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Geochemical and Modal Data for Igneous Rocks Associated with Epithermal Mineral Deposits

Data Series 875

U.S. Department of the Interior
U.S. Geological Survey

COVER. The Standard Mill and the south slope of Bodie Bluff in the Bodie district, eastern California. Photo taken by Edward A. du Bray, U.S. Geological Survey, 2012.

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U.S. Department of the Interior
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U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia: 2014

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Suggested citation:
du Bray, E.A., 2014, Geochemical and modal data for igneous rocks associated with epithermal mineral deposits: U.S. Geological Survey Data Series 875, 13 p., *http://dx.doi.org/10.3133/ds875*.

ISSN 2327-638X (online)

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By Edward A. du Bray

Introduction

The purposes of this report are to (1) present available geochemical and modal data for igneous rocks associated with epithermal mineral deposits and (2) to make those data widely and readily available for subsequent, more in-depth consideration and interpretation. Epithermal precious and base-metal deposits are commonly associated with subduction-related calc-alkaline to alkaline arc magmatism as well as back-arc continental rift magmatism (Simmons and others, 2005). These deposits form in association with compositionally diverse extrusive and intrusive igneous rocks. Temperature and depth regimes prevailing during deposit formation are highly variable. The deposits form from hydrothermal fluids that range from acidic to near-neutral pH, and they occur in a variety of structural settings. The disparate temperature, pressure, fluid chemistry, and structural controls have resulted in deposits with wide ranging characteristics. Economic geologists have employed these characteristics to develop classification schemes for epithermal deposits and to constrain the important genetic processes responsible for their formation.

Most epithermal deposit classification schemes recognize two principal classes of epithermal deposits, as defined by their gangue mineralogy (Simmons and others, 2005). One class typically includes quartz, adularia, calcite, and illite (abbreviated herein as quartz-adularia deposits); the associated deposits are generally synonymous with the low- to intermediate-sulfidation epithermal deposits of Einaudi and others (2003). The other assemblage typically includes quartz, alunite, pyrophyllite, dickite, and kaolinite (abbreviated herein as quartz-alunite deposits); these deposits are generally synonymous with high-sulfidation epithermal deposits. A third, somewhat distinct, class of epithermal gold-silver ± tellurium deposits, with relatively few members but important because of their large size, occur in alkaline volcanic rocks. The compilation described here was undertaken in support of updating mineral deposit models for quartz-adularia and quartz-alunite epithermal deposits; a parallel effort (K.D. Kelley, oral commun., 2014) will produce a new model for alkaline intrusion-related epithermal gold deposits. Accordingly, data compiled as part of the effort described here are restricted to the igneous rocks associated with the quartz-adularia and quartz-alunite types of epithermal deposits.

Data Compilation Methods

Simmons and others (2005) defined a representative subset of epithermal deposits whose characteristics exemplify those of this broad class of deposits. The quartz-adularia and quartz-alunite members of the representative deposit subset of Simmons and others (2005) (but excluding alkaline intrusion-related epithermal gold deposits) served as the basis for data compilation described here. In particular, primary reference citations itemized for each of the representative deposits were examined and then pertinent geochemical and modal data were compiled. The search for additional data was further expanded by examining potentially pertinent references cited in each of the primary publications.

Demonstrating that a particular epithermal deposit is genetically related to an individual igneous rock unit is seldom possible. Nearly any rock type can host these deposits, but host relations do not demonstrate genetic relations. Therefore, criteria to establish plausible relations between deposit formation and associated igneous rocks must be established. Igneous rocks that are temporally and spatially related to a particular epithermal deposit may be associated with the genesis of that deposit. For this report, igneous rocks whose ages are within several million years, either older or younger, of the deposit age and located within ≤10 kilometers of the deposit are considered to have a possible genetic relation to the particular deposit. Consequently, igneous rocks having these spatial and temporal associations with an epithermal deposit are accepted as those whose characteristics best exemplify the igneous rocks associated with deposit genesis; the geochemical and modal data for these rocks are included in the compilation described here.

Original data source materials (subsequently referred to as sources), including published reports and theses, were used to add information to the database. Altered samples were identified using standard geochemical criteria. Specifically, for the purposes of this compilation, altered samples are those with any of the following characteristics: SiO_2 abundances greater than 79 weight percent, Na_2O abundances less than 1.0 weight percent, $Na_2O/K_2O > 7$, CO_2 concentrations greater than 1.5 weight percent, sulfur abundances greater than 0.5 weight percent, or loss on ignition (LOI) values greater than 4 weight percent; samples with any of these characteristics probably do not preserve primary igneous rock compositions, and the associated data were excluded from the compilation. These metrics are somewhat beyond abundances typical of igneous rocks, but because most rocks within the halo of epithermal deposits have at least some hydrothermal alteration, some weakly altered rocks may have been retained in the compilation.

Compiling analytical methods and associated estimates of precision and accuracy associated with the reported data was beyond the scope of this effort. Analytical protocols, precision, and accuracy were highly variable among sources. Fortunately, most sources document these parameters so that associated questions can be resolved by referring to the appropriate data source.

Reference lists contained in the data sources were examined and used to identify additional potential data sources. In this way, data for 1,497 samples from 60 sources were identified and incorporated in the database. This process has probably resulted in identification and incorporation of the majority of compositional data available for the representative epithermal deposits. For a sample to be included in the database, at least a sample identification and a major oxide analysis were required. Data were compiled using Microsoft Excel and can be accessed using software compatible with .xlsx files. The database release file is titled EpiMdlDB.xlsx.

Starting with original information extracted from the sources, the geochemical data were processed to enhance their usability. Specifically, all censored values were replaced by blank cells and because different sources report iron concentrations determined by different analytical protocols, the mode of iron-abundance data presentation required standardization. For some samples, abundances of both ferric and ferrous iron were reported in the source. In contrast, other sources report only total iron abundances as either Fe_2O_3 or FeO. In most samples, reported ferrous- and ferric-iron abundances are unlikely to represent magmatic values because of variable oxidation during late- to post-magmatic processes. Therefore, to facilitate meaningful comparison of oxide abundances, all iron abundances were converted to ferrous iron (reported in the FeO_pct column), and each major oxide analysis was recalculated to 100 percent on a volatile-free basis. Modal data, the relative proportions of phenocrysts in particular rock samples, were determined for some igneous rock samples for which geochemical data were compiled. All modal data contained in the source publications are included in the data compilation (appendix 1). The worksheet tab titled GeochemData contains the data described above.

Disproportionately large numbers of geochemical analyses are available for igneous rocks associated with several of the representative epithermal deposits. Inclusion of all of these analyses in the interpretation of the geochemical systematics of igneous rocks associated with epithermal deposits would bias the interpreted dataset. Accordingly, an abbreviated, derivative version of the principal database was created by reducing the number of analyses of samples of igneous rocks associated with the Bodie and Aurora, Comstock, Martha Hill-Favona, and Banska deposits. The randomly selected subset of analyses for igneous rocks associated with these deposits constitutes an appropriately abridged, derivative version of the main data compilation; this is the dataset most suitable for synthesis and interpretation. The worksheet tab titled GeochemDataSubset contains the data described above.

Data Fields

Geochemical and petrographic data are presented in columns or sets of related columns (appendix 1) in a Microsoft Excel 2010 workbook (.xlsx format). The contents of appendix 1 include geochemical and modal data for analyzed samples (data fields defined in table 1). Geochemical data in some worksheet cells may appear to be more precise than displayed values, but the implied precision is a misleading artifact of computational processes (for instance, recalculation to 100-percent volatile free) used to create data-cell contents. Blank cells in the worksheet appendix indicate null values or that no data are available. In appendix 1, some blank cells reflect abundances that were reported as “less than the detection limit”; these values were replaced by blank cells to enable statistical analysis of the uncensored data.

Table 1. Definition and characterization of data fields included in appendix 1.

FIELD_NAME	FIELD_DESCRIPTION
Deposit_name	Name of deposit as defined by Simmons and others (2005)
Country	Name of country in which deposit is located
Deposit_type	The primary gangue-mineral assemblage, whether quartz-adularia or quartz-alunite, and defines which of the epithermal model subtypes each deposit represents
Field_Number	Field-assigned sample identifier as defined in the publication identified in the Data_source column
Lithology	Sample composition according to the classification scheme of Le Maitre (2002) for volcanic rocks or Streckeisen (1976) for intrusive rocks
Ign_Form	Form (lava flow, lava dome, dike, sill, plug, pluton, tuff, and so forth) of the igneous rock represented by each sample, where known
SiO2_pct	Silicon, as silicon dioxide, in weight percent; based on major oxide data recalculated to 100 percent on a volatile-free basis
TiO2_pct	Titanium, as titanium dioxide, in weight percent; based on major oxide data recalculated to 100 percent on a volatile-free basis
Al2O3_pct	Aluminum, as aluminum trioxide, in weight percent; based on major oxide data recalculated to 100 percent on a volatile-free basis
FeO_pct	Total iron, as ferrous oxide, in weight percent; based on major oxide data recalculated to 100 percent on a volatile-free basis
MnO_pct	Manganese, as manganese oxide, in weight percent; based on major oxide data recalculated to 100 percent on a volatile-free basis
MgO_pct	Magnesium, as magnesium oxide, in weight percent; based on major oxide data recalculated to 100 percent on a volatile-free basis
CaO_pct	Calcium, as calcium oxide, in weight percent; based on major oxide data recalculated to 100 percent on a volatile-free basis
Na2O_pct	Sodium, as sodium oxide, in weight percent; based on major oxide data recalculated to 100 percent on a volatile-free basis
K2O_pct	Potassium, as potassium oxide, in weight percent; based on major oxide data recalculated to 100 percent on a volatile-free basis
P2O5_pct	Phosphorus, as phosphorus pentoxide, in weight percent; based on major oxide data recalculated to 100 percent on a volatile-free basis
LOI_pct	Volatile content lost on ignition, in weight percent
H2Ob(+)_pct	Structurally bound or essential water, in weight percent
H2Om(-)_pct	Nonessential moisture, in weight percent
CO2_pct	Carbon dioxide, in weight percent
Cl_pct	Chlorine, in weight percent
F_pct	Fluorine, in weight percent
S_pct	Sulfur, in weight percent
Total_I_pct	Initial, pre-recalculation sum of oxide abundances, in weight percent
Volatile_pct	Total volatile content, in weight percent; calculated as the sum of moisture, bound water, carbon dioxide, chorine, fluorine, and sulfur or as the content lost on ignition
Ba_ppm	Barium, in parts per million
Be_ppm	Beryllium, in parts per million
Cs_ppm	Cesium, in parts per million
Rb_ppm	Rubidium, in parts per million
Sr_ppm	Strontium, in parts per million
Y_ppm	Yttrium, in parts per million
Zr_ppm	Zirconium, in parts per million
Hf_ppm	Hafnium, in parts per million

Table 1. Definition and characterization of data fields included in appendix 1.—Continued

FIELD_NAME	FIELD_DESCRIPTION
Nb_ppm	Niobium, in parts per million
Th_ppm	Thorium, in parts per million
U_ppm	Uranium, in parts per million
Ga_ppm	Gallium, in parts per million
La_ppm	Lanthanum, in parts per million
Ce_ppm	Cerium, in parts per million
Pr_ppm	Praseodymium, in parts per million
Nd_ppm	Neodymium, in parts per million
Sm_ppm	Samarium, in parts per million
Eu_ppm	Europium, in parts per million
Gd_ppm	Gadolinium, in parts per million
Tb_ppm	Terbium, in parts per million
Dy_ppm	Dysprosium, in parts per million
Ho_ppm	Holmium, in parts per million
Er_ppm	Erbium, in parts per million
Tm_ppm	Thulium, in parts per million
Yb_ppm	Ytterbium, in parts per million
Lu_ppm	Lutetium, in parts per million
Ag_ppm	Silver, in parts per million
Au_ppm	Gold, in parts per million
Co_ppm	Cobalt, in parts per million
Cr_ppm	Chromium, in parts per million
Ni_ppm	Nickel, in parts per million
Sc_ppm	Scandium, in parts per million
V_ppm	Vanadium, in parts per million
Cu_ppm	Copper, in parts per million
Mo_ppm	Molybdenum, in parts per million
Pb_ppm	Lead, in parts per million
Zn_ppm	Zinc, in parts per million
Sn_ppm	Tin, in parts per million
W_ppm	Tungsten, in parts per million
Ta_ppm	Tantalum, in parts per million
As_ppm	Arsenic, in parts per million
Sb_ppm	Antimony, in parts per million
B_ppm	Boron, in parts per million

Table 1. Definition and characterization of data fields included in appendix 1.—Continued

FIELD_NAME	FIELD_DESCRIPTION
Data_source	Source of data; for a few samples, data were culled from two or more sources; for example, major oxide data may have been compiled from one source and trace element data from another. Data_Src entries are indexed to numbered entries below: 1. du Bray and others (2013) 2. du Bray, E.A., U.S. Geological Survey, unpublished data, 2014 3. du Bray and others (2008) 4. Vikre (1985) 5. John and others (2003) 6. John, D.A., U.S. Geological Survey, unpublished data, 2014 7. Losada-Calderon and others (1994) 8. Nemeth (1976) 9. Redwood (1987) 10. du Bray and others (1995) 11. Kamenov and others (2007) 12. Dubé and others (1998) 13. Warren and others (2004) 14. Kay and others (1987) 15. So and others (1998) 16. Blesa (2004) 17. Thompson and others (1994) 18. Fytikas and others (1986) 19. Simmons and Browne (1990) 20. Van Leeuwen and others (1990) 21. Izawa and others (1990) 22. Izawa and Cunningham (1989) 23. Loucks and others (1988) 24. Izawa and Zeng (2001) 25. Booden and others (2012) 26. Booden and others (2010) 27. Staude (1995) 28. Noble and McKee (1999) 29. Hedenquist and others (1998) 30. Roşu and others (2004) 31. Cunningham and others (1989) 32. Arribas and others (1995) 33. Di Battistini and others (1987) 34. Konečný and others (1995) 35. Steven and Ratté (1960) 36. Weihed and others (1996) 37. Altunkaynak and Yılmaz (1998) 38. Ratté and Steven (1967) 39. Lipman (1975) 40. Hwang and Meyer (1983) 41. Turner (1997) 42. Chen and Huh (1982) 43. Boden (1994) 44. Nash and others (1990) 45. Nash and others (1995) 46. Henry and others (2003) 47. Wells (1937) 48. Maksaev and others (1984) 49. Leavitt and Arehart (2005) 50. Innocenti and others (1981) 51. Ransome and others (1910) 52. Sherlock (1993) 53. Thorson (1971) 54. Jiang and others (2013) 55. Hollings and others (2011) 56. Chiaradia and others (2004) 57. Chiaradia and others (2009) 58. Longo and others (2000) 59. Montgomery (2012) 60. Bissig and others (2003)

Table 1. Definition and characterization of data fields included in appendix 1.—Continued

FIELD_NAME	FIELD_DESCRIPTION
Strat_Name	Available formal or informal stratigraphic nomenclature for igneous rock represented by sample
Abd_Pl_phenos	Modal abundance of plagioclase phenocrysts relative to the whole rock, in volume percent; TR, trace (<0.5 volume percent) amounts
Abd_AlkFld_phenos	Modal abundance of alkali feldspar phenocrysts relative to the whole rock, in volume percent; TR, trace (<0.5 volume percent) amounts
Abd_Qtz_phenos	Modal abundance of quartz phenocrysts relative to the whole rock, in volume percent; TR, trace (<0.5 volume percent) amounts
Abd_Hbl_phenos	Modal abundance of hornblende phenocrysts relative to the whole rock, in volume percent; TR, trace (<0.5 volume percent)
Abd_Opx_phenos	Modal abundance of orthopyroxene phenocrysts relative to the whole rock, in volume percent; TR, trace (<0.5 volume percent) amounts
Abd_Cpx_phenos	Modal abundance of clinopyroxene phenocrysts relative to the whole rock, in volume percent; TR, trace (<0.5 volume percent) amounts
Abd_Ol_phenos	Modal abundance of olivine phenocrysts relative to the whole rock, in volume percent; TR, trace (<0.5 volume percent) amounts
Abd_Bt_phenos	Modal abundance of biotite phenocrysts relative to the whole rock, in volume percent; TR, trace (<0.5 volume percent) amounts
Abd_Opq	Modal abundance of opaque iron-titanium oxide minerals relative to the whole rock, in volume percent; TR, trace (<0.5 volume percent)
Abd_Alt	Modal total alteration mineral content relative to the whole rock, in volume percent; TR, trace (<0.5 volume percent) amounts

Acknowledgments

Data compilation undertaken for this study was conducted as part of the New Mineral Deposit Models for Gold, Phosphate Rare Earth Elements, and Placer Rare Earth Element-Titanium Resources Project funded by the U.S. Geological Survey Mineral Resources Program. The staff of the U.S. Geological Survey Denver Library used the interlibrary loan process to obtain many of the geologic reports on which this compilation is based. Constructive reviews by Jeffrey L. Mauk and Matthew Granitto are much appreciated and helped clarify data presentation.

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Publishing support provided by:

Denver Publishing Service Center

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Appendix

Appendix 1. Geochemical and Modal Data for Epithermal Deposits

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ISSN 2327-638X (online)
http://dx.doi.org/10.3133/ds875