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Rifting, Bimodal Volcanism, and Bonanza Gold Veins

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In a comprehensive analysis of the tectonomagmatic controls and styles of epithermal Au mineralization in the northern Great Basin of the western United States, John (2001) distinguishes two contrasting environments: first, high-sulfidation and base metal-bearing low-sulfidation deposits hosted by calc-alkaline andesitic and dacitic volcanic rocks as part of a conventional arc assemblage; second, base metal-deficient low-sulfidation deposits associated with a bimodal basalt-rhyolite suite generated during rifting. Although the northern Great Basin is arguably the world's best-documented epithermal province, these three epithermal types and their relations to specific tectonomagmatic settings are nevertheless readily recognizable worldwide. This commentary draws special attention to the low-sulfidation vein deposits associated with rifting and bimodal volcanism because this setting is perhaps less widely appreciated than the volcanic arc terranes. The low-sulfidation veins in such rift settings are typified by low sulfide and manganoan carbonate as well as low base metal content, low Ag/Au ratios, minor amounts of arsenopyrite and pyrrhotite, and occurrence of marcasite and, in some examples, selenides (Sillitoe, 1993; John, 2001).

A spectrum of rift settings

Base metal-deficient low-sulfidation Au deposits are formed in a variety of continental and island-arc rifts: intra-, near-, or back-arc settings during subduction of oceanic lithosphere, postarc settings following cessation of subduction, and postcollisional settings. Depending on the environment concerned, the rifting is often attributed to one or more of trench retreat (rollback) consequent upon steepening or waning subduction, asthenospheric upwelling caused by removal of mantle lithosphere and/or attached underthrust slabs, gravitationally controlled lateral expansion (tectonic collapse) of thickened crust following an episode of contractional deformation, and mantle-plume (hot spot) activity (e.g., Sonder and Jones, 1999). Rifting is commonly accompanied by bimodal volcanism: basalt or basaltic andesite plus rhyolite or rhyodacite of calc-alkaline and/or tholeiitic affinities. The bimodality is consistent with generation of the basaltic magma by partial fusion of the upper mantle and the felsic magma by crustal anatexis.

Bimodal volcanic suites and low-sulfidation epithermal Au deposits characterize several extensional arcs: the Paleocene arc in the central Andes of northern Chile hosts the rhyolite dome-related El Peñón veins (Robbins, 2000); the Middle to Late Jurassic arc in the Patagonian Andes of southern Argentina is the site of the Esquel veins which share faults with synmineralization andesite-basaltic andesite and rhyolite dikes (Sillitoe et al., 2002); and the Quaternary arc in southern Kyushu, Japan, is nearby the Hishikari veins and coeval rhyodacite domes emplaced alongside the Kagoshima graben (Izawa and Urashima, 1989; Y. Watanabe, writ. commun., 2001).

Most of the low-sulfidation Au deposits (Ivanhoe, Midas, Mule Canyon, Sleeper) in the northern Great Basin of the western United States were generated over a 2-m.y. interval of the Miocene within and near the northern Nevada rift, a product of back-arc extension related by some investigators to the Yellowstone mantle plume (John, 2001). Nevertheless, extension, bimodal volcanism, and low-sulfidation vein mineralization (Bullfrog) became more widespread in the Great Basin once subduction ceased at the adjacent Pacific margin (John, 2001). Somewhat similar is the back-arc region of the Patagonian Andes in southern Argentina, where many low-sulfidation vein systems (Cerro Vanguardia) of Late Jurassic age—broadly coeval with the intra-arc Esquel low-sulfidation deposit—are hosted by voluminous rhyolitic ignimbrite accompanied by minor basaltic products (Schalamuk et al., 1997). The bimodal volcanism, coincident with a series of north-northwest-trending rifts that presaged opening of the South Atlantic Ocean, is attributed on petrochemical grounds to the far-field effects of mantle-plume activity (Riley et al., 2001). Back-arc rifting and bimodal volcanism during the Miocene in the Kitami region of northeastern Hokkaido, Japan, are also intimately related to formation of numerous low-sulfidation veins (Konomai), although slab steepening rather than mantle-plume activity is believed to be the cause (Watanabe, 1995). The Republic and Wenatchee low-sulfidation vein deposits of Eocene age in northern Washington, USA, also formed in back-arc grabens linked to slab steepening as andesitic-dacitic volcanism gave way to low-volume basaltic activity (Berger and Bonham, 1990).

In marked contrast, rifting to form the Gulf of California and Salton trough in northwestern Mexico and contiguous California is due to the East Pacific Rise spreading center being overridden by the Pacific margin of North America. The resulting bimodal volcanic suite and related low-sulfidation Au occurrences (Modoc) border the Gulf of California (Staude and Barton, 2001). Postcollisional extension is nicely exemplified by the Early Cretaceous rifts of the Mongol-Okhotsk belt in the trans-Baikal region of Russia and contiguous northeastern Mongolia. Rifting resulted from tectonic collapse following collision between the Siberian and Mongolia-North China cratons, and gave rise to relatively minor amounts of rhyolitic and basaltic igneous rocks and a few low-sulfidation Au veins, including the giant Baley deposit (Zorin et al., 2001).

The characteristically low relief of these diverse rift settings leads to widespread accumulation of siliciclastic sequences of fluvial and/or lacustrine origin. The sedimentation is broadly contemporaneous with hydrothermal activity, and low-sulfidation veins are commonly hosted by or occur near the sedimentary rocks. Such settings are conducive to formation and preservation of hot spring sinter, present in most of the low-sulfidation vein provinces mentioned herein. The volume of intercalated or crosscutting igneous rocks in the sedimentary sequences is commonly relatively minor and may be dominated by felsic or mafic products or roughly equal proportions of both, although this is not everywhere the case (e.g., the rhyolite-dominated Patagonian back arc). Other geologic features observed in the general vicinities of some rift-related low-sulfidation deposits include metamorphic core complexes, related detachment faults, and rift-bounding listric normal faults. However, these low-angle faults do not normally host the Au veins.

Bonanza gold veins

Bonanza epithermal veins, which I define informally as those containing roughly 1 million metric tons or more averaging at least 1 oz/t Au (i.e., ~30 metric tons Au), occur sparingly in a number of different epithermal provinces, and constitute appreciably less than one percent of epithermal Au veins worldwide. Bonanza veins of high-sulfidation and base metal-rich and base metal-poor low-sulfidation types are all well known but, somewhat surprisingly, nearly 60 percent of them are of the last type and occur in rifts associated with bimodal volcanism. The bonanza ore shoots may comprise high-grade cores to individual veins (Cerro Vanguardia), single veins in multivein districts (El Peñón), or essentially entire deposits (Hishikari).

Both structural and lithologic controls, or combinations thereof, may be invoked to explain exceptionally high Au content in some epithermal veins. However, these reasons fail to account satisfactorily for the clear dominance of bonanza veins in rift settings, for which a more fundamental explanation may be required. The mafic contribution to rift-related bimodal suites has a direct mantle source, but seems to show petrochemical evidence for variable, either direct or indirect contributions from subducted oceanic crust (e.g., Riley et al., 2001). Perhaps the mantle-derived melts and their felsic crustal-fusion products, both typically hotter, drier, and more reduced than equivalent arc magmas (John, 2001), are capable of generating fluids intrinsically richer in gold or somehow able to generate higher gold concentrations. Indeed, as John (2001) points out, Giggenbach (1995) showed that the present-day volatile input to low-sulfidation geothermal systems related to rifting in the Taupo Volcanic Zone, New Zealand, is partly of mantle origin, and compositionally distinct from that in similar systems linked to the contiguous subduction-related andesitic arc.

Exploration consequences

The same spectrum of rift settings and bimodal volcanic rocks that contains the base metal-deficient low-sulfidation vein Au deposits discussed herein also hosts polymetallic volcanic-associated

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massive sulfide (VMS) deposits (Barrett and MacLean, 1999; Sillitoe, 1999). The only difference is that the VMS deposits are generated under submarine conditions, whereas the low-sulfidation Au deposits are subaerial. The consistently higher salinity of VMS ore fluids, consequent upon their seawater component, enables the transport and precipitation of much larger amounts of base metals than are found in the base metal-poor low-sulfidation veins. A practical consequence of this common tectonomagmatic setting is that low-sulfidation Au veins may be found either stratigraphically beneath or along strike of VMS provinces as parts of volcanosedimentary rift sequences that accumulated subaerially in response to more limited subsidence. Such a relationship is clearly observed today in the western Pacific region where the low-sulfidation geothermal systems in the Taupo Volcanic Zone are the onland equivalent of VMS formation along strike in actively opening marginal basins. In this regard it is interesting to note that the Eskay Creek VMS deposit, British Columbia, formed with bimodal magmatism under shallow-marine conditions during rifting of an andesitic arc (Roth et al., 1999), displays geologic features, including bonanza Au grades, suggestive of a transition to the low-sulfidation epithermal environment.

Bonanza Au deposits make attractive exploration targets, especially during times of depressed Au prices, because of their potential to yield high rates of financial return. Hence, a strong argument can be made for concentrating the search for base metal-deficient low-sulfidation Au veins in rift settings characterized by bimodal volcanism. In some places, however, this bimodality may not be particularly obvious because of the regional dominance of andesitic-dacitic volcanic sequences (e.g., southern Kyushu), the restricted volume of basalt accompanying rhyolitic volcanics (e.g., Patagonian back arc), or the prevalence of sedimentary over volcanic rocks (e.g., trans-Baikal region). Numerous rift environments worldwide, especially those beyond convergent plate boundaries, have seen little Au exploration and could offer unsuspected potential. Furthermore, bimodal sequences in rifted primitive oceanic arcs, long considered to be metallogenically infertile, have recently been shown to contain VMS mineralization (Iizasa et al., 1999). Perhaps the subaerial parts of such bimodal sequences in the Izu-Bonin-Mariana and Tonga-Kermadec arcs, as well as their ancient analogues, could also be prospective for low-sulfidation bonanza Au veins.

As emphasized by John (2001) for the northern Great Basin, hydrothermal alteration associated with rift-related low-sulfidation veins is minimal, thereby seriously hampering both their direct and indirect recognition. With this in mind, it is instructive to note that although three of the low-sulfidation vein Au deposits considered herein (Cerro Vanguardia, El Peñón, Esquel) are partly exposed, they were not recognized until eventual discovery from the late 1980s onward. Exploration for bonanza Au deposits is even more problematic because, realistically, future discoveries are likely to be "blind." In the case of bonanza low-sulfidation veins discovered during the last 20 years or so, concealment is due either to premineral rocks, resulting in subtle (Hishikari, Midas, Golden Promise vein at Republic) or nonexistent (Quebrada Colorada vein at El Peñón) surface expressions, or to postmineral cover (Sleeper).

REFERENCES

Barrett, T.J., and MacLean, W.H., 1999, Volcanic sequences, lithogeochemistry, and hydrothermal alteration in some bimodal volcanic-associated massive sulfide systems: Reviews in Economic Geology, v. 8, p. 101–131.

Berger, B.R., and Bonham, H.F., Jr., 1990, Epithermal gold-silver deposits in the western United States: time-space products of evolving plutonic, volcanic and tectonic environments: Journal of Geochemical Exploration, v. 36, p. 103–142.

Giggenbach, W.F., 1995, Variations in the chemical and isotopic composition of fluids discharged from the Taupo Volcanic Zone, New Zealand: Journal of Volcanology and Geothermal Research, v. 68, p. 89–116.

Iizasa, K., Fiske, R.S., Ishizuka, O., Yuasa, M., Hashimoto, J., Ishibashi, J., Naka, J., Horii, Y., Fujiwara, Y., Imai, A., and Koyama, S., 1999, A Kuroko-type polymetallic sulfide deposit in a submarine silicic caldera: Science, v. 283, p. 975–977.

Izawa, E., and Urashima, Y., 1989, Quaternary gold mineralization and its geologic environments in Kyushu, Japan: Economic Geology Monograph 6, p. 233–241.

John, D.A., 2001, Miocene and Early Pliocene epithermal gold-silver deposits in the northern Great Basin, western USA: Characteristics, distribution, and relationship to magmatism: Economic Geology, in press.

Riley, T.R., Leat, P.T., Pankhurst, R.J., and Harris, C., 2001, Origins of large volume rhyolitic volcanism in the Antarctic Peninsula and Patagonia by crustal melting: Journal of Petrology, v. 42, p. 1043–1065.

Robbins, C.H., 2000, Geology of the El Peñón gold-silver deposit, northern Chile, *in* Cluer, J.K., Price, J.G., Struhsacker, E.M., Hardyman, R.F., and Morris, C.L., eds., Geology and ore deposits 2000: The Great Basin and beyond: Reno, Geological Society of Nevada, p. 249–264.

Roth, T., Thompson, J.F.H., and Barrett, T.J., 1999, The precious metal-rich Eskay Creek deposit, northwestern British Columbia: Reviews in Economic Geology, v. 8, p. 357–373.

Schalamuk, I.B., Zubia, M.A., Genini, A., and Fernández, R.R., 1997, Jurassic epithermal Au-Ag deposits of Patagonia, Argentina: Ore Geology Review, v. 12, p. 173–186.

Sillitoe, R.H., 1993, Epithermal models: Genetic types, geometrical controls and shallow features: Geological Association of Canada Special Paper 40, p. 403–417.

——1999, VMS and porphyry copper deposits: Products of discrete tectono-magmatic settings, *in* Stanley, C.J., et al., eds., Mineral deposits: Processes to processing, v. 1: Rotterdam, Balkema, p. 7–10.

Sillitoe, R.H., Cooper, C., Sale, M.J., Soechting, W., Echavarria, D., and Gallardo, J.L., 2002, Discovery and geology of the Esquel low-sulfidation epithermal gold deposit, Patagonia, Argentina: Society of Economic Geologists Special Publication 9, in press.

Sonder, L.J., and Jones, C.H., 1999, Western United States extension: How the west was widened: Annual Review of Earth and Planetary Sciences, v. 27, p. 417–462.

Staude, J.-M.G., and Barton, M.D., 2001, Jurassic to Holocene tectonics, magmatism, and metallogeny of northwestern Mexico: Geological Society of America Bulletin, v. 113, p. 1357–1374.

Watanabe, Y., 1995, A tectonic model for epithermal Au mineralization in NE Hokkaido, Japan: Resource Geology Special Issue, No. 18, p. 257–269.

Zorin, Yu. A., Zorina, L.D., Spiridonov, A.M., and Rutshtein, I.G., 2001, Geodynamic setting of gold deposits in Eastern and Central Trans-Baikal (Chita Region, Russia): Ore Geology Review, v. 17, p. 215–232.

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