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A Special Issue on the Timing and Duration of Hydrothermal Events

Preface

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WHY would anyone spend their time dating or modeling ore deposits? In a society where "timing is everything" and "computers are king," it seems a bit curious to even ask this question. As geoscientists, however, we know the value of dating in determining the genesis of ore deposits. For example, we are well aware how our long-standing difficulties in dating Mississippi Valley-type Pb-Zn deposits have limited our ability to relate them causally to other geologic events. And, although we all probably still tend to the intuitive view that a fully adequate amount of time must always be available to make something as valuable as an ore deposit, as this issue will emphasize, we now must recognize that ore-forming episodes may be but brief punctuations within much longer lived geologic cycles.

This century has seen the development, but not necessarily the confluence, of two technologies that powerfully address the timing and duration issues: radiometric dating and computer modeling. The measurement and calculation of absolute geologic time became possible with the invention of mass spectrometry. For the first time, geologic events could be discussed in an absolute sense relative to one another. Initially, knowledge of the correct decay constants for parent isotopes was a limitation in providing accurate age information. More recently, we have been able to produce not only accurate but also highly precise ages that can resolve even the most subsidiary perturbations within the larger geologic scheme. This thinner and thinner slicing of geologic time has been possible with low blank laboratories and continually advancing mass spectrometry. Our appetite for precision will probably always exceed our technological capabilities, but the precisions now possible with modern techniques are truly astounding, particularly to those who have not closely followed (and been frustrated by involvement in) rapidly developing fields in geochronology. As an example pertinent to this volume, one need only look at the recent explosion of papers in the literature demonstrating the direct and highly precise dating of ores using the Re-Os method. The Re-Os method is the only radiometric dating tool that can be applied to suites of cogenetic sulfide and/or oxide minerals, typically characterized by highly variable Re/Os ratios, thereby permitting better isochron resolution and more precise age determinations. At the same time, computer modeling techniques (with their own set of internal annoyances) have developed to the point where we can now realistically incorporate into models precise radiometric ages and the complicated patterns of intrusion and faulting provided by geologic mapping. These numerical models will be particularly effective in establishing and testing causative connections in ore-forming processes.

It is within this context that the papers in this special issue of *Economic Geology* are offered. The papers are based largely on presentations made at a Society of Economic Geologists' symposium on "The Timing and Duration of Hydrothermal Events," held November 8, 1995, in New Orleans. The symposium sought to assess and compare estimates of the duration of hydrothermal events derived from numerical modeling with results derived from radiometric age determinations. The symposium theme arose in part from the relatively long-held perception that modeling estimates for the duration of hydrothermal events, which spanned tens of thousands of years, were incompatible with radiometric estimates for ore-forming systems, which spanned several millions of years. The conference broadly addressed the duration and episodicity of ore-forming activity in the intrusive, diagenetic (sedimentary basin), and metamorphic environments. The papers in this issue show that the full array of dynamic geologic events associated with hydrothermal and mineralizing episodes may, in fact, encompass several millions of years, but the actual duration of ore-forming pulses is on the scale of only tens to hundreds of thousands of years (i.e., about 10,000–200,000 yr). This represents an important consensus between laboratory and computer results.

The first group of six papers addresses the duration and episodicity of mineralization processes associated with igneous events. The first two papers in this set use numerical modeling to estimate duration; the next three papers approach the duration question using radiometric dating at spe-

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cific mineral districts; the last paper examines the effects of plume-related magmatism on the global scale, with specific reference to changes in the marine environment.

In the first paper, Cathles et al. (1997), explore the question: "How long can a near-surface hydrothermal system be sustained by emplacement of a single intrusion?" System duration is maximized if a large volume of magma intrudes deeply into a host environment just permeable enough to allow convection. A 40- × 2-km-thick sill, emplaced between a 16- and 18-km depth, can sustain geothermal activity for ~800,000 yr at a single, near-surface site. Since, in this model, all parameters were chosen at the end of the geologically plausible range which maximizes hydrothermal duration, the authors consider one million years a reasonable estimate for the longest period of time that a hydrothermal system could be sustained by a single intrusion.

In the next paper, Mizuta and Scott (1997), applying experimental data on iron diffusivity to sphalerite containing chalcopyrite and pyrrhotite inclusions, devise a "sphalerite speedometer" to estimate the cooling time of skarn deposits. This is achieved by modeling depletion in the iron content of sphalerite within 70 μ of pyrrhotite inclusions which ceased exsolving from the sphalerite host at ~350°C. Iron diffusion ceased at 245°C. From the distinctive error function form of the iron depletion halo near the sphalerite laths, Mizuta and Scott calculate a cooling rate of 0.5°C/1,000 yr and show that the time needed to cool from 350° to 245°C took no longer than 210,000 yr.

In the first paper utilizing radiometric dating, Marsh et al. (1997) obtained high resolution $^{40}Ar/^{39}Ar$ ages for primary phenocrysts and related hydrothermal minerals from seven intrusive centers in the Potrerillos Cu-Au-Ag district in Chile. They show that although porphyry and related mineralization districtwide occurred over a period of more than 8 m.y., the emplacement, mineralization, and cooling associated with individual porphyry stocks was of short duration, spanning only about 10,000 to 100,000 yr. Dating by the $^{40}Ar/^{39}Ar$ method is sufficient to tie together definitively individual intrusions with their associated mineralization. They also note that when using the $^{40}Ar/^{39}Ar$ method on relatively young (Eocene-Oligocene) rocks, the percent uncertainty in the analytical method translates to an absolute time interval which is very near the time required to complete a single intrusive hydrothermal cycle. In other words, we can barely resolve the duration of ore-forming episodes for young deposits. This emphasizes the need to improve our dating resolution further.

The paper by Henry et al. (1997) shows that the 16 Moz Au deposit at Round Mountain, Nevada, formed in an environment where the hydrothermal activity associated with Au deposition lasted 50,000 to 100,000 yr. Gold was deposited within 500 m of the paleosurface along the ring fractures of a caldera which had collapsed 500,000 yr earlier. The Au mineralization at Round Mountain was most likely produced by an as yet unidentified intrusion into the ring fracture. Again, the intrusion of a stock, mineralization, and cooling sequence was completed within a time interval that approaches the analytical uncertainty in the $^{40}Ar/^{39}Ar$ dating method. As a result, the intrusion-mineralization-cooling sequence could be significantly less than 50,000 yr.

The paper by Stein et al. (1997) presents highly precise Re-Os ages from two molybdenite deposits in the East Qinling molybdenum belt, Shaanxi Province, China. A highly unusual carbonatite-hosted Mo-Pb deposit is exposed in the Qinling belt, and seven replicate analyses yield an Re-Os age of 221.5 ± 0.3 (0.15%), which is known to be a time of regional compression. An Re-Os age of 138.4 ± 0.5 Ma, based on two analyses, was obtained for a Climax-type granite molybdenum system located within a few kilometers of the carbonatite Mo-Pb deposit. Stein et al. suggest that the East Qinling molybdenum belt provides a rare glimpse of the mantle's role in producing a molybdenum-fertile lower crust which can be subsequently tapped during periods of tectonic extension. This model may be applied to other regions containing well-developed Climax-type molybdenum mineralization, for example, the Colorado mineral belt. This study emphasizes that regional-scale preparatory geologic events may take tens of millions of years to set the stage for very short episodes of ore deposition.

Finally, Sinton and Duncan (1997) investigate the consequences of the submarine extrusive eruption of a volume of flood basalt similar to the sill volume modeled in the first paper by Cathles et al. (1997; ~10,000 km^3, in both cases). Single flows with volumes of thousands of cubic kilometers have been mapped in continental flood basalts. Three major ocean plateaus were constructed from plume-related basalts that were extruded near the Cenomanian-Turonian boundary at ~92 Ma: the Caribbean plate (93–87 Ma), the Ontong-Java plateau (second phase of construction 94–84 Ma), and the Madagascar flood basalt province with a mean age of 87 ± 0.6 Ma. Sinton and Duncan argue that the fertilizing effects of the sudden discharge of 10,000 km^3 of Fe-rich, reducing hydrothermal fluids could have driven the world's oceans anoxic, thus accounting for marine extinctions and the increase in the accumulation and preservation of organic-rich sediments (black shales) that is observed at the Cenomanian-Turonian boundary.

The next group of two papers addresses mineralization and episodic fluid movements in sedimentary basins. Tompkins et al. (1997) present a detailed study of the Cadjebut Mississippi Valley-type Pb-Zn deposit on the Lennard shelf, Western Australia. In this example, the regional stress shifted from weak extension to weak compression (reverse faulting) as mineralization occurred. From this structural examination, as well as from stable isotope evidence, the authors argue that mineralization occurred over a 35-m.y. period, starting close to the time of maximum basin development (Late Devonian) and extending into a subsequent period of uplift and erosion (mid-Carboniferous). They document that at least six pulses of basin brine contributed metals to the Cadjebut deposit. The ores became progressively more hydrocarbon rich, and the mineralizing fluids became increasingly overpressured with time. They suggest that heating of the basin, resulting from uplift and passing through the ocean thermocline, may have led to rapid gas generation, to the episodic expulsion of overpressured basin brines, and to pulses of hydrocarbon-rich mineralization.

Some of the best data for understanding the architecture and behavior of sedimentary basins comes from observation of basins that are currently active. Roberts and Carney (1997) provide this perspective with their paper on episodic fluid, gas, and sediment venting in the northern Gulf of Mexico. The most rapid venting, consisting of a slurrylike mixture of sediment, gas, water, and unaltered crude oil at a >2,000-m depth, occurs at mud volcanoes ~35 m high and ~500 m in diameter. Mud volcanoes are aligned along and clearly controlled by faults. The venting rate and sediment instability strongly inhibit biologic activity, and as a result, mud volcano sites are usually barren except for bacterial mats. Swirls in these mats sometimes reveal convection in the muds filling the axial craters of the volcanoes. Following the mud volcano stage of rapid venting, slower but sustained leakage feeds clathrate accumulations, and together both the venting and clathrates sustains methane- and sulfide-based chemosynthetic organisms (e.g., mussels, tube worms, bacterial mats). Hydrocarbon oxidation at this stage provides CO_2 for carbonate mounds and hardgrounds; hydrocarbon reduction of sulfate provides H_2S for sulfide-based tubeworms. Finally, as venting wanes to levels that can sustain only *Beggiatoa* mats, the vents become sites for carbonate and barite deposition. Little is known about the temporal variability of venting, but water temperature and clathrate stability are most likely controlled by the passage of Gulf Stream loop currents several times a year. The venting cycle, from active mud volcanoes to the quiet venting that deposits mainly carbonates, probably lasts hundreds to thousands of years. Overall, control is exerted by the 100,000-yr glacial cycle which produces cyclic changes in sea level, sedimentation, and salt diapirism.

The volume concludes with a numerical modeling paper by Hanson (1997) that provides a fascinating look at metamorphically produced fluid movements on the continental scale. He demonstrates that metamorphic reactions can expel 10^6 kg/m^2 of water over the ~30 m.y. following continental overthrusting. The pattern of expulsion is independent of crustal permeability because the fluids are able to hydrofracture their environment, creating the permeability they need to escape. The magnitude of venting is less than the 10^8 kg/m^2 which others have suggested is necessary to account for observed alteration, but focusing of expelled fluids might overcome this difference. Hanson's figures clearly show how any chemical signature (ore deposit) associated with metamorphic venting would tend to be erased by topography-driven meteoric water flow in the more permeable upper few kilometers of the crust.

The papers in this volume provide a brief but hardly complete overview of the capabilities and potential of modern radiometric dating and computer modeling. In the intrusive, diagenetic, and metamorphic setting, the total duration of the geologic events associated with mineralization is tens of millions of years, but in all three settings there is ample evidence that episodic fluid venting and ore formation are short lived, on the scale of tens to hundreds of thousands of years or less. Remarkably, the very different geologic settings covered in this volume provide quite a consistent story, undoubtedly for very different reasons. In contrast to the perception that motivated the symposium, the papers in this volume find no discrepancy between estimates of the duration of hydrothermal activity and/or ore deposition derived from modeling and derived from radiometric dating. Indeed, both approaches indicate pulses of fluid expulsion (magmatic, hydrocarbon, or aqueous) in a much longer lived framework of intrusions and volcanism, sedimentation, or continental-scale mountain building and erosion. The old view that it takes many, many millions of years to create an ore deposit is correct in the broadest sense, but we now can appreciate the brevity of the actual ore-forming episodes themselves.

The examples given in the papers containing radiometric ages illustrate the importance of precise dating (small uncertainties) and also the remarkable accuracy possible with modern analytical techniques. It is self evident, but worth emphasizing, that specific knowledge of the age of ore formation provides a vital key to determining the geologic and genetic relationships of mineral deposition. We believe that the papers in this volume also illustrate the complimentary nature of field, laboratory, and modeling studies. Geologic mapping and radiometric dating provide the geometry and timing for realistic fluid-flow modeling, which can then predict the time duration, cumulative fluxes, and alteration central to any exploration or resource assessment. Modern analytical and computer techniques have just become adequate to the task of determining the timing and duration and simulating ore-forming systems. The confluence and application of these techniques to ore deposits in the next decades should prove particularly instructive and exciting.

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