercury mining had occurred from these in the last century. How many discrete fracturing and vein filling episodes have occurred? What controls the development of banding and oscillatory lamination in veins? (*b*) Discrete development of silica laminae and colloform masses of gold (brass yellow). What chemical and physical processes control the switch between deposition of silica and gold? How can such processes be so selective in what is deposited at any instant? (Photographs courtesy of R Sherlock. Figure 1*a* has a scale of a few centimeters, and 1*b* about 2 centimeters).

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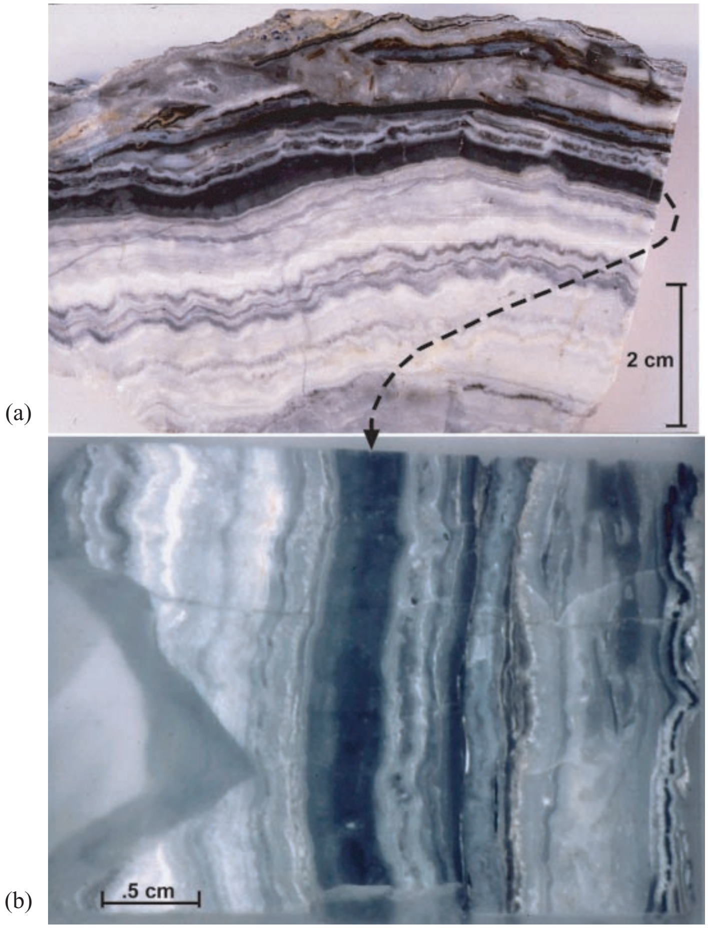

Figure 4 Typical delicate banding and lamination in a sample from an epithermal gold-silver vein at Golden Cross, New Zealand. The lower photograph shows the sub-sample from which laser-ablation ICP scan data were developed (Figure 6). The Golden Cross mine was discovered over a hundred years ago in the Coromandel Peninsula, east of Auckland, New Zealand. The deposit is one of several well-known deposits that include the veins of the Thames district, Kharangahake, and the presently active Martha Mine at Waihi. These deposits all developed in the Pliocene, coincident with felsic volcanism and following the evolution of a Miocene andesite arc. They are associated with the early subduction phase of the arc and are localized along reactivated, approximately arc-normal transfer fault structures that developed coincident with andesite formation. The Golden Cross mine was reopened in 1990 after the discovery of a series of deep high-grade ore zones comprising complex vein arrays (*a*), and has been mined continuously until recently. De Ronde & Blattner (1988), CRJ Simpson et al (1995), and MP Simpson et al (1995) have provided detailed descriptions of the deposit and its setting, along with an interpretation of fluid sources and temperatures based on stable isotope and fluid inclusion data. The sample analyzed (*a*) has a bulk sample grade of about 16 gm/tonne gold and well-defined oscillatory banding and lamination defined by both mineralogy and thickness.

Figure 14 View looking north-northeast at the Bingham Canyon, Utah, porphyry copper mine. At the time of this photograph, the open pit was ~2.5 km wide, and the distance from the bench levels where the picture was taken to the north side of the pit was 3–4 km. Discovered in the 1860s, the Bingham Canyon mining district has had a long history of production, initially of polymetallic Pb-Zn-Ag-Au ores from veins and replacements in Late Paleozoic carbonate and siliclastic rocks intruded by the Eocene Bingham Intrusive Complex. Open-pit mining of the porphyry Cu-Au-Mo ores began in the early 1900s and has continued to the present. With ~3 billion tons of copper ore at 0.67% Cu (Babcock et al 1995), Bingham is one of the giants among porphyry copper deposits worldwide. How do deposits get this large? Why are other deposits of this size lower in copper grade?

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equilibrium or near-equilibrium paradigm as the basis for modeling and interpreting geochemical processes may be appropriate for steady-state long timescale (1–10 Ma) systems such as those recorded by regional-scale metamorphic zonation (Fyfe et al 1958), it is clearly not a well-justified paradigm for the analysis of epizonal mineralization. The imposition of equilibrium as a limiting condition may constrain the models that we develop and preclude us from investigating a rich and exciting range of alternatives related to simple crustal processes. What then are the alternatives to equilibrium or near-equilibrium assumptions in our analysis of epizonal deposits?

EPIZONAL DEPOSITS AND DETERMINISTIC CHAOS

The search for underlying order in unraveling the detailed database for epizonal deposits, the determination of common threads, is traditionally underpinned by a number of simplifying assumptions. First among these is the self-evident assumption that mineral deposit formation occurs within the timescale of hot fluid availability—notwithstanding any subsequent supergene processes that transform sub-grade mineralization into economic ore. Second, it is presumed that fluid composition varies or fluctuates within the timescale of mineral deposition because of external fluctuations in the source of fluids. It is this second assumption that is questioned below through the recognition that perturbations induced by external stress are highly localized within active hydrothermal systems and lead to complex feedback processes and oscillation at the eventual deposit scale. It follows that the timescale of mineral deposit formation is related to the timescales of crustal deformation rather than to the longevity of crustal scale thermal events alone (measured, for example, by the time interval over which particular magmatic suites are intruded).

A third traditional assumption is that the sampling of the products of mineralization provides a reliable base from which to commence the modeling of processes. The underlying principle for fluid inclusion methods, for example, is that inclusions sample and trap fluid at the time of deposition. It is now recognized that selective leakage of components may occur in some settings, so care is required in applying the assumption. However, it is most important to note that for fluid inclusions, isotopes, and parageneses, the sampling assumption is valid only if we constrain our interpretation to determination of fluid composition at the depositional site. There is then the special case that fluid composition at the depositional site is the same as that of the system scale fluid. Is such an equality possible?

For any given hydrothermal system, the dissipation of energy through the crust leads to self-ordered[7] convective flow structures (cf Figure 8) and chemical pat-

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[7] Self-ordered systems are sometimes referred to as dissipative to emphasize that they themselves continually dissipate and redevelop. Convection is a dissipative, self-ordered

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terns within them, such as ‘‘layering’’ of steam-heated and bicarbonate-rich waters. Similarly, the characteristic alteration zonation and mineralization patterns that are used as guides to exploration are also self-organized chemical structures arising from dissipation of solutes within convective systems. Magma generation, migration, and intrusion are parts of lithothermal systems that are similarly self-ordered. They have the additional property of transferring incompatible elements from stressed or mixed mantle lithosphere into the middle and upper crust, where subsequent vapor loss carries some of them further into the hydrothermal regime. Fracture arrays, developed by reactivation of basement structures into overlying younger rock sequences in volcanic terranes or creation of new fault-arrays, are also responsible for localizing both magma emplacement and convective fluid-flow systems; they thus contribute positive feedback within evolving hydrothermal systems. Fracture arrays are themselves emergent or dissipative structures evolved within stressed crust by dispersion of mechanical energy, and have fractal or power law scaling (cf Marrett et al 1999).

Conventional scientific analysis requires that in the absence of randomness, the distribution and scale of deposits are inherently deterministic in time and space. As noted previously (Figure 7), however, it may be argued that the magnitude of mineralization and frequency of occurrence for any particular style of epizonal deposit follow a power law distribution. The distribution, grade, and precise style of hydrothermal ore deposits may therefore be more usefully addressed as the product of crustal systems in a state of deterministic chaos.[8] Well-understood processes such as rock fracturing, fluid expansion, and fluid-rock reactions, for example, are deterministic, but their inter-relationships (and therefore their products) are probabilistic (i.e. chaotic, but not random). In other words, ‘‘the ‘rules’ governing the ‘game’ (of hydrothermal ore formation) are

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structure (Kondepudi & Prigogine 1998). Such systems evolve from a set of initial starting conditions to quite distinctive later states and are highly sensitive to the initial conditions. As an analogy, in a growing sand pile on the verge of instability, once the next sand grain is added there will deterministically develop a self-similar history of avalanches and fractal form, but the occurence of large or small avalanches in time and space is probabilistic (Bak 1997). The sand pile is a dissipative system. Dissipative systems are frequently referred to as dynamical to emphasize their deterministic appearance despite possession of an amount of randomness (Lorenz 1993).

Epizonal deposits may be described similarly in terms of self-similar form and histories. We may presume from observations worldwide that the characteristics and tonnage-grade relations of any given deposit are sensitive to the initial crustal and mantle conditions at the time of ore deposition, as well as to their processes of formation. Such outcomes may be self-similar at a mineral-belt scale because of the scales at which rock sequences and fault systems develop, but may be only self-affine between otherwise similar belts—i.e. similarities are not scale dependent (Mandelbrot 1999).

[8] The emergence of dissipative or self-ordered structures are a characteristic of deterministic chaos. For instructive reviews of chaos theory and terminology, see Schroeder (1990) and Lorenz (1993).

ultimately unpredictable'' (Schroeder 1990). We are thus forced to begin a search for underlying controls on the relations between the scale or magnitude of deposits and their frequency of occurrence and to look carefully at how their processes of formation interact with each other.

Henley & Hoffman (1987) showed that the flux of metal through a hydrothermal system, ΣM_m, could be expressed as the product of terms controlling the permeability of the hydrothermal system, K_p; its total heat transfer via convection, expressed as a function of the thermal gradient across the system, $\Delta\theta$; and the potential of the fluid to transport metals of interest, K_C. The quantum of metal deposited from such a system can then be expressed by including some factor, ε, that describes the time-integrated depositional efficiency of the system

$$\cdot\ \Sigma M_m = \varepsilon f K_p . \Delta\theta K_C . \tag{2}$$

Equation 2 is clearly non-linear because there is strong interdependence of these factors. For example, the total heat flow and fluid flow of a system are related through terms controlling the connected permeability of the system (Equation 1). These, in turn, depend on stress-strain relations of the crustal regime hosting the system. The potential of system fluids (K_C) to transport metals (i.e. relative saturation) is determined by its source characteristics, temperature-dependent rock-fluid interactions, and contributions from magmatic or metamorphic sources, and is therefore a function of $\Delta\theta$. In similar fashion, the efficiency of metal deposition is related through fluid flow to the dynamics of creation and maintenance of system permeability. Such coupling relations (cf Tsang 1999) between processes introduce the possibility of feedback and the amplification or dampening of coupled phenomena within individual systems—a topic to which we shall return in the context of giant ore deposit formation. This behavior infers that the magnitude of a given occurrence is not simply the product of the probabilities of each controlling process. Rather, it is a non-linear product involving conditional probabilities. For the system described in Equation 2, each function is coupled to the others so that, for example, $PK_p . = f\Delta\theta^n$, where P is the conditional probability for the permeability function (K_p) of the system, and n is an exponent that in some cases may be 0. The magnitude of metal transport over time within the system lifetime is then related to a product of conditional probabilities and may be a power function. For deposition to form mineral deposits, the term ε adds another conditional probability governing the efficiency of metal deposition in a set of m sites, where $m > 0$. These relationships then underlie the power law distribution of occurrence scale (Figure 7). Variables in the probability function and small differences in initial conditions, such as rock competence, govern the magnitude of feedback in any given mineral depositing system, and feedback may trigger oscillatory processes and amplification and/or ultimately chaos. In the epizonal context, we would infer from such a multiplicity of distinctive deposits that no level of categorization would be possible because each deposit would be truly unique as a result of the interplay of its formative processes. Instead, the relatively limited number of styles of epizonal deposits is indicative of self-

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ordering at the system and deposit scales. It follows that since mineral deposits emerge from systems in a state of deterministic chaos, questions concerning feedback mechanisms and the influence of initial conditions (i.e. the so-called butterfly effect) become crucial to understanding individual deposits as well as sets of like deposits. In our subsequent discussion of epizonal deposits and the hydrothermal systems within which they form, our goal is to explore how feedback occurs between common physical and chemical processes, and ultimately to glimpse how this may lead to very large, economically attractive deposits.

The Dynamics of Depositional Processes

Convective flow involves the net transfer of mass (i.e. intermixed groundwaters and magmatic vapor and its condensate) across the thermal gradient developed within and by the system. In general terms, a typical system transfers around 10 million tonnes of silica per 10,000 years from within the system to either be deposited in the near surface regime or be dispersed by ground water mixing at the margins of the system. Such mass transfer has prompted a number of authors to suggest that hydrothermal systems are inevitably self-sealing, but this is contradicted by the sustained discharge of systems, pressure data for undisturbed systems, and the observed rapid spread of shallow pressure disturbances over wide areas during exploitation (e.g. Allis 1981). This in turn requires that the permeability-destruction that is inevitable through silica deposition and other water-rock interactions be continuously countermanded by recreation of fracture permeability. The fracture density and style within an active fault system is related to the bulk modulii of the rock suite; these are dictated by initial stratigraphic conditions, and later modified by mineral deposition (silica, K-feldspar, carbonate) and alteration. Positive feedbacks between fluid flow, mineral deposition, rock failure, and heat transfer are therefore localized where fracture arrays are initiated and propagated. Moreover, the relative permeability of rocks adjacent to active faults is dependent on accumulated strain, and may increase by one or two orders of magnitude prior to failure or refracturing (Cox 1995, 1999; Nguyen et al 1998). Contrariwise, strong clay alteration lowers the bulk modulus and provides a negative feedback on fracturing and fluid flow. Given that mineral deposition rapidly changes flow paths and bulk flow through fracture arrays, such feedback therefore provides the dominant control on the localization of mineralizing systems and favorable zones within them for ore deposition (cf Cox 1995, Nyugen et al 1998). This clearly applies to epithermal veins, replacement deposits, and the stockwork zone of VHMS deposits but is likely to be true also for the differing members of igneous rock suites in the porphyry copper environment.

Some of the most striking and elegant periodic phenomena in epizonal deposits develop where such feedbacks occur. In replacement deposits, these occur as a range of textures including bands, rods or blades, and ‘‘bird’s eyes’’ consequent on reactions involving carbonate dissolution adjacent to fractures. In veins, banding, fine-scale oscillations, complex growth phenomena, and intra-mineral com-

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positional variations record incremental stages of vein filling and depositional processes within the vein. Observations of bonanza gold deposition (e.g. Saunders et al 1996) consistently point to the rapid ‘‘blasting’’ of open veins by particulate gold, with the development of colloform textures (e.g. Figure 1*a*,*b*; see color insert.). All of these features point to complex thermo-mechanical-chemical feedback processes and rapid deposition from highly reactive fluids. In turn, the latter suggests that high supersaturations are essential to the processes that generate economic mineralization. As noted previously, however, field evidence commonly shows that metal concentrations in the ambient system fluid are below saturation by a factor of 0.2 or less (Brown 1986, Skinner et al 1967).[9] Localized adiabatic boiling in a dilated fracture over a temperature interval of, say, 200°C yields a vapor fraction of about 40% by mass and results in solute concentration increases of 70%. Even though supersaturation and the initiation of metal or metal sulfide deposition may develop because of changes in solute concentration and concomitant pH changes due to partitioning of acidic gases (such as CO_2) to the vapor phase (Henley & Brown 1985, Henley et al 1984), metal concentrations do not change by more than an order of magnitude in adiabatic boiling. If initial concentrations are ten times lower than saturation prior to boiling, this process is unlikely to yield the high metal supersaturations that are required for fast, efficient metal deposition. How, then, can low initial metal concentrations be amplified in order to account for these phenomena?

The Coupling of Deformation and Chemical Processes

Veins form in discrete transient open spaces within more extensive fracture arrays. Periodic, localized dilation within such arrays is inevitable and is a trigger for vein-forming processes (Sibson 1987, 1992). For an epizonal system whose ambient fluid is initially close to the vapor saturation curve, dilation immediately leads to adiabatic phase separation and lowering of the temperature of the two-phase fluid relative to the wallrock. Because the surface area over which fluid is exposed to hotter rock is large, conductive and diffusive heat transfer occurs across the wallrock vein interface leading to further evaporation of the liquid (Henley & Hughes 2000). Fluid temperature is constrained by the vapor pressure curve rather than the host rock until total evaporation occurs. Such an excess heat effect has been documented for several bore hole discharges in active geothermal fields (cf Christenson & Hayba 1995) and indicated by transient high-salinity fluid inclusions in veins (McInnes et al 1990, Simmons & Browne 1997, Scott & Watanabe 1998).

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[9] Traditionally, it is argued that metal transport occurs at or close to the solubility of the metal (as some designated mineral species). Again, this may be a special case within a more general constraint on modeling ore transport. What is the probability that metal is at that saturation condition during transport?

Figure 12 shows, on a log scale, the steam fraction of fluids that evolve in response to a single dilation event in a fractured porous medium, along with consequent excess heat effects. The scenarios shown are (*a*) isolated veins, (*b*) vein arrays, and (*c*) close-spaced fracture mesh (e.g. stockwork). The increase in concentration of dissolved components relative to the ambient state is also shown. There are two important results:

1. Supersaturation and high reactivity of vein fluids are coupled directly to dilation of the vein-fracture and scale phenomena (e.g. heat transfer) in the fracture mesh feeding into it.
2. The chemistry at any point and time in a vein system is a function of (*a*) the initial chemistry of the fluid and (*b*) the magnitude of the heat transfer from wallrock.

For simple fractured rock scenarios, this excess heat effect suggests that extreme steam fractions close or equal to 1 are commonly achieved as a result of fracture dilation. This is an important result because it accounts for

1. transient anomalies in fluid inclusions salinity and stable isotope compositions in vein fillings (e.g. the composition paradox addressed above);
2. occurrences of metastable precipitates such as opaline silica and colloidal depositional fabrics in settings involving highly dilute system fluids; and
3. oscillatory lamination and paragenetic sequences that may be linked directly to the fracture geometry of the depositional environment.

McNabb & Henley (1998) have suggested that nonhomogeneous distribution of vapor and liquid in the fracture array (i.e. due to the relative volumetric proportions of liquid and vapor) feeding veins may then lead to oscillatory effects that may be preserved as vein lamination. Bogie & Lawless (1999) have argued that these processes may account for oscillatory fabrics at the Waihi epithermal precious metal deposit in New Zealand. As shown in Figure 12, development of steam fractions >0.95 (relative to an adiabatic steam fraction of 0.4) increases solute concentrations by 20 times or more. Silica, initially at saturation and with respect to quartz, may increase from 300 to 6,000 mg/kg, providing the chemical potential for the sequential deposition of metastable silica polytypes such as opaline silica, chalcedony, etc. Even higher steam fractions may develop in highly fractured rocks or by heat exchange between liquid bubbles and flowing vapor. Thus, metal and gangue mineral concentrations may increase by several orders of magnitude; this would enable gold, for example, to transiently increase from 2 ppb to perhaps 2,000 ppb and trigger the nucleation of gold particles (colloid scale) and the consequent depositional process discussed by Saunders et al (1996). Mauk et al (1999) have suggested that the rate of silica deposition is determined by supersaturation and fluid flow rates; the latter is indicative of diffusivity as a critical control on colloid particle size and therefore the morphology of the precipitate. The structural state of adularia laminae also may reflect flow rates.

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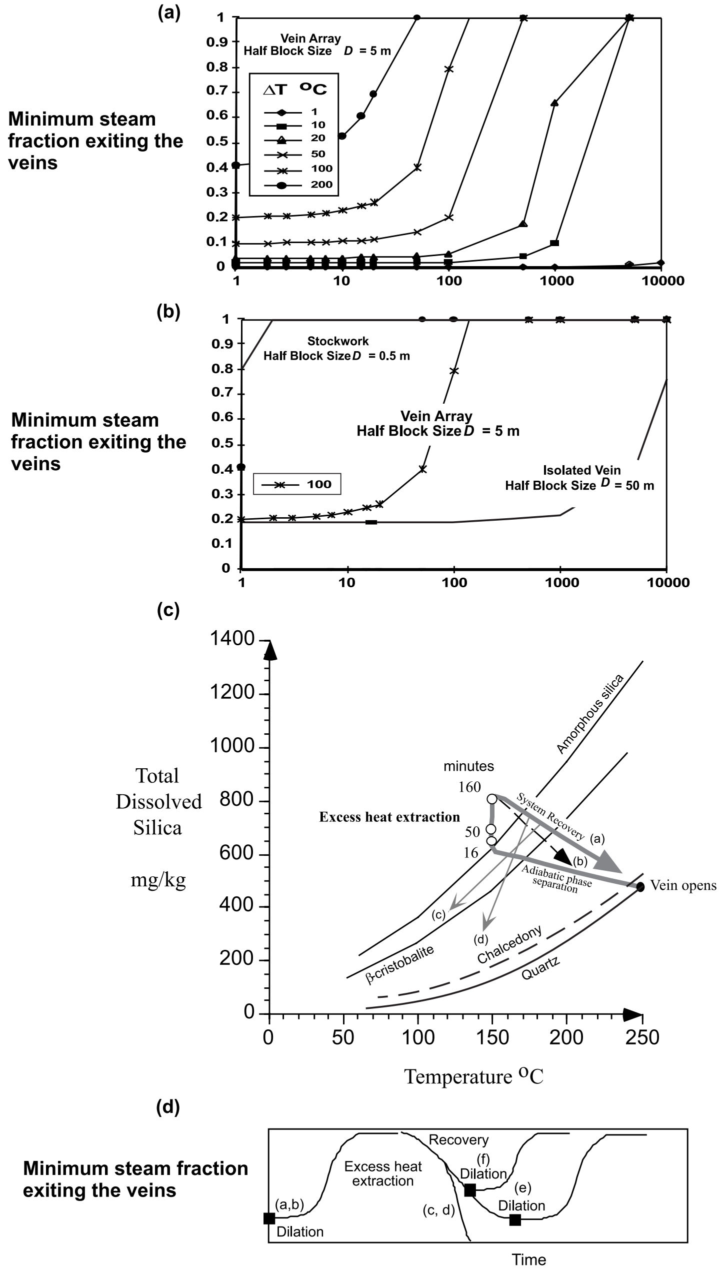

Figure 12

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In a number of mineral districts, high-grade mineralization preferentially occurs at the interface and below distinctive lithologies such as mudstones or basalt flows. These rocks are often considered to ‘‘pond’’ fluids—a terminology quite the opposite of any reflecting the dynamics of ore formation by focused fluid flow coupled with chemical effects such as vigorous boiling or wallrock reaction. Moreover, data for undisturbed hydrothermal systems (McNabb & Dickinson 1995) suggest that stratigraphy does not control pressure distribution. It is more appropriate to recognize that brittle failure is reflected by differences in fracture style between lithologies. Thus, a single fracture in a competent lithology transiently draws flow from underlying, less competent porous units via more extensive fracture networks. This focuses excess heat effects below the interface with the more competent unit. In the analogous Wairakei setting, for example (Figure 9), the most intense mineralization would occur immediately below the mudstone units, and perhaps in competent units within them. The distribution of veins and disseminated gold-silver mineralization at Round Mountain, Nevada, may also be interpreted in this light.

Individual dilation events may therefore account for the banding seen in vein and replacement deposits potentially reflecting the frequency of seismic events, but is there another level of ordering at a finer scale reflected by delicate growth textures and lamination (Figure 1, see color insert; Figures 2 and 3; Figure 4, see color insert)?

Depositional Processes at the Molecular Scale

Heat transfer, two-phase phenomena, and near-vein fracture flow together provide sources of instability in solute concentrations that may become manifest in oscillatory vein textures such as banding. However, finer-scale oscillations are also

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Figure 12 Steam fractions and silica saturation as a function of time for the liquid phase in a two-phase flow in veins following dilation and excess heat extraction from host rocks (Henley & Hughes 2000). (*a*) Comparison of steam fractions exiting a vein array over time (minutes) since dilation (see Henley & Hughes 2000). The feeder array has a half-block size of 5 m, and an array cross-section $A = 10{,}000\ \mathrm{m}^2$ with 5% porosity. The total mass flux is 20 kg/s, giving $M = 2 \times 10^{-3}\ \mathrm{kg/m^2s}$. Curves are plotted for a fracture array of cross-sectional area $A = 10000\ \mathrm{m}^2$ with porosities ϕ of 0.5 and 5% and mass fluxes of 1, 10, and 100 kg/s ($M = 1 \times 10^{-4}$, 1×10^{-3} and $1 \times 10^{-2}\ \mathrm{kg/m^2s}$, respectively). (*b*) Comparison of steam fractions for an isolated vein, a vein array, and a stockwork at $\Delta t = 100^{\circ}\mathrm{C}$ and with the same characteristic modeling parameters as in (*a*). (*c*) Silica concentration as a function of time for the vein array in scenario (*a*). Note that lamination develops only during the recovery stage. (*d*) A sequence of dilation events and consequent steam fraction variations. Fluid mixing (curves *c* and *d*) may also occur as cooler groundwaters flow toward any low-pressure parts of the system developed by outflow, but may be succeeded by longer-term recovery to the initial high-temperature reservoir condition. Each cycle is recorded as a distinctive band comprising several fine-scale laminae of silica polymorphs and/or adularia (see text).

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observed, such as those between adularia and silica laminae, as well as the intermittent metal sulfide and sulfo-salt laminae shown in Figure 6. Such monominerallic laminae may be considered a result of rapid flip-flop between the deposition rates of different minerals. The lamina depositing at any instant and position represents the fastest reacting sub-system of molecules in the chemical system at any given instant. How does such ‘‘switch-on switch-off’’ mineral deposition occur?

In far-from-equilibrium systems, such as those developed by rapid phase separation, equilibrium quotients cease to be the immediate control on system behavior, so that what is deposited at any instant is dependent on which chemical pathway is being followed by the system. Individual depositional reactions are dependent on short-range inter-molecular or inter-species reactions, but ordered instabilities may develop that involve long-range order and the action of the system as a whole—a significant difference to the equilibrium paradigm whereby the state of the system is independent of its size.[10] As noted by Prigogine (1980), the reaction paths are therefore not independent of the history of the system because they are required to be in near-equilibrium scenarios. The chemical pathways adopted by any non-equilibrium set (or ensemble) of molecules when moving through phase space toward a stationary or equilibrium state are essentially unlimited. One of the most intriguing scenarios that arises relates to the potential for occurrence of chemical feedback (i.e. autocatalytic) mechanisms in reacting systems and the development of oscillating self-ordered chemical systems (Prigogine & Stengers 1984, Scott 1993). These are commonly referred to as chemical clocks. Ortoleva (1994), Ortoleva et al (1987a,b), and Wang & Merino (1995) have examined self-organized mineral deposition at low temperatures, and emphasized the importance of relative species diffusivities and the effects of initial non-homogeneity in development of equivalent textures, for example in agate. Both may contribute at the higher temperatures of vein formation.

The oscillatory lamination of adularia and silica in epithermal veins may be examined from this perspective. The overall reaction involved for adularia deposition is

$$3Si(OH)_4 + Al^{3+} + K^+ \rightarrow KAlSi_3O_8 + 4H^+ + 4H_2O,$$

whereas for silica laminae, a simpler overall reaction occurs to SiO_2, (as quartz,

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[10] As a system reacts in response to imposed far-from-equilibrium conditions, species distribution and reaction rates may combine to develop dissipative chemical structures—systems of interacting molecules that generate molecular order, but which themselves dissipate through time. These are termed stationary states. Neither such self-organization nor the resulting products represent the equilibrium state of the system. Fast response may also induce chemical waves through the space occupied by the reactive system. This in turn provides a mechanism for synchronous deposition along veins and a mechanism for development of mineral stratigraphy such as distinctive sphalerite banding and lamination sequencing.

cristobalite, chalcedony or opaline silica) with deposition occurring via development of colloidal-scale particles (Mauk et al 1999). Given the rapidity by which silica and adularia deposit from highly supersaturated geothermal fluids and evidently in veins, we can speculate that some chemical feedback process occurs in addition to the sequence of condensation reactions resulting in polymeric species.

For common species in supersaturated alkaline hydrothermal solutions, these may be written as a sequence of bimolecular reactions such as

1. $Si(OH)_4 \rightarrow SiO(OH)_3^- + H^+$
2. $2SiO(OH)_3^- + Si(OH)_4 \rightarrow 3SiO(OH)_3^- + H^+$
3. $SiO(OH)_3^- \rightarrow SiO_2(OH)_2^{2-} + H^+$
4. $SiO_2(OH)_2^{2-} \rightarrow$ silica or adularia via condensation reactions

In step 2, the silicate ion polymerizes and facilitates further deprotenation of silicic acid thus producing an autocatalytic effect. Silica or adularia deposition then occurs discretely depending on the activity of potassium and aluminum species at the reaction site. The relative diffusivities of aluminium and potassium may, through kinetic feedbacks, then control the development of oscillations, which are preserved as mineralogical and grain-scale laminations. Such a system of reactions can be simulated using general purpose kinetics simulators, such as Markov 5 (BK Selinger, personal communication; Nott & Selinger 1972, Sutherland & Selinger 1995), based on a Markov Chain method with a probability matrix derived from rate equations. Figure 13 shows such a simulation where, with total dissolved silica [as silicic acid, $Si(OH)_4$] and the effective solubilities of the solid phases held constant, instability and oscillation develop and result in silica-adularia lamination. Here we have forced the interpretation based on silicate ions through an analogy with the theoretical Brusselator mechanism (Kondepudi & Prigogine 1998; BK Selinger, personal communication), and in so doing, provide a challenge for the close examination of hydrothermal precipitation mechanisms and experimental simulation. The truth is that despite a wealth of experimental data on hydrothermal solubilities we are no closer to knowing what species are potentially involved in actually forming deposits! Much more information is required to rigorously identify reaction steps; however, this analogy is sufficient to support the proposition that fine-scale mineral layering is kinetically controlled at the molecular scale.[11] This approach contrasts strongly with propositions that discretization of mineral precipitation results from longer-range injections of specific fluids from magmatic sources, for example.

When this approach is taken together with the recognition that excess heat effects are dependent on fracture geometries, it then becomes apparent why individual deposits each have distinctive banding and lamination patterns. The patterns reflect the unique fracture flow and heat transfer properties of the host rock.

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[11] In some cases, hyperthermophyllic microorganisms may play a critical kinetic role (KL Brown, personal communication).

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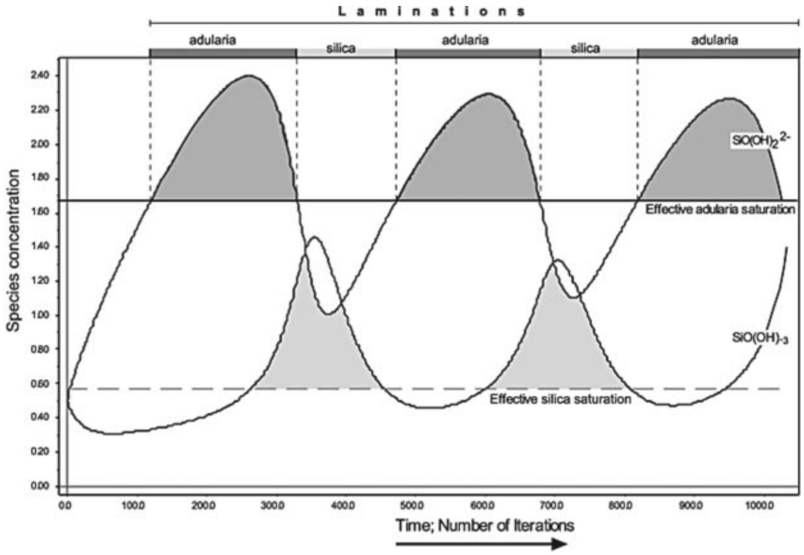

Figure 13 Simulation of possible oscillations in reactive species concentrations involved in silica and adularia deposition following a vein dilation event. Whereas excess heat effects increase overall solute concentrations, kinetically controlled cycling of reactive species controls mineral deposition to develop fine-scale oscillatory fabrics. By drawing a possible analogy with the Brusselator reaction sequence (see references in text), it is possible to qualitatively compare the modeled concentrations of silicic acid and silicate species with relative solubilities for adularia and silica. In turn, this provides a concept for the development of oscillatory lamination of the kind shown in Plate 3. Such oscillatory lamination is then seen as a consequence of local effects such as excess heat transfer and fracture geometries specific to the vein context, rather than any larger-scale oscillation related to fluid sources for the system.

Perhaps the complexity of lamination fabric, in turn, reflects mineral grade? Interestingly, high-grade zones in some epithermal deposits have associated anomalous gangue minerals. Reyerite ($[Na,K]_4Ca_{14}(Si,Al)Si_{24}O_{60}(OH)_5, 5H_2O$) occurs at Hishikari, Japan and Lebong Donok, Sumatra, (Henley 1991), perhaps reflecting extreme supersaturation conditions; also, the occurrence of roscoelite (vanadium-mica) at Porgera, Papua New Guinea (Cameron 1998) may indicate how the excess heat effect amplifies trace metal concentrations derived from local rocks. Corrosive textures are commonly seen in laminated silica-adularia veins, again showing how chemical pathways flip-flop across depositional boundaries.

Gold is often associated with a range of sulfides and sulfo-salts, and requires some set of redox reactions to control deposition. Our starting assumption in discussing deposition is that reaction rates are likely to be related to the concentrations of the more reactive (less stable, lower-abundance) complex species, rather than to the most abundant, most stable species. For example, it is perhaps

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more reasonable to assume that for fast gold deposition to occur, aurous ions (Au^{+}_{aq}), one of the least abundant species in the ensemble, are reduced to gold in response to electrochemical changes, rather than to assume that the dominant gold species, $Au(HS)^{2-}$, simultaneously loses both protonated sulfur ligands. The more stable and therefore higher-concentration aurous species then disproportionate rapidly toward reestablishing equilibrium between the complexes or cycling through some stationary state.

Although dissipative chemical structures have been observed to develop through such electrochemical processes, very little is known about them (Goldberg & Kheifets 1992). A series of experiments on pyrite precipitation at elevated temperatures by Schoonen & Barnes (1991) illustrate the most probable sulfide deposition mechanisms that take place in most environments. Schoonen & Barnes (1991) found that, in the temperature range of 250–300°C, pyrite nucleation is fast when there is initial development of metastable FeS*(s). This implies that Fe^{2+} becomes available (from, say, Fe-aluminosilicate alteration reactions) and first reacts with dissolved sulfur

$$Fe^{2+}(aq) + H_2S \rightarrow FeS^* + 2H +$$

to yield the intermediate product FeS*(s), and then

$$FeS^* + H_2S \rightarrow FeS_2 + 2H$$

liberates hydrogen(H). The simplest possible gold deposition reaction may then be coupled to the formation of pyrite, as is commonly observed in auriferous pyrite:

$$Au^+ + H \leftrightarrow Au + H^+.$$

Oscillation in this reaction sequence may occur through the development of nonhomogenous species distributions because of imperfect mixing (Epstein 1995), the relative diffusivities (for example, the diffusivity of iron from alteration sites), or autocatalytic reactions between reduced sulfur species under far-from-equilibrium conditions. The correlations in element deposition that are shown in a scan of an epithermal vein (Figure 6) may result from such reaction coupling, with particular mineral species a consequence. Coherent destabilization of metals (e.g. silver, arsenic, sulfur, antimony, etc) may then account for the more exotic sulfo-salts that occur in veins without requiring that we invoke exotic solutions to account for them. Thompson & Arehart (1990) speculated that the banding in replacement style ores in the Leadville district, Colorado resulted from autocatalytic reactions. Cameron (1998) has documented dissolution of auriferous sulfide from early high-grade vein material at Porgera, Papua New Guinea, again indicating the flip-flop from supersaturated to undersaturated conditions during vein formation.

Sulfide replacement and pyrite formation rates may also be dependent on oscillations in a redox state manifested by the concentration of thiosulfate (Howd & Barnes 1975, Schoonen & Barnes 1991); recent data (Dadze & Sorokin 1993)

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suggest that may be more common in hydrothermal systems than generally assumed. Kucha & Viaene (1991) and Kucha & Piestrzynski (1991), for example, report inclusions of thiosulfate and sulfite within carbonate rock-hosted banded sulfides, including sphalerite, galena, and chalcopyrite, from several localities in Europe. This then allows us to propose that oscillatory sulfide fabrics in ore environments are also controlled by the diffusivities of thiosulfate and hydrogen ions. Although the experimental data for thiosulfate and polythionates under higher-temperature hydrothermal conditions are limited, it is possible to consider a range of possible reactions to produce them as transient species.

Thiosulfate and polythionate are the more likely available reactants in natural hydrothermal systems because of the slightly acid pHs of these systems (Giggenbach 1974a,b). Schoonen & Barnes (1991) found that the rate of pyrite formation from FeS*(s) is highly dependent on an intermediate reacting sulfur species—elemental sulfur, polysulfides, thiosulfate, H_2S, or HS^-. The first three species cause a much faster conversion than either H_2S or HS^- (cf Schoonen & Barnes, 1991):

$$\mathrm{FeS^*(s)} + \mathrm{S_2O_3^{2-}} \rightarrow \mathrm{FeS_2} + \mathrm{SO_3^{2-}}.$$

The interactions of complex polysulfide intermediate species potentially contribute to the establishment of autocatalytic reaction sequences (Nicolis & Prigogine 1977) in sulfide-depositing systems. We suggest that the precipitation of other sulfides such as sphalerite and chalcopyrite (cf Cowper & Rickard 1989) are also path dependent and proceed according to similar reaction mechanisms. Chalcopyrite and gold are co-precipitants in epizonal deposits over a much wider temperature range, perhaps as high as 600°C in porphyry copper-gold deposits. This latter setting is interesting, given the relation to active magma degassing and availability of SO_2 to potentially provide thiosulfate species.

Upon cursory examination, the relative simplicity of the base-metal depositional reactions seems to provide little scope for developing the kind of oscillatory reaction sequences discussed above. Pseudo-eutectic and zebroid sphalerite-galena textures are common, however, and indicative of co-precipitation in replacement deposits. Because base metals require relatively high salinities for significant metal transport (Henley 1985), a synoptic depositional reaction is

$$\mathrm{ZnCl_2} + \mathrm{H_2S} \rightarrow \mathrm{ZnS} + 2\mathrm{H^+} + 2\mathrm{Cl^-}.$$

H^+ is an important species such that the depositional reaction may be coupled through removal of H^+ to the dissolution of carbonate, and far-from-equilibrium reactions between sulfur species may also induce oscillatory precipitation.

The fine-scale oscillatory fabrics observed in epithermal vein and replacement deposits potentially provide clues to chemical mechanisms and feedback processes at the molecular scale. Molecular diffusivity and autocatalysis in chemical systems that have been driven far-from-equilibrium may be considered one of the most important controls that arises on depositional mechanisms and resulting textures, such as delicate growth structure and oscillatory fabrics (cf. Wang &

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Merino 1992); this may also account for the coherence in metal deposition responsible for mineral stratigraphy along individual veins [e.g. the OH vein, Creede, Colorado (Barton et al 1977)].[12] Interestingly, in a vein, the relative mass of ore and non-ore components determines the grade. It follows that if ore deposition occurs from fluids that have been locally and transiently evolved to a highly reactive, far-from-equilibrium state, we must accept that reaction kinetics provide significant controls on the grade, as well as the parageneses and texture of ores. The latter are determinants on extractive metallurgy and therefore the economics of exploitation of a given deposit.

To summarize, the chemical responses of hydrothermal fluids to coupled processes involving heat and mass transfer are fast and efficient. They result in monomineralic veins and fracture fillings, exotic mineralogies, and sometimes cycles of deposition in all kinds of epizonal deposits. Fine-scale mineral laminae and oscillations may be attributed to fast molecular scale processes over timescales of much less than a year. Sets of laminae or bands reflect individual mineralization events (perhaps associated with deformation of a fracture array) and the geometry and physical properties of the environment of deposition. Stages, composed of bands, record longer time-scale variations in the chemical and thermal properties of the system and how it responds to localized stress release.

PERSPECTIVES ON EPIZONAL DEPOSITS

In previous sections, the processes that form deposits have been discussed, with emphasis on how they may be coupled over a range of scales and how complex oscillatory fabrics may develop. The extent to which feedback occurs between processes determines the characteristics of the deposit that forms, as well as the eventual size and form of the deposit. Feedback processes are probabilistic, but individual characteristics are the outcome of the deterministic processes that are involved. As a result, there simply is no single prescriptive element within the geology of a deposit, or its geochemical or geophysical expression, that determines whether it is a giant or simply an interesting prospect. By contrast, it is traditionally assumed that certain deterministic indicators (e.g. observations of brecciation style or the primary geochemistry of host rocks) must be able to predict the economic potential of a deposit, if only we could recognize them. Experience shows that this is certainly not the case, even with the impressive range of modern mapping, sampling, and data analysis techniques at our disposal. Perspectives on how selected deposits evolve are provided in this section, with emphasis on why certain deposits are so much larger than others.

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[12] Consider two cogenetic veins. At a sample point in each, vein material shows a similar paragenesis of chalcopyrite, followed by sphalerite and then galena. Were the two samples formed at exactly the same time, or were they formed at quite different times by the similar chemical response to separate dilation events on the fractures?

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Feedback: Keys to Giantism

Much that has been written and collated on the origin of giant mineral deposits has focused on defining key determinants of hydrothermal systems and their host rocks that might control giantism. Thus, tectonic setting, magma chemistry, and so on have each from time to time been deemed to be such determinants. However, Sillitoe (1992) and Clarke (1992), among others, have been forced to conclude that ‘‘unusually large porphyry copper deposits are not anatomically distinctive,’’ and that ‘‘we are a long way from defining the requisite package of large scale lithotectonic criteria.’’ What, then, are the factors or processes that determine the ultimate size and grade of an ore deposit?

The distributions of occurrence scale for epizonal deposits appear to follow power laws indicating first a similarity of genetic processes across all scales, rather than any uniqueness in the genetic processes responsible for giant deposits, and second the importance of feedback in achieving size. It is then important to recognize that the fabrics and textures observed indicate that the formation of epizonal deposits occurs incrementally. Giant deposits may also be considered to develop through myriad small steps that are spatially focused by feedback mechanisms, rather than originating through some single sustained event. Expressed in this way, we change the question of giantism from ‘‘How do anomalous epizonal systems develop?’’ (e.g. perhaps some specific source rock chemistry), to ‘‘How may multiple increments of efficient mineral deposition be focused in normal epizonal systems, and what small event triggers a cascade of increments to be focused in the one place?’’ Which butterfly flapped its wings to initiate, for example, the formation of a giant deposition Lihir Island (Papua New Guinea)? Here, at the Ladolam deposit, this occurred through sector collapse of the preexisting Luise volcanic cone, perhaps as a result of movement on faults controlling the location of magmatism. However, the flow focusing was amplified by dissolution of matrix anhydrite deposited in the undisturbed preexisting hydrothermal system, and by the Ghyben-Hertzburg buoyancy effect squeezing hot groundwater above denser cooler sea water (Henley & Etheridge 1995). For Ladolam, as well as for several other deposits, it was not a catastophic event such as volcano collapse that caused a giant deposit to form, it was the feedback between consequent events that resulted in giantism.

It is an important characteristic of chaotic systems that tiny influences, such as a small difference in initial rock competence, can suddenly become amplified in a way that transforms the system. Such sensitivity to initial conditions determines whether a given epizonal system may become a giant deposit or whether it remains a tantalizing, low-grade prospect. Competence contrasts, for example, are expressed as distinct rock fabrics and mineralogy. These small differences lead to different failure modes between rocks, become amplified as alteration processes involving reactive fluid occur, and then focus ongoing brittle failure and consequent mineralization. The three cameos that follow are designed to

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highlight feedback processes and the influence of initial conditions on the formation of economically viable deposits.

Cameos

Porphyry copper-gold deposits: incremental greatness Porphyry copper deposits are large tonnage deposits developed within intermediate intrusions and their country rock carapaces. They are giants in the context of total contained metals, and some, such as Grasberg, Irian Jaya, Indonesia, and Bingham Canyon, Utah, are orders of magnitude larger than others (Figure 14, see color insert). Metal grades at the deposit scale, however, are not as spectacular relative to normal crustal abundances because they are in epithermal and replacement-style epizonal deposits. What influences and controls the scale of these deposits?

Porphyry deposits are clearly associated spatially and temporally with ongoing volcanism and the evolution of sub-volcanic intrusive complexes (Gustafson & Hunt 1975, Sillitoe 1973); the localization of magma emplacement and hydrothermal activity by active strike-slip and reactivated fault systems has already been noted. They occur as complex asymmetric fracture arrays over a range of different scales, as stockworks and as breccia bodies (Sillitoe, 1973, 1991), and are characterized by well-developed alteration zonation that extends well beyond economic mineralization. Stable isotope and paragenetic information strongly suggests that mineralization occurs from magmatically derived fluid, in contrast to the dominantly groundwater-derived fluids that form other epizonal vein deposits.

Much of the popular genetic debate for these deposits ignores the important role of structural history in porphyry deposit formation and focuses on how magma genesis and fluid exsolution from evolved intrusions provide the source of metals and the immediate cause of giantism. It may be argued, however, that the principal source of metals and magmatic fluids may be the magma source regime, rather than the host intrusion, so that the latter plays a passive role. Thus, it is well known that the form of an intrusion is dependent on the interplay of magma pressure transmitted from the magma source and the deviatoric stresses existing or developing in the brittle crust. The complex topology of cupolas developed by this interplay imposes additional heterogeneity into the crust (Gudmundsson 1998), strongly influencing subsequent brittle failure history, heat loss, fluid flow, and consequent mineralization. This provides an important feedback relation, particularly in determining the subsequent distribution and magnitude of porphyry mineralization (BR Berger, unpublished data).

Cox (1999) has emphasized the importance of fluid pressure and shear stress in determining the style of fracturing in mesothermal or shear-zone deposits. This is equally important in the porphyry environment where fluid pressure is related to crystallization stages in the intrusion or deeper fluid generation in the source regime (Burnham 1979). In porphyry copper deposits, the earliest fractures are short millimeter- and centimeter-scale tensile fractures and relatively scarce

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longer shear fractures (BR Berger, unpublished data). These are succeeded by later, longer shear fractures, and where these dominate fracturing, deposits tend to be of lower grade. In many cases, the fractures are only barely traceable in thin sections through contiguous ore mineral sites because of rapid annealing at magmatic temperatures and subsequent alteration. The stress regime within which this mesh developed in porphyry deposits may sometimes be interpreted from fracture mapping (Heidrick & Titley 1982) or analysis of detailed grade information (Stanley et al 1995). These observations suggest that while regional scale faulting controls magma emplacement and large-scale fluid flow, the early evolution of mineralized stockworks is controlled by stress release internal to intrusions and their carapace. By implication, stress release on the controlling faults over a different timescale may enhance fracture linkage and the development of a connected fracture array through to the surrounding hydrothermal system. The timing of formation of this linkage becomes crucial to the development of either a large porphyry deposit or large vein and replacement deposits. We suggest that the complex small-scale fracture arrays that typify high-grade porphyry deposits represent the interaction of fracture tips during fracture propagation (cf Olson & Pollard 1989).

Giantism in porphyry-style deposits is determined by the product of ore tonnage (i.e. size) and mineralization grade. The competence of host rocks determines their response to internal and external stress (Fialko & Rubin 1997), so this initial condition is crucial to the development of confined stockworks and fracture arrays—i.e. the tonnage of the deposit. In turn, these are influenced by the form of intrusions and external strain rate. The geometry and therefore tonnage of the deposit is the integral of successive increments of brittle failure, whereas the grade distribution records the efficiency of mineral deposition, fracture by fracture, during the generation of the deposit. Each local increment of dilation within and of the fracture mesh provides a transient ‘‘micro-reactor’’ within which decompression of the ambient low-salinity vapor occurs; this leads to separation of high-salinity liquid along with localized excess heat effects, both eventuating in highly efficient deposition of ore and gangue components (Figure 10). Examined in this way, the complex feedbacks between magma emplacement, magmatic fluid release, and internal and external stress release become clearer. These are the processes that lead to the power law distribution of contained metals in porphyry systems (Figure 7). Dissipative processes involved in magma generation may lead to periodicity and add another dimension to the problem (Shaw 1991).

Giant epithermal precious metal deposits: the Comstock Lode, Nevada In contrast to porphyry deposits, giantism in epithermal vein deposits is controlled by grade rather than tonnage. This requires highly efficient and focused mineral deposition. How does such focusing occur in vein settings? The Comstock Lode, Virginia City, Nevada, with production of over 8 million ounces of gold and 170 million ounces of silver, is a giant among epithermal deposits worldwide. The deposit is related to a Miocene volcanic field and is localized along one sidewall

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of an extensional duplex linking en échelon strike-slip faults (Berger 1996). The contrasts between sub-economic veins and ore bodies in the Comstock Lode highlight the interactions between thermal, mechanical, and hydraulic phenomena in the generation of giant epithermal vein deposits.

Fluid-inclusion data (Vikre 1989) may be interpreted to show that there was no substantive difference between the primary fluid composition and temperature of the fluid that formed the sub-economic mineralization, and that which formed the bonanza ores at Comstock. What did differ between the general veins and bonanza ores was the nature of the fracture permeability of the host rocks through which the fluids flowed. The sub-economic mineralization comprises thick, continuous sequences and anastomosing swarms of well-banded veins that originally extended along the extensional Comstock fault for ∼3 km. By contrast, the economic and bonanza ores were deposited while the Comstock fault and the contained veins were subsequently being deformed by cross-basin strike-slip faults. The ore bodies are hosted by the earlier stage vein material that was ground to the grain size of granulated sugar during deformation (King 1870), and occur in lozenge-shaped pipes or chimneys developed in narrow zones of extension. The deformation also created thick clay seams in the country rock surrounding the granulated vein material, and these clay seams average nearly 0.5 m in thickness. Thus, deformation directly localized the zones of high permeability, increased the fracture density, triggered excess heat transfers and interconnectivity, and constrained lateral flow in the system as a result of the clay seams. Because early-stage mineralization does not differ significantly in composition from bonanza ores, and fluid inclusion data for both sets are similar (cf Vikre 1989), the feedback between deformation and ore formation also had to have had a dramatic effect on the ore-depositing efficiency of the hydrothermal fluid. Granulation of earlier brittle vein material provided for optimum heat transfer during fluid decompression as new veins formed.

The opposite case of negative feedback due to alteration occurs at Temora and Peak Hill, New South Wales (Australia). In these deposits, intense ductile advanced argillic clay alteration constrained mineralization to highly localized zones of silicification along shears, resulting in relatively small dispersed deposits with consequent mining difficulty (Allibone et al 1995, Allibone 1998).

Polymetallic replacement deposits: chemical trapping Polymetallic vein and replacement deposits are commonplace in regions where epizonal magmas intrude continental basement terranes and overlying miogeoclinal rocks, such as in the Cordilleras of North and South America and the Paleozoic magmatic arcs of Central Asia. Although not giants in comparison with other styles of mineralization, the deposits are generally valuable for Zn, Pb, Cu, Ag, and Au (Beaty et al 1990). The most valuable ores in this style of deposit occur as replacements of carbonate rocks within active fault zones—for example, upward-branching strike-slip faults, in the Leadville, Colorado district or within pull-apart structures in the Tintic, Utah district (cf Lindgren & Loughlin 1919).

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In vein deposits of all types, there is a negative feedback between fluid flux and mineral deposition countermanded by periodic brittle failure. In replacement deposits, repetitive brittle failure consequent on active faulting occurs, but carbonate dissolution of host rock couples with brittle failure to enhance fracture-related permeability. ‘‘Dirty’’ carbonate rocks such as marls are commonly productive host rocks because the mixture of silicate minerals in the carbonate matrix facilitates the development of interconnected pore space in the same way that selective dissolution occurs in the host rocks of the Carlin district (Bakken & Einaudi 1986). The rates of pore formation and growth are controlled by dissolution and deposition rate (Rege & Fogler 1989), and therefore by the diffusivities of reactants and products.

At Leadville, granitoid sills formed in a compressive regime within the host strike-slip fault system prior to mineralization. By contrast, many of the veins developed in faults with normal displacement and negative flower structures, which indicates that ore formation was related to a change in the orientation of principal stresses resulting in fault reactivation during hydrothermal activity (cf Emmons et al 1927). Vein-form ore bodies occur preferentially in interbedded carbonate and quartzite units while veins pinch down considerably in shale and porphyry. Mineralization on faults occurs in the sheeted damage zones adjacent to or between gouge zones. Granular masses best characterize the vein ores, although banded or crustified structures occur. At Tintic, Utah (Lindgren & Loughlin 1919) and Lake City, Colorado (Irving & Bancroft 1911), polymetallic veins occur within extending fault zones, and in plan, develop mesh-like patterns. Where mineralized fractures encounter favorably oriented carbonate-bearing beds, vein ores effectively disappear and mantos or blanket ores form (Emmons et al 1927). Mantos follow specific sets of beds, and favorable facies without low-permeability ‘‘cappings’’ of porphyry sills or shale horizons allowed the solutions to escape upward along mineralized vertical fractures, where replacement blankets again occur beneath such low-permeability ‘‘caps.’’ Replacement zones follow generally restricted trends (one to two), probably controlled by the near-field principal stresses. Parallel replacement walls in many ore bodies underscore the importance of favorably oriented replaceable horizons. Thick zones of permeable rocks result in more tabular ore bodies. Emmons et al (1927, p. 191) compare the form of ore bodies to the ‘‘general form of the caves that have formed by solution of limestone by underground streams.’’ The lamellar textures of massive replacement ores pseudomorphic of the host-rock laminations (Figure 2) imply that banding is closely related to carbonate dissolution. In addition to finely laminated ores, spherical or ellipsoidal banded ores are also common.

Models for the formation of replacement deposits commonly focus on relatively passive processes such as the migration of reaction fronts (e.g. Ortoleva 1994). The importance of syn-mineralization faulting, however, permits a more dynamic interpretation. In addition, by analogy with the cappings in epithermal deposits, efficient metal deposition may result from periodic decompression dur-

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ing fracture dilation. Thus, secondary porosity develops by carbonate dissolution as fluid pressure increases prior to failure,

$$\mathrm{Ca\ CO_3 + H_2O + CO_2 \rightarrow Ca^{++} + 2HCO_3^-},$$

but on decompression,

$$\mathrm{Zn^{++} + H_2S + 2HCO_3^- \rightarrow ZnS + CO_2 + H_2O}.$$

The scale of replacement deposits is therefore determined by initial conditions: the competence and reactivity contrasts of heterogenous carbonate facies rocks, lithological discontinuities, and the behavior of preexisting faults during continued or renewed stress. Decompression following fault failure also promotes a range of mixing possibilities between formation fluids and evolved system fluids, and therefore distinctive ore occurrences.

CONCLUSION

Hydrothermal ore deposits are emergent self-organized phenomena whose formation is a consequence of structurally localized perturbations within crustal scale hydrothermal systems. These complex dynamical systems are generated by the coupling of deformation, magmatism, groundwater flow, and magmatic vapor interactions over a wide range of scales from the molecular to the regional. Epizonal mineralization characteristically develops incrementally through the complex interaction of a range of short timescale processes resulting from phase separation effects, consequent heat transfer and fluid flow effects, and molecular scale interactions between solutes and reactive host rocks. Such interactions lead to non-linear feedback processes between fluid and host rock and the potential to amplify small differences in rock properties, for example, through to the formation of giant metal deposits, as well as to the diversity between deposits of similar style.

The concepts of feedback, self-ordering, and far-from equilibrium processes triggered by stress release provide us with powerful guiding principles through which to explore the complexity of ore formation at the system, deposit, and grain scale. Mineral parageneses and fabrics are seen as dependent on the length scales operative in the localized depositional regime of the system and the interplay of reaction kinetics, rather than necessarily reflecting any time evolution of the bulk fluid chemistry of the system responsible for transport of metals. These concepts also challenge some established basic assumptions in interpreting diagnostic data, such as fluid inclusion data, from hydrothermal ore deposits. For example, if homogenization temperatures from individual inclusions in a single band of quartz truly reflect the thermal conditions at the sample site at the time of deposition, then the range of measured temperatures is itself a record of the dynamical behavior of the system and the fluctuations induced locally in response to fault movements. The nature of this record provides the clues to the processes occurring during ore formation and is of far greater importance in ore genesis studies than an average homogenization temperature or apparent salinity. To understand porphyry deposits, it becomes crucial to acknowledge that the brine inclusions observed in them may be artifacts of the depositional process, rather than representative of the ambient fluid in the system or expelled from magmas. Stable isotope data may also require re-examination in the light of far-from-equilibrium processes; transient enrichment in a heavy isotope, for example, may indicate evaporative effects rather than introduction of a magmatic fluid (e.g. Scott & Watanabe 1998).

The recognition of the complex, interactive properties and inherent unpredictability of ore-forming systems is not a catastrophe for explorationists. It has often been stated that large deposits form where an inventory of ingredients occur together. The step taken here is to recognize the processes, their coupling, and the probabilistic context rather than assuming a linear or additive relationship between certain ingredients. Because the magnitude of deposits can be recognized as having a power law distribution, the process of exploration and assessment becomes one of careful risk management. This recognition makes it possible to link geologic probability to investment analysis at all steps in the process of exploration. As shown in Figure 7, the probability of any single occurrence of, say, porphyry mineralization being economic is at best one in 10^3 or 10^4. Managing investment in exploration therefore requires that we focus academically and professionally on understanding these dynamical systems and their feedback processes over a range of scales. This approach potentially underpins a sounder basis for understanding the variation of metal grade within deposits and their dimensions, and may thence influence our mining, grade control, and reserve estimation practices. Similarly, by focusing on the problem of the interactive processes involved in how ore is formed and determining the ultimate scale of an evolving deposit, we may also better structure key observational data into our exploration decision processes. Thus we know that small competency differences are reflected in the propensity of certain rocks to host ore bodies, and we pragmatically identify this by focusing exploration on specific host rocks. However, the lithological association may lead us to believe in a causative relation rather than to examine its distinctive physical properties. Specific members of igneous suites may be interpreted this way, such that exploration traditionally fans out looking for equivalent intrusives, rather than focusing on how the mineralized rock sequence has developed fractures and then focused flow to localize mineral deposition. For example, discontinuities in rock properties and consequent focused heat transfer effects during deformation may localize bonanza mineralization. The Porgera gold deposit (Papua New Guinea), for example, is located immediately below the regional-scale 1200 m-thick Dari Limestone (Cameron 1998). In the Carlin district, detailed mapping and logging have enabled costly deep drilling to locate discrete ore bodies closely associated with the interfaces of distinct lithologies (Vikre et al 1997). Heterogeneous igneous rock compositions evolve during magma mixing and cooling, and develop distinctive textures (such as porphyritic

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in contrast to aphanitic texture) that have different bulk-rock moduli. Likewise, as composite materials, different varieties of breccia may have a different propensity for mineralization as a result of their response to stress. To rephrase, a given style of breccia may have a greater probability of hosting mineralization, when effected by faulting, than another lithology, but exploration seldom is represented in this probabilistic way. The practical approach to exploration then becomes one of calibration of rock behavior within a district so that it becomes predictive, at least in a probabilistic sense. But at what scale do rock properties trigger feedback to occur? Or is it the sequencing of rock units that provides a greater control, as perhaps is indicated by the occurrence of ore deposits at major lithological boundaries?

Perhaps the most common means of achieving feedback between fracturing, hydrothermal activity, and consequent mineralization is the reactivation of earlier fault systems and their interaction, in the upper crust, with new fault arrays (e.g. Henley & Etheridge 1995). In each case, episodic release of fluid pressure or rock stress initiates and focuses deposit formation. Understanding the histories and geometries of fault systems over a range of scales then becomes a powerful tool for targeted mineral exploration.

Notwithstanding their past and future economic significance, epizonal deposits carry their own intrinsic beauty in their form, their distribution, and the delicacy of the characteristic textures that develop within them under extreme conditions. The intent of this review has been to highlight these aspects of the dynamical systems responsible for mineral deposits and encourage a less reductionist approach to the understanding of, and thus the exploration for, epizonal mineral deposits. In so doing, we hope to have raised more questions than we have provided answers. For example, complex, dynamical systems may often be quantified such that some characteristic “attractor” can be recognized within their phase space (i.e. their modeling parameters). Is it possible to conceive that self-organized phenomena such as metal deposits are related to some attractor? If so, how would we search for it? Would the parameters emerge, for example, from the coupling of rates of stress and thermal energy dissipation in hydrothermal systems? Understanding epizonal deposits in their own right,[13] rather than their economic context, may then become recognized as a cornerstone in further developing our understanding of the history of the earth and its geochemistry.

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[13] The economic connotations of epizonal deposits provide both opportunities for their investigation and limitations on their scientific study. All too often the minerals industry is charged with the task of funding the basic pure research required to progress our knowledge of them.

Sellinger, have helped us sharpen our thinking to its present dissipative state! Philip Henley, Ross Wylde-Brown, and Larisa North provided invaluable support in editing and graphics. Don Singer kindly provided access to data sets for epizonal deposits and provided stimulating discussion.

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