Economic Geology
Vol. 86, 1991, pp. 892–902

DISCUSSIONS

EPITHERMAL DEPOSITION OF GOLD DURING TRANSITION FROM PROPYLITIC TO POTASSIC ALTERATION AT ROUND MOUNTAIN, NEVADA—A DISCUSSION

R. W. HENLEY

Research School of Earth Sciences, Australian National University, Canberra, A.C.T. 2614, Australia

Sir: Sander and Einaudi (1990) have provided a very welcome, carefully documented case study of alteration and gold mineralization in the upper few hundred meters of a large hydrothermal system in a silicic volcanic pile. Alteration data suggest that a progression of alteration occurred from propylitic through potassic to silicic-intermediate argillic with temperatures initially, at the potassic stage, of about 265°C. Subsequent cooling to about 150°C occurred which developed the silicic-clay alteration overprint and mineralization. From these data, the authors argue that gold deposition was a consequence of wholesale ground-water dilution in the late stage of the life of this system.

Notwithstanding the absence of the upper discharge portion of the system due to erosion, Sander and Einaudi highlight a number of spatial and mineralogical correlations with active geothermal systems. In modeling the chemistry of ore deposition, fluid compositions were derived in part from a reference composition for the evolved fluid phase itself based on selected geothermal fluid data. However, the thermochemical analysis leads them to argue that the evolved fluid had a tightly constrained composition with $\Sigma S \geq \Sigma CO_2$, unlike that of well-documented geothermal system fluids.

This paradox arises directly from their estimation procedure for the minimum ΣS in the evolved fluid which is based on the single assumption of redox buffering through pyrite-magnetite equilibration. Magnetite is reported, however, as a minor accessory mineral in the tuff of Round Mountain and is therefore inappropriate as the choice of a redox sulfur buffer, particularly in the presence of more abundant high Fe chlorite. Barton et al. (1977) recognized that redox controls at Creede, Colorado, required a role for chlorite which overlapped the stability field of magnetite in the simple Fe-O-S system. Giggenbach (1980) has also shown that CO_2-S relations in the upflow regime of active systems are constrained by alteration assemblages involving FeO silicates similar to those recorded at Round Mountain and that these define a mineral-fluid geothermometer of similar precision to that of the Na/K geothermometer.

Although thermodynamic data for chlorites are not well constrained, both theoretical (Walshe, 1986) and empirical data (Giggenbach, 1980) are available which offer alternative constraints on the fluid composition at Round Mountain based on (FeO)-chlorite-pyrite relations. Sander and Einaudi diagnose brunswigite as the dominant chlorite composition. Following procedures described by Walshe (1986) this composition suggests $a_{H_2S} \sim 10^{-3.5}$ ($\sim$10 mg/kg), in the temperature range 150° to 240°C, in broad agreement with the value estimated by Sander and Einaudi. Compositional data for the Round Mountain chlorites would be required for more refined thermochemical analysis. A similar approach can be taken based on alteration epidote.

Inclusion of chlorite (and/or epidote) in the modeling, however, extends the permissable range of fluid compositions to lower pH values and releases the very tight constraint imposed on ΣCO_2. This in turn resolves the gas ratio paradox and therefore the implied uniqueness of the Round Mountain system. Also implied is a lower fluid pH, commensurate with the previously assumed ΣCO_2 content of the fluid phase, and in turn, a lower gold solubility than estimated using the magnetite-pyrite redox assumption. The fluid composition as estimated is then very similar to that at Broadlands and Kawerau, New Zealand, whose fluid compositions were otherwise adopted as a basis for the modeling exercise. These two systems are representative of the high gas content Taupo volcanic zone systems (Henley, 1990), whereas the Wairakei geothermal system is representative of the low gas set of systems: in both cases, $\Sigma S \ll \Sigma CO_2$.

It is as inappropriate to attempt to force a data set into the well-established model of active geothermal systems as it is to develop an alternate model for otherwise analogous fossil hydrothermal systems which does not fully utilize the wealth of quantitative geologic, chemical, and physical data from active fields. Rather, a combination of the two data sets can lead to a stronger understanding of both. This is the basis of the following comments.

The constraints imposed on the analysis of fluid composition at Round Mountain also lead to the implication that widespread alteration K feldspar is evolved by fluid dilution. Alteration potassic and sodic feldspar is commonplace in the upper few hundred meters of active geothermal systems; its presence relates to the singular characteristic of such high level systems in maintaining a net transfer of potassium and sodium from depth to the near-surface alteration zones. Carbon dioxide introduced to the upflow leads to the formation of K mica (sericite, white mica, illite) in alteration zones. Phase separation along the closed-system boiling point depth curve for CO_2-H_2O-X_{Cl} in the upper portion of the systems (i.e., above, say, 1,500 m) transfers the liquid phase composition into the stability field of feldspar. With the loss of pH control due to removal of CO_2 to the coexisting vapor phase, the stable alteration phases are albite and K feldspar and fluid compositions become dependent on this alteration pair as indicated by the widespread successful use of K/Na as a geothermometer in active geothermal fields. Thus the presence of widespread alteration feldspar is a normal consequence of boiling within a high-level hydrothermal system and not, per se, of ground-water mixing. The latter may occur on the margins of this environment or in association with fracture systems but is a second-order effect relative to heat loss by phase separation until pressure loss in the upflow regime occurs. At Wairakei, equivalent effects are presently occurring as a consequence of a pressure drop in the reservoir due to exploitation for electricity generation (Brown et al., 1988). The process of focused dilution proposed by Sander and Einaudi involves heat balance and spatial problems which may be overcome by considering more limited fracture-controlled mixing with a two-phase feldspar-stable fluid derived by phase separation. This may also contribute to the understanding of the argillic alteration assemblage developed late in the Round Mountain paragenesis.

An additional inference by Sander and Einaudi is that gold deposition in many epithermal systems is a consequence of an episode of intense fracturing and inundation by cold ground waters and further that this process defines the waning stage of hydrothermal activity. Since the heating and cooling stages of high-level hydrothermal systems require on the order of 2×10^4 yrs (Cathles, 1980; Henley and Ellis, 1983) and systems may live for 10^5 yrs or more, the waning-stage deposition model both increases the volume of source magma or rock required to supply the system and implies dispersion and/or loss to the system of some five times the mass of the mineable resource (5×300 metric tons of gold) before depositional activity. Geothermal systems in all volcanic terranes are characterized by an association with an active tectonic environment so that it is paradoxical that at Round Mountain a discrete intense fracturing event should occur only late in the history of the system. Moreover, such fracturing is also likely to favor focusing of upflow fluid into the surface regime through high permeability pathways with consequently greater pressure gradient and open-system boiling. The waning stage of a system, sensu stricto, must be associated with a decline of heat supply from the source regime which in turn changes the balance of pressure between hot upflow (and gold supply) and surrounding ground water and leads to progressive inundation of the system.

Critical to the formation of a substantial gold deposit such as Round Mountain is the maintenance of the system upflow; the latter is responsible for the supply of nutrient gold, sulfur, potassium, etc. Thus any increase in the pressure gradient controlling the upflow may allow nutrient fluid to encounter previously feldspar-altered rocks and permit the feldspar-driven gold depositional reaction suggested by Sander and Einaudi. Perhaps this is what has happened at Round Mountain—perhaps an episode of tectonic or magma-related fracturing produced an array of high permeability paths to the near-surface regime, transiently increased the upflow rate due to the steeper pressure gradient, and consequently focused gold deposition into its present setting. Subsequent loss of pressure due to drawdown in the source regime would lead to decrease of the gradient and consequent invasion of the upper part of the system (the depositional regime) by ground water—perhaps.

In summary, reinterpretation of mineralogical and fluid inclusion data for the Round Mountain deposit suggests that the host system was very similar in all aspects to those presently active in felsic volcanic terranes elsewhere. In many cases such active systems have been shown conclusively through observation of dispersed electrum in reservoir rocks (Krupp and Seward, 1987; Christenson, 1988; Anstiss, 1989) and of gold in well discharges (Brown, 1986) to be actively depositing gold. The magnitude of the gold resource in these systems has not been tested by drilling; drilling is designed to test deep (>2 km) hot water resources and, because of the tourist value of hot springs and fumeroles and the intrinsic drilling difficulties, drill holes are generally sited well away from active discharge areas—lamentably they also do not generally recover core from the upper few hundred meters. Systems such as that hosting the Ladolam deposit, Lihir Island (Papua New Guinea, Moyle et al., 1990), provide adequate testimony to the realization that the epithermal systems of the past are indeed the equivalents of the systems active today and that late fracturing and brecciation are perhaps critical to the development of a major bulk-tonnage epithermal gold deposit.

Discussions with P. R. L. Browne, C. A. Heinrich, and J. L. Walshe were helpful during the preparation of this discussion.

January 2, 1991

REFERENCES

Anstiss, R. G. 1989, Metal transport and deposition in the Broadlands geothermal system: Unpub. Ph.D. dissert., Victoria Univ. of Wellington, 167 p.

Barton, P. B., Jr., Bethke, P. M., and Roedder, E., 1977, Environment of ore deposition in the Creede mining district, San Juan Mountains, Colorado: Part III. Progress toward interpretation of the chemistry of the ore-forming fluid for the OH vein: ECON. GEOL., v. 72, p. 1–24.

Brown, K. L., 1986, Gold deposition from geothermal discharges in New Zealand: ECON. GEOL., v. 81, p. 979–983.

Brown, K. L., Henley, R. W., Glover, R. B., Mroczek, E. K., and Plum, H., 1988, Dilution and boiling in the Wairakeu field due to exploitation 1959–1982: New Zealand Geothermal Workshop, 10th, Univ. Auckland, Proc., p. 263–269.

Cathles, L. M., 1981, Fluid flow and genesis of hydrothermal ore deposits: ECON. GEOL. 75TH ANNIV. VOL., p. 424–457.

Christenson, B. W., 1987, Fluid-mineral equilibria in the Kawerau hydrothermal system, Taupo volcanic zone, New Zealand: Unpub. Ph.D. dissert., Univ. Auckland, 444 p.

Giggenbach, W. F., 1980, Geothermal gas equilibria: Geochim. et Cosmochim. Acta, v. 44, p. 2021–2032.

Henley, R. W., 1990, Ore transport and deposition in epithermal environments: Univ. Western Australia, Geology Dept., Pub. 23, p. 51–69.

Henley, R. W., and Ellis, A. J., 1983, Geothermal systems ancient and modern, a geochemical review: Earth Sci. Rev., v. 66, p. 1–50.

Krupp, R. E., and Seward, T. M., 1987, The Rotokawa geothermal system, New Zealand: An active epithermal gold-depositing environment: ECON. GEOL., v. 82, p. 1109–1129.

Moyle, A. J., Doyle, B. J., Hoogvliet, H., and Ware, A. R., 1990, Ladolam gold deposit, Lihir Island: Australasian Inst. Mining Metallurgy Mon. 14, v. 2, p. 1793–1806.

Sander, M. V., and Einaudi, M. T., 1990, Epithermal deposition of gold during transition from propylitic to potassic alteration at Round Mountain, Nevada: ECON. GEOL., v. 85, p. 285–311.

Walshe, J. L., 1986, A six-component chlorite solid solution model and the conditions of chlorite formation in hydrothermal and geothermal systems: ECON. GEOL., v. 81, p. 681–703.

EPITHERMAL DEPOSITION OF GOLD DURING TRANSITION FROM PROPYLITIC TO POTASSIC ALTERATION AT ROUND MOUNTAIN, NEVADA—A REPLY

MARK V. SANDER

Magma Copper Company, 7400 North Oracle Road, Tucson, Arizona 85704

AND MARCO T. EINAUDI

Department of Geology, Stanford University, Stanford, California 94305

Sir: In our original paper (Sander and Einaudi, 1990), we documented the rock and microthermometric record in time and space of the Round Mountain hydrothermal system; we proceeded to deduce from that record the genetic processes leading to deposition of more than 300,000 kg of mineable gold. In his discussion, Henley (1991) presents an alternative genetic scenario which is more consistent with processes thought to apply to active geothermal systems but which is inconsistent with the geologic record at Round Mountain. His discussion proceeds from misrepresentation of fundamental observations or interpretations clearly stated in our paper to issues of more substantive contention. Readers of both the original paper and this reply will realize the great debt we owe Henley and others for describing active systems and supplying parameters by analogy that are not measurable at Round Mountain. Many of our contended conclusions arise from applying that same information to the rock record at Round Mountain.

Henley commences with an incorrect summary of the alteration-mineralization sequence that we documented for Round Mountain by stating "that a progression of alteration occurred from propylitic through potassic" and that "subsequent cooling occurred . . . to develop the silicic-clay alteration overprint and mineralization." As is abundantly documented in our paper, transport and deposition of virtually all gold in the system occurred during feldspar-stable propylitic and potassic alteration, respectively, not during the silicic-clay overprint. Furthermore, the propylitic-potassic transition itself represents significant cooling. Henley apparently missed this important point and much of his subsequent discussion therefore becomes moot.

To recap our sequence, deposition of nearly all gold in the system is constrained on the basis of clear macroscopic, microscopic, and microthermometric evidence to the temporal and spatial transition from propylitic alteration (assemblage: quartz-adularia (sanidine)-albite-chlorite-pyrite-calcite ± epidote at 265°C) to potassic alteration (assemblage: quartz-adularia(sanidine)-muscovite-pyrite-calcite as temperatures declined from 265° to <200°C). Propylitic alteration is pervasive and unrelated to throughgoing veins (i.e., it occurred in largely unfractured host rocks). Superimposed potassic alteration is restricted to coalescing envelopes of gold-bearing, sheeted quartz-adularia-pyrite-calcite "phenocryst overgrowth" veins. Formation of these veins represents the earliest widespread fracturing of the host rocks. It is our interpretation that intense fracturing allowed cool ground water into the hydrothermal reservoir, triggering temperature decline, change from propylitic to potassic alteration, and formation of the huge gold orebody. Continued stability of the assemblage quartz-adularia-pyrite throughout the propylitic-potassic sequence provides the key to understanding the change from gold transport to gold deposition: the pH-f_{O_2} stability field of this assemblage sweeps across