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Geochemical Database for Igneous Rocks of the Ancestral Cascades Arc—Southern Segment, California and Nevada

Data Series 439

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

Cover photograph: Miocene volcanic rocks of the ancestral Cascades arc, southern segment, host epithermal precious metal deposits on Bodie Bluff, east of historic Bodie, California.

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By Edward A. du Bray, David A. John, Keith Putirka, and Brian L. Cousens

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Introduction

The importance of Cenozoic subduction and magmatism associated with the Cascades magmatic arc in understanding the geologic evolution of western North America is widely recognized. Cenozoic volcanic rocks of the Cascades magmatic arc have been traditionally divided into two components: (1) those derived from Pliocene to Quaternary volcanoes of the active High Cascades arc (McBirney, 1978; Hildreth, 2007) and (2) those associated with deeply dissected Tertiary (mostly Eocene to late Miocene) volcanoes of the ancestral Cascades arc. In Oregon and Washington, ancestral Cascades arc rocks form the well-studied (see du Bray and others, 2006) Western Cascades (Callaghan, 1933; Thayer, 1937; Peck and others, 1964), whereas the southern extension of the ancestral Cascades arc along the California-Nevada border was first suggested by Noble (1972) and verified by Christiansen and Yeats (1992). Although subsequent work by Putirka and Busby (2007), Busby and others (2008a, b), and Cousens and others (2008) has added considerably to our understanding of the ancestral arc segment between just north of Lake Tahoe and Mono Lake, California, much of the rest of this diffuse arc remains poorly studied.

Data presented in this report pertain to the geochemistry of igneous rocks that constitute the southern segment of the ancestral Cascades magmatic arc and were compiled as part of the Mineral Systems of the Ancestral and Modern Cenozoic Cascades Arcs and central California Coast Ranges project conducted by the U.S. Geological Survey. A previously completed companion compilation (du Bray and others, 2006) pertains to igneous rocks that constitute the northern segment of the ancestral Cascades arc in Washington and Oregon. The geographic area addressed in this compilation extends south between lats 42°N. (the California-Oregon border) and 37°N. throughout the northwest-elongate region that spans the California-Nevada border (fig. 1). The area is covered by voluminous accumulations of Cenozoic volcanic rock. Although Tertiary phaneritic intrusive rocks are essentially absent in this arc segment, shallowly emplaced dikes, sills, intrusive lava dome complexes, and small plugs are relatively common. Abundant Tertiary igneous rocks preserved in the study area are demonstrably products of subduction-related arc magmatism that prevailed along the west edge of the North American plate during the Cenozoic (Putirka and Busby, 2007; Busby and others, 2008a, b; and Cousens and others (2008).

Decades of geologic investigations in the study area, including those by Thompson and White (1964), O'Neil and others (1973), Silberman and McKee (1973), Ashley and Silberman (1976), Whitebread (1976), Vikre (1989), and John (2001), for example, have highlighted the association between igneous rocks and mineral deposits in the southern segment of the ancestral Cascades arc. These associations suggest that many deposits, representing diverse mineral deposit types, are spatially, temporally, and probably genetically related to ancestral Cascades magmatic arc processes. Although many local studies have been conducted, including Master's and Doctoral theses, volcanic rocks of the southern Cascades arc segment have not been as thoroughly studied as have been the products of modern arc volcanism. Despite the abundance and importance of igneous rocks in the study area, geochemical data available for these rocks have been neither compiled nor synthesized. The geochemical database presented here represents the first phase of an effort to synthesize and interpret the geochemistry of igneous rocks that constitute the southern segment of the ancestral Cascades arc. The ultimate goal of this effort is an evaluation of the time-space-compositional evolution of magmatism associated with the southern Cascades arc segment and identification of genetic associations between magmatism and mineral deposits in this region.

Acknowledgments

We would like to thank a number of individuals who helped make this effort possible. The staff of the USGS Denver library, who used the interlibrary loan process to obtain many of the geologic reports on which this compilation is based, were critical to the success of this compilation. We thank Tatanisha Pettes for her efforts; data from many sources were available only in analog form and had to be painstakingly

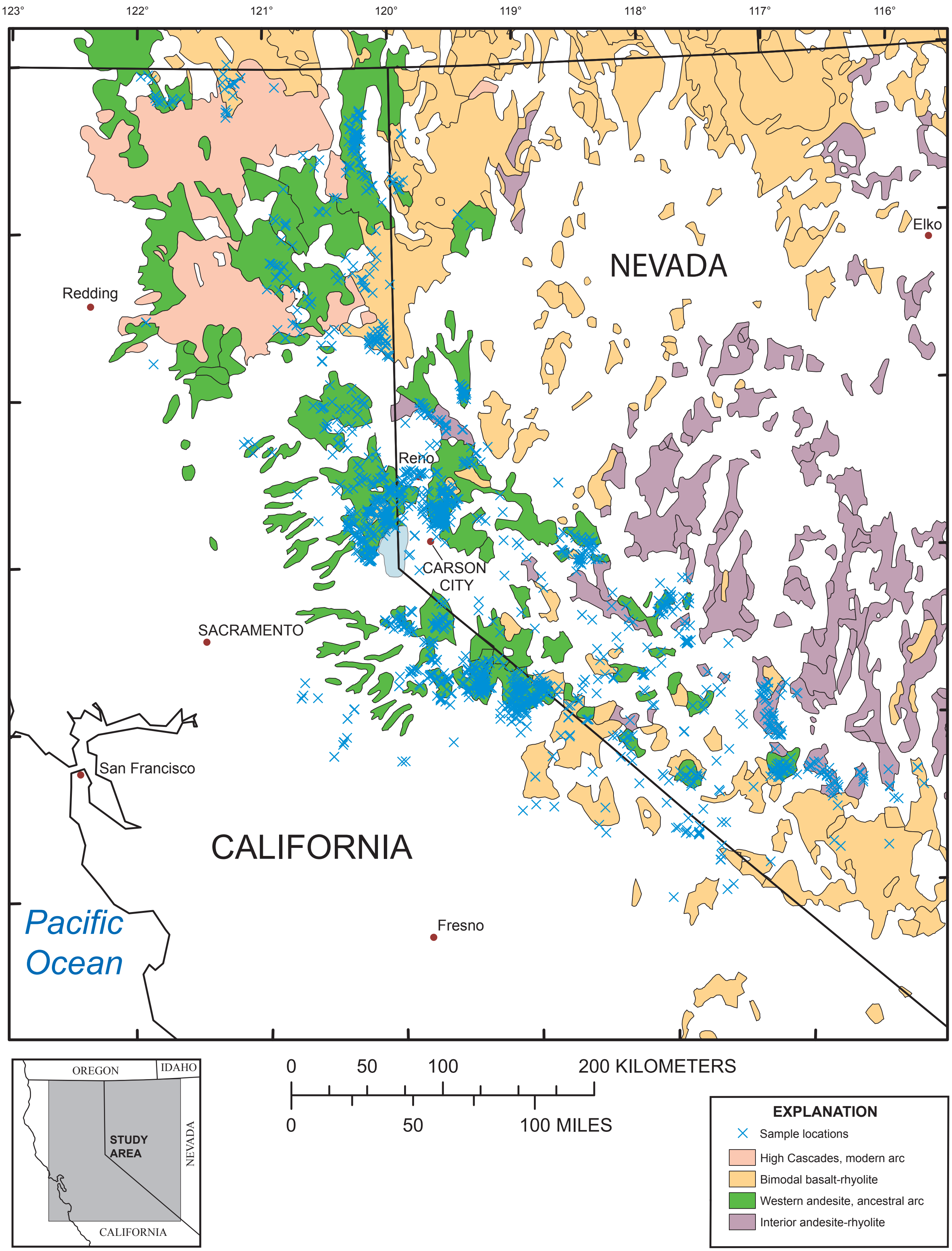

Figure 1. Index map (compiled from King and Beikman, 1975, and Ludington and others, 1996) showing approximate distribution of Cenozoic igneous rocks and analyzed samples, southern Cascades arc segment.

typed. Many geologic researchers tracked down missing bits of information that allow this database to be as complete as it is. These individuals include Matthew Granitto, C.D. Henry, G.R. Priest, P.G. Vikre, A.B. Wallace, M.W. Ressel, M.F. Diggles, J.G. Smith, and R.P. Ashley. We also thank J.C. Hagan, M.M. Jean, Dylan Rood, and R.K. Sharma for their considerable efforts in the X-ray fluorescence lab at California State University, Fresno; they helped generate a significant part of the data contained in this compilation. Finally, we gratefully acknowledge technical reviews by D.L. Fey and S.A. Giles that helped improve this report.

Igneous Rocks of the Southern Cascades Arc Segment—Constituents of the Database

No clear-cut definition distinguishes constituents of the southern segment of the ancestral Cascades magmatic arc. The identity of rocks that are unequivocally part of this arc, as opposed to those that (1) clearly pre- or post-date the arc, or (2) represent geospatially coincident rocks whose genesis is unrelated to magmatic arc processes, is not well delineated. Based on the work of Christiansen and Yeats (1992), Ludington and others (1996) assigned Tertiary volcanic rocks of Nevada to one of three assemblages: (1) 43–19 Ma interior andesite-rhyolite, (2) 20–0 Ma bimodal basalt-rhyolite, or (3) 31–12 Ma western andesite (fig. 1). In Nevada, rocks associated with the southern Cascades arc segment are broadly equivalent to those of the western andesite assemblage. For the purposes of this compilation we used the following criteria to differentiate plausible constituents of the southern Cascades arc segment from other volcanic rocks exposed in the compilation area:

1. Tertiary igneous rocks exposed between lats 42°N. and 37°N. The eastern limit of the southern arc segment is approximately coincident with the east side of the Walker Lane belt (Stewart, 1988); to the west, these rocks, especially lavas and lahars that are presumably products of stratovolcanoes and domes aligned along the crest of the ancestral arc, extend down the gently sloping west flank of the Sierra Nevada.

2. Generally spatially coincident with the distribution of the western andesite assemblage of Ludington and others (1996) and conversely spatially distinct from the distributions of bimodal basalt-rhyolite and interior andesite-rhyolite assemblage rocks.

3. Ages mostly between 25 and about 4 Ma, but may include rocks as young as 3 Ma in the area immediately around Lake Tahoe (Cousens and others, 2008) and as old as 30 Ma in the Warner Range of northeastern California (Duffield and McKee, 1986; Carmichael and others, 2006).

4. Calc-alkaline compositions (though some samples, especially from the Warner Range, the Pyramid Range, and other isolated locales, have a tholeiitic affinity).

5. Lava flows or lahars—rock types consistent with eruption from composite stratovolcanoes that predominate in subduction-related magmatic arcs. Otherwise, age-appropriate ash-flow tuffs exposed within the study area are considered far-traveled, interior andesite-rhyolite assemblage rocks unrelated to southern Cascades arc segment magmatism. Data for the Eureka Valley tuff (erupted from the Little Walker caldera) are included in the database because Priest (1980) suggested an arc-related source; however, Busby and others (2008b) proposed an origin related to Basin and Range magmatism and associated structural controls.

6. Miocene to Pliocene tholeiitic, high alumina (low potassium) olivine basalts in the Modoc plateau of northern California and southern Oregon are considered to represent magmatism associated with back-arc spreading or continental extension and are not included in the database (Hildreth, 2007).

7. Middle Miocene volcanic rocks temporally and chemically equivalent to the voluminous Columbia River Basalt Group, including the Steens and Lovejoy Basalts, are not related to southern Cascades arc magmatism and are not included in the database.

8. Tertiary potassic and ultra-high potassium basalts, mostly in the Sierra Nevada (Moore and Dodge, 1980), are not related to southern Cascades arc magmatism and are not included in the database.

9. Samples of lava flows, debris flows, intrusions, and some pyroclastic deposits are included in the database, whereas data for volcaniclastic sedimentary rocks are not.

10. Samples of rocks from volcanoes that retain primary constructional morphology are considered related to Quaternary High Cascades magmatism and are not included in the database.

Considerable efforts have been made to consistently apply the criteria just outlined. However, because some geochemical data sources present incomplete sample documentation, it has not been possible to prevent inclusion of potentially inappropriate data. The amount of inappropriate data inadvertently included in the database is probably small and should not significantly affect data interpretation.

Data Compilation Methods

Copies of original data source materials (subsequently referred to as sources), including published reports and Master's and Doctoral theses, were used to add data to the database. Reference lists contained in sources of data were examined and used to identify additional data sources. In this way, data for more than 2,000 samples from 82 sources were identified and incorporated into the database. We believe that this process has probably resulted in identification and incorporation of most of the compositional data that have been produced for magmatic-arc related igneous rocks in the study area. In order for a sample to be included in the database, at least a sample number and major oxide analysis were required; most available trace element and (or) isotopic data for these samples were also included in the database. Samples for which only trace element or isotopic data were available were not included in the database. Small amounts of additional geochemical data can be gleaned by consulting the appropriate data sources. Data presented in source materials were included in the database, without modification (with the exception of recalculation of major oxide data, as described in the section pertaining to major oxide data), and all input subsequently verified. No effort was made to exclude hydrothermally altered samples from the compilation. Rather, all igneous rock compositional data were compiled and samples known to be altered were coded accordingly.

Data were compiled using Microsoft Excel and can be accessed using software compatible with .xls files. The database release (file, SW Casc geochem DB.xls) includes several worksheets that are accessed using tabs arrayed along the base of the spreadsheet screen display. The tab labeled "Main SWCasc db" accesses the primary data compilation. The tab labeled "db no cens or alt" accesses a worksheet that contains a copy of the primary data compilation in which censored data (data coded as less than some specified value) and samples that violate the filtering criteria defined in the next paragraph have been deleted. The tab labeled "alt" accesses a worksheet that contains data for altered samples, as defined in the next paragraph, and can be used to evaluate the geochemistry of alteration processes. The database release also includes a tab-delimited, text file version of the database (file, SW Casc geochem DB.txt).

For the purposes of this compilation, hydrothermally altered samples are those samples with any of the following characteristics: SiO_2 abundances greater than 78 or less than 47 percent; total volatile content greater than 4 percent; Al_2O_3 abundances greater than 22 or less than 10 percent; total iron abundances (as FeO) greater than15 percent; MnO abundances greater than 0.6 percent; CaO abundances greater than 15 percent; Na_2O abundances greater than 7 or less than 1 percent; K_2O abundances greater than 7.5 or less than 0.15 percent; or values of Na_2O/K_2O less than 0.5. Samples with any of these characteristics probably do not preserve primary igneous rock compositions and were removed from the data accessed via the "db no cens or alt" tab and included in the data accessed via the tab labeled "alt." In addition, samples with initial analytic totals greater than 102 percent or less than 98 percent (in samples for which at least some volatile abundances were determined) or less than 96 percent (in samples for which no volatile abundances were determined) were identified and removed from the data accessed via the "db no cens or alt" tab; samples with these characteristics probably indicate unusable, inaccurate analyses and were also included in the data accessed via the tab labeled "alt." Row entries in the data accessed via the "alt" tab are sorted into subsets of samples that share the same alteration characteristic (in red, at the top of each subset of data rows).

Data Fields

Data fields presented and described herein represent those considered most critical to addressing questions concerning the tectonic, petrologic, and metallogenic evolution of magmatism in the study area. Data for each of these fields constitute a column, or set of related columns, in the database. Data in these columns can be sorted, queried, and interpreted to address questions concerning the history, development, and implications of magmatic activity in the study area. Sample number records are aggregated in blocks of data that share a primary geochemical data source.

Blank cells in the database indicate that no data are available for the corresponding column. Some sources report values of zero for some database fields. These values indicate that an abundance determination was attempted but that the constituent was not detected in the sample. Similarly, some sources present qualified data. In particular, records for some samples include less than (<) symbols. These data indicate that the constituent was detected but that its concentration was unquantifiable beyond the fact that its concentration is less than the indicated value. Actual analytical precision (number of significant figures) associated with each database entry is portrayed by each displayed onscreen value. Data in some cells appear to be more precise than displayed values, but this is a misleading artifact of computational processes (for instance, recalculation to 100 percent volatile free), which may have been used to create data cell contents. Precision varies within individual columns in accordance with specific analytical protocols and the way data are reported in individual sources. In most cases, the number of significant figures defined in data sources was retained. However, in some cases, the level of precision implied is implausible given either the analytical protocol or the corresponding analytical state of the art; accordingly, some numeric data contained in the database have been rounded to indicate a plausible level of analytical precision.

field_number

Identifiers for analyzed sample materials were compiled from sources and presented without modification; except, all blank spaces were removed from sample identifiers.

lithology

In most cases, the composition of analyzed samples was compiled from information contained in the sources. All volcanic rock compositional names derived from the source were evaluated and updated as necessary, relative to the volcanic rock total alkalis versus silica nomenclature grid (LeBas and others, 1986). Many sources also classify the composition of intrusions (dikes, sills, stocks, and so forth) using volcanic rock nomenclature. These designations suggest that these shallowly solidified, and therefore, fine-grained rocks were not evaluated by modal analysis, and that subsequent name assignment using the nomenclature of Streckeisen (1973) for intrusive igneous rocks was not possible. In accordance with procedures defined by the International Union of Geological Sciences, composition names for intrusive rocks are defined using the relative modal proportions of quartz, alkali feldspar, and plagioclase relative to the classification scheme of Streckeisen (1973).

ign_form

The form of the igneous rock represented by each sample is given where known. In some cases, source materials do not specify whether the sample represents lava, a pyroclastic deposit, or some form of intrusion; in these situations, lava is presumed. Samples coded as representing dikes or sills represent thin tabular bodies that are discordant and concordant with enclosing rocks, respectively. Larger intrusive bodies, generally discordant to enclosing rocks, are coded as plutons, stocks, and plugs depending on their size; plutons are the largest of these bodies, whereas plugs are the smallest. In most cases, samples from intrusions coded as plutons represent bodies that cooled slowly, at the greatest depths, and are phaneritic, whereas samples from intrusions coded as plugs represent the subvolcanic environment, many have a quenched groundmass, and some may represent parts of endogenous to exogenous volcanic flow domes.

alteration

Many sources explicitly indicate that some analyzed samples are altered. Other sources provide sufficient descriptive information about samples that alteration can be inferred. Some sources simply indicate that samples are altered; these samples are simply coded as “Yes” in the “alteration” column. Other alteration terms used to code altered samples are advanced argillic, argillic, deuteric, hydrated glass, opalized, oxidation, potassic, propylitic, sericitic, and silicification. Each of these terms is applied in accordance with their standard usage, defined for instance by Guilbert and Park (1986). These terms are appended with a “?” when the proper alteration nomenclature is ambiguous due to the nature of available descriptive information.

longitude and latitude

An effort was made to obtain location data for all samples with composition data. Most sources contain some form of location information. Missing sample location data were requested from authors, most of whom were able to provide missing information. Accordingly, location data are available for all but a very few samples. Latitude and longitude data are reported as decimal degrees (relative to the North American Datum of 1927). In the study area, longitude is reported as a negative value (western hemisphere) and latitude as a positive value (northern hemisphere).

Location data are of variable quality as a consequence of the manner in which they were initially acquired and subsequently reported. The number of significant figures presented as part of location data in the “longitude” and “latitude” columns indicates relative levels of sample location precision, as follows:

- four significant figures indicate that the given location is accurate within tens of meters,
- three significant figures indicate that the given location is accurate within hundreds of meters,
- two significant figures indicate that the given location is accurate within thousands of meters, and
- one significant figure indicates that the given location is accurate within tens of thousands of meters.

Some sources report sample location in terms of Township, Range, and Section values, usually to the closest quarter of a section. Township-Range-Section data were digitized to obtain decimal degree location; within the appropriate quarter section quadrilaterals, digitized points were usually selected to coincide with a road, trail, stream bottom, quarry, or natural cliff, any of which might represent a likely sampling location. Some sources do not include numerical sample location data but do contain sample maps. Location data for these samples were obtained by digitizing sample sites. A very few sources merely describe sample locations; these were used to estimate a sample location, which was then digitized.

SiO2, TiO2, Al2O3, FeO*, MnO, MgO, CaO, Na2O, K2O, and P2O5

Sources report whole rock, major oxide data in a variety of formats. In addition, these data were produced by a wide array of analytical procedures, each with its own associated analytical precision and accuracy. Compositions for some of the samples included in the database are presented in their sources already recalculated to 100 percent, volatile free. Some information loss occurs when data are reported solely in this fashion. 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 reference to the appropriate data source. The database includes columns for the abundances of SiO_2, TiO_2, Al_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O, and P_2O_5. However, because diverse analytical protocols were used to analyze samples, not all sources contain data for each of these constituents. Cell entries of “bdl” indicate that the abundance of the indicated constituent is below detection limit.

Several different schemes are possible for reporting iron contents. In addition, reported abundances of ferrous versus ferric iron in many of these rocks are unlikely to represent magmatic values, because of oxidation during late- to post-magmatic hydrothermal processes. Consequently, total iron abundances were recalculated as ferrous iron oxide and denoted as FeO*. Interaction with postmagmatic fluids caused compositions of many rocks of the study area to change in other ways as well. In particular, many of these rocks were hydrothermally altered (as indicated by secondary clay minerals, sericite, and (or) chlorite). Both processes caused volatile contents of the affected samples to increase, and correspondingly caused relative abundances of all other constituents to decrease. Therefore, to facilitate meaningful oxide abundance comparisons among samples, all analyses were recalculated to 100 percent on a volatile-free basis. The resulting data are reported in columns identified by SiO_2, TiO_2, Al_2O_3, FeO*, MnO, MgO, CaO, Na_2O, K_2O, and P_2O_5. All these data are reported as weight percent. To facilitate comparison of ancestral Cascades—southern arc segment major oxide data to those for other magmatic arc rocks, the compiled data are presented on several standard variation diagrams (figs. 2, 3, 4).

LOI, H2O+, H2O-, CO2, Cl, F, and S

The data sources report volatile constituent contents of igneous rock samples in widely disparate ways. In order to capture important information concerning the volatile contents of these rocks, an array of data columns was designated to account for various analytical protocols and data reporting formats. Volatile constituents whose abundances are commonly determined include LOI (loss on ignition), H_2O+ (structurally bound), H_2O- (nonessential moisture), CO_2, Cl, F, and S. Of these, few sources contain halogen and S abundance data. Similarly, data for H_2O+, H_2O-, and CO_2 are rarely and nonsystematically reported. However, given the potential importance of these constituents in hydrothermal processes, compiling all available data for these components seems warranted. Several sources present data for H_2O and do not specify whether this species is bound water (+) or nonessential moisture (-). These data have been included in the H_2O+ column of the database. Cell entries of “bdl” indicate that the abundance of the indicated constituent is below detection limit.

total_I

One measure of major oxide analytical accuracy is how nearly the sum of the determined constituents approaches 100 percent. Consequently, the database includes a column that reports initial oxide sum analytical totals as reported by the source. Some sources do not include totals; totals for these samples were computed and added to the database. Initial analytical totals reported in the sources were spot checked for accuracy; discrepancies were noted and corrected in a number of cases. Many sources present abundances for the major oxides but include no abundance data for volatile constituents. Initial analytical totals for these samples tend to be from several to 5 or 6 percent less than 100 percent. It is impossible to determine whether these low initial totals result from inaccurate analyses and (or) unreported volatile constituent abundances.

vol_sum

The total volatile content of igneous rocks in the study area can provide some insight concerning whether abundances of other constituents accurately represent primary magmatic values. Samples with elevated volatile contents, for example greater than 3 weight percent, are likely to have experienced some fluid-mediated, postmagmatic chemical modification. Given the wide range of analytical protocols used in analysis of these samples, the best possible measure of sample volatile content is total volatile content. For the purposes of the compilation, if LOI data are the only information contained in source data compilations concerning volatile content, LOI values were designated as total volatile content. Alternatively, if the source includes data for H_2O+, H_2O-, CO_2, Cl, F, or S, these data were summed to yield total volatile content. All data are presented as weight percent.

Ba, Be, Cs, Rb, Sr, Y, Zr, Hf, Nb, Th, U, Ga, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Ag, Au, Co, Cr, Ni, Sc, V, Cu, Mo, Pb, Zn, Sn, W, Ta, As, Sb, and B

The sources present data for inconsistent sets of trace elements. Of these, data for Ba, Be, Cs, Rb, Sr, Y, Zr, Hf, Nb, Th, U, Ga, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Ag, Au, Co, Cr, Ni, Sc, V, Cu, Mo, Pb, Zn, Sn, W, Ta, As, Sb, and B were compiled; all data are in parts per million. These constituents are among those for which sources most often contain data and also are considered sufficient to address

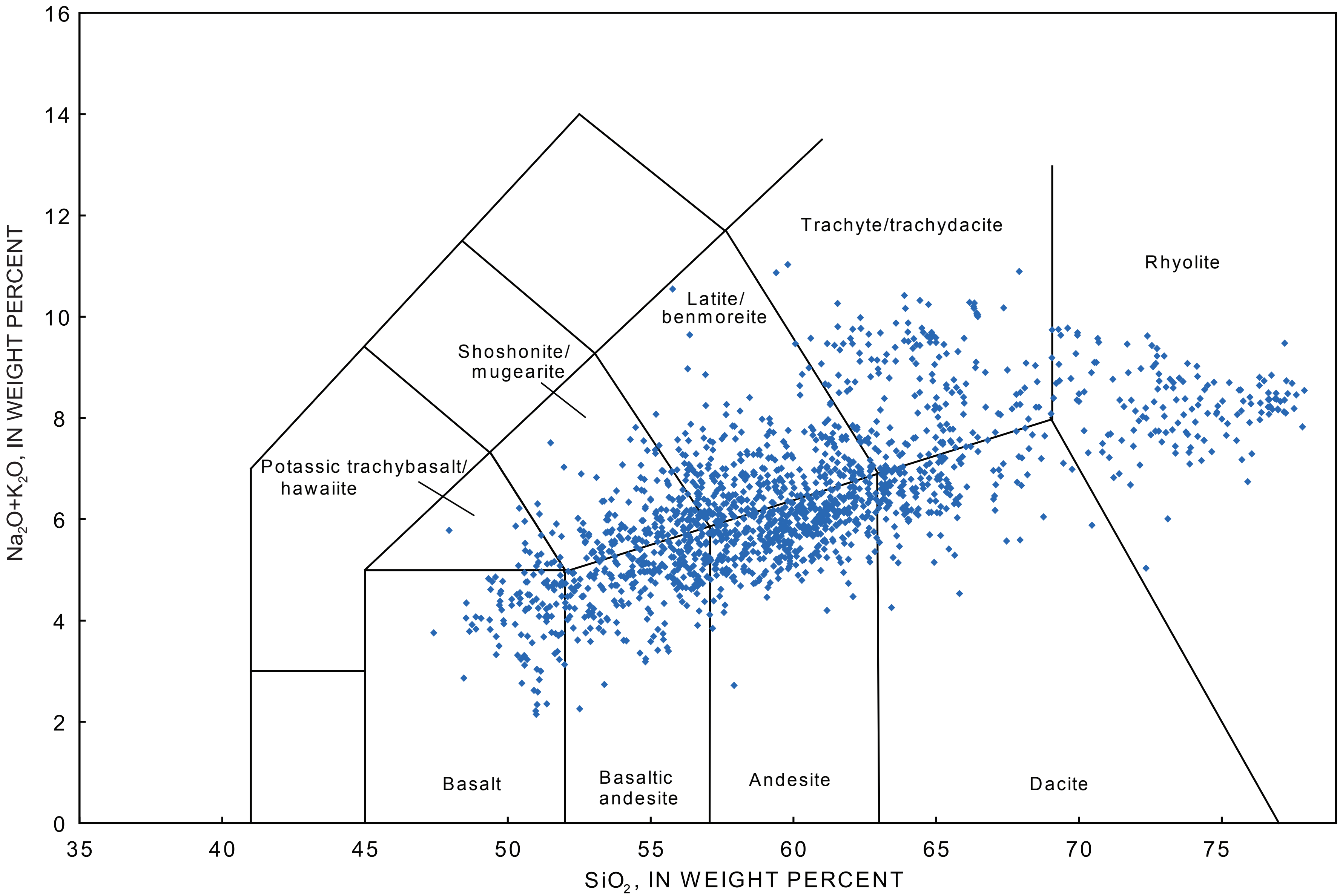

Figure 2. Total alkali-silica variation diagram showing compositions of ancestral Cascades—southern arc segment rocks. Field boundaries from Le Bas and others (1986).

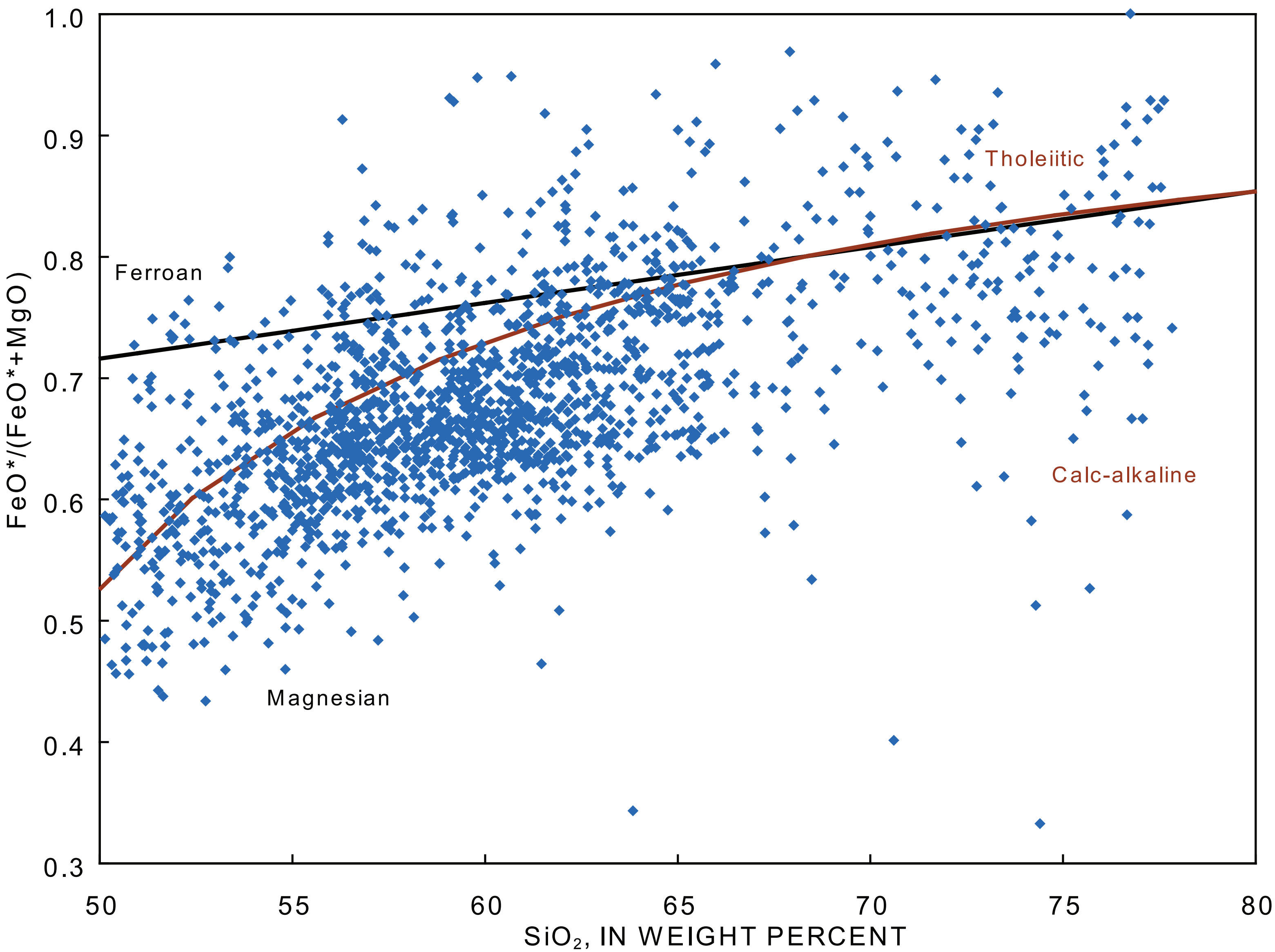

Figure 3. FeO/(FeO+MgO) variation diagram showing the composition of ancestral Cascades—southern arc segment rocks relative to boundaries between ferroan and magnesian rocks as well as between tholeiitic and calc-alkaline rocks. Ferroan versus magnesian boundary (black line) from Frost and others (2001), tholeiitic versus calc-alkaline boundary (red line) from Miyashiro (1974).

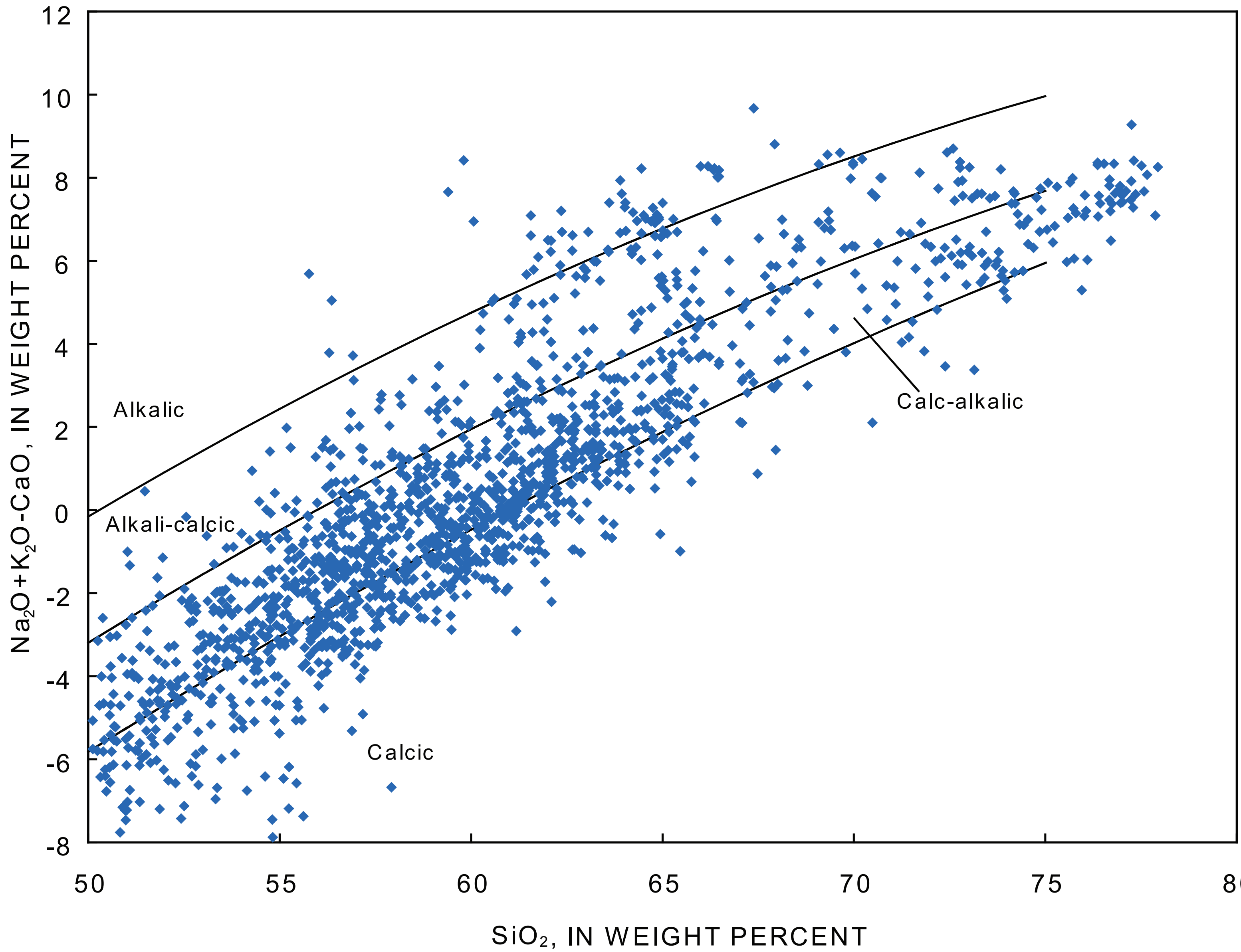

Figure 4. Na_2O+K_2O-CaO versus SiO_2 variation diagram showing the composition of ancestral Cascades—southern arc segment rocks relative to boundaries between alkalic, alkali-calcic, calc-alkalic, and calcic rock series. Boundaries between various rock series from Frost and others (2001).

many petrologic, tectonic, and metallogenic questions. Cell entries of “bdl” indicate that the abundance of the indicated constituent is below detection limit. To facilitate comparison of ancestral Cascades—southern arc segment trace element data and their tectonic implications to those for other magmatic arc rocks, the compiled data are plotted on a Rb versus Y + Nb variation diagram (fig. 5).

chem_src

Chemical and location data for each sample included in the database were compiled from primary data sources, in most cases a single source. 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. Entries in the “chem_src” column of the database are keyed numerically to sources identified in the following list. Sources of geochemical information include publications of the U.S. Geological Survey, unpublished data contained in the U.S. Geological Survey National Geochemical Database, Master’s theses, Doctoral dissertations, articles published in journals, and publications of the Nevada Bureau of Mines and Geology.

Entries in the “chem_src” column of the database are keyed numerically to sources identified below:

1. King (2006)
2. Noble and others (1976)
3. Ransome (1898)
4. Priest (1980)
5. Brem (1977)
6. John (2001)
7. Crowder and others (1972)
8. Ross (1961)
9. O’Neil and others (1973)

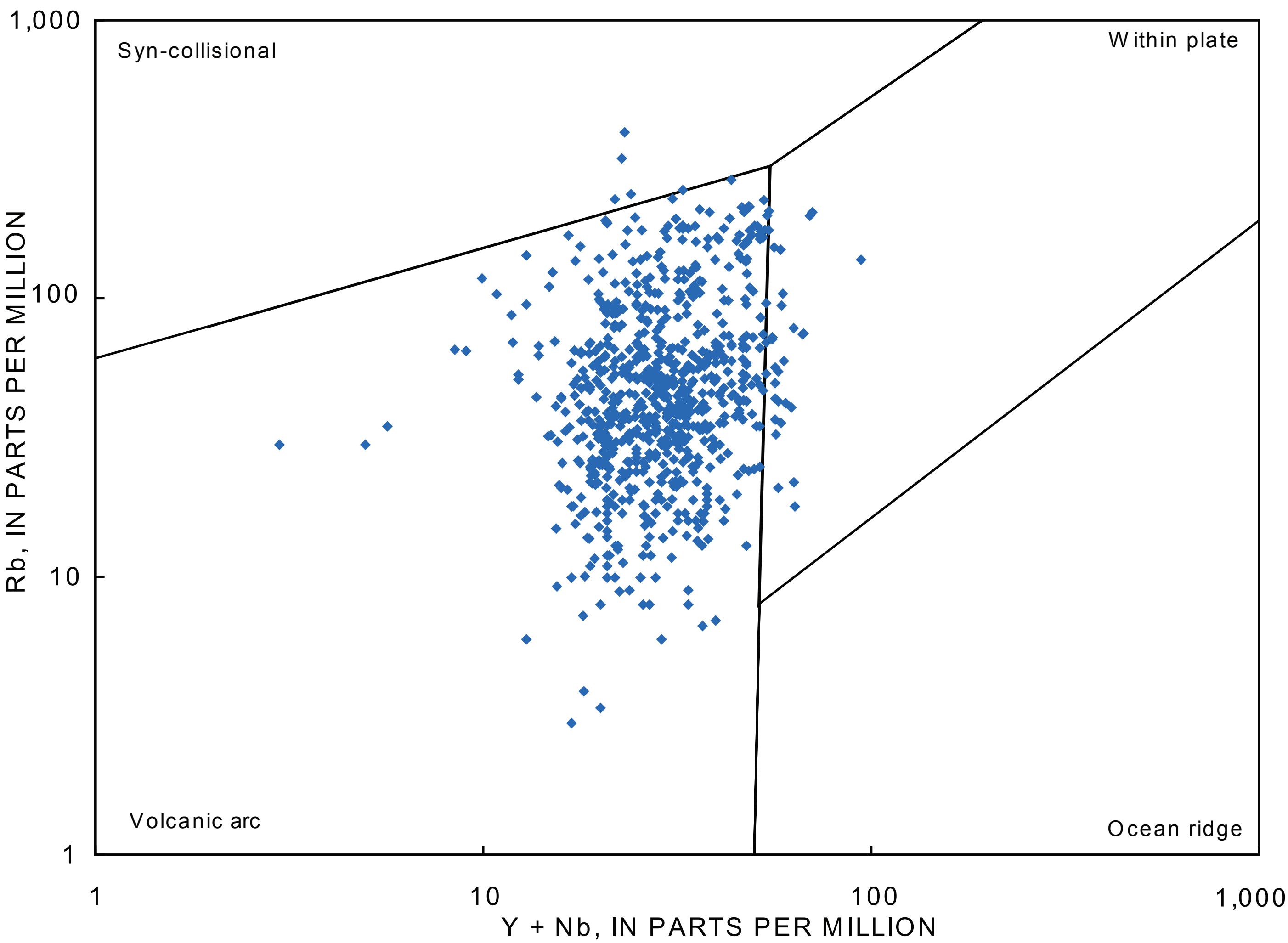

Figure 5. Trace-element, tectonic-setting–discrimination variation diagram showing the composition of ancestral Cascades—southern arc segment rocks. Tectonic setting-composition boundaries from Pearce and others (1984).

10. Knopf (1918)
11. Halsey (1953)
12. Spurr (1901)
13. Curtis (1951)
14. Bonham and Garside (1979)
15. Putirka, Keith, University of California, Fresno, unpublished data, 2007
16. Cornwall (1972)
17. Thompson and White (1964)
18. Ransome (1909)
19. Busby and others (2008a)
20. Busby and others (2008b)
21. Cousens, B.L., Carleton University, unpublished data (#1), 2007
22. Whitebread (1976)
23. Schwartz (2001)
24. Garrison (2004)
25. John (1992)
26. Latham (1985)
28. Al-Rawi (1969)
29. Chesterman and others (1986)
30. Osborne (1985)
31. Carmichael and others (2006)
32. Garside and Bonham (2006)
33. Henry and others (2004)
34. Garside and others (2003)
35. Egger, A.E., Stanford University, unpublished data 2008
36. Garside and Nials (1998)
37. John, D.A., U.S. Geological Survey, unpublished data (#1) 2007
38. Bingler (1978)
39. Schoen and White (1967)
40. Castor and Henry (2000)
41. Vikre (1989)
42. Ekren and others (1971)
43. Robinson (1972)
44. Silberman and Chesterman (1995)
45. Keith (1977)
46. Wallace (1975)
47. Pullman (1983)
48. Luethe (1974)
49. John, D.A., U.S. Geological Survey, unpublished data (#2), 2007
50. Mallin (1989)
51. Hudson (1977)
52. Garside (1979)
53. Bosma-Douglas (1987)
54. du Bray, E.A., U.S. Geological Survey, unpublished data, 2008
55. Ressel (1996)
56. Kistler (1974)
57. Bartow (1980)
58. Dodge and Calk (1986)
59. Tooker and others (1970)
60. Wilshire (1957)
61. John, D.A., U.S. Geological Survey, unpublished data (#3), 2008
62. Grose and McKee (1986)
63. Putirka and Busby (2007)
64. Grose and others (1992)
65. Youngkin (1980)
66. Bean (1980)
67. Tuppan (1981)
68. Grose and others (1990)
69. Diggles, M.F., U.S. Geological Survey, unpublished data, 2008
70. Finn (1987)
71. Jean (2007)
72. Vikre, P.G., U.S. Geological Survey, unpublished data, 2008
73. U.S. Geological Survey, National Geochemical Database, 2008
74. Ormerod (1988)
75. John, D.A., and Colgan, J.P., U.S. Geological Survey, unpublished data (#1), 2008
76. John, D.A., U.S. Geological Survey, unpublished data (#4), 2008
77. Hudson and others (2009)
78. Sharma (2008)
79. John, D.A., and Colgan, J.P., U.S. Geological Survey, unpublished data (#2), 2008
80. John, D.A., U.S. Geological Survey, unpublished data (#5), 2008
81. du Bray, E.A., and John, D.A., U.S. Geological Survey, unpublished data, 2008
82. Cousens, B.L., Carleton University, unpublished data (#2), 2009

rad_age

The ages of the igneous rocks in the study area have been of considerable interest and many age determinations have been made. The database column titled “rad_age” contains radiometric ages, in millions of years, for samples of Tertiary igneous rocks in the study area. Multiple geochronologic age determinations have been obtained for some samples. Ages recorded in the “rad_age” column are the best possible estimates based on information contained in the age sources.

uncert

The database column titled “uncert” contains data, in millions of years, for the analytical uncertainties (as presented in the source) associated with each of the age determinations reported in the “rad_age” column.

age_src

Sloan and others (2003) have recalculated ages using currently accepted decay constants, as appropriate, and compiled most of the isotopic age data available for rocks in the southern Cascades arc segment. This compilation was used to identify the primary data sources (identified in the database column titled “age_src”) from which geochronologic data for the study area’s igneous rocks were extracted to compile ages of samples included in the database. In many cases, geochemical and geochronologic data are contained in the same source; the age source for each of these samples is numerically keyed to a previously identified source of geochemical data (database column “chem_src”). For the relatively small number of samples for which geochemical and geochronologic data have different sources, age source(s) data are keyed to alpha-coded citations listed below:

A. Noble and others (1974)
B. Silberman and Chesterman (1972)
C. Silberman, Bonham, and others (1979)
D. Silberman and McKee (1972)
E. Castor and others (2005)
F. Silberman, White, and others (1979)
G. Saucedo and Wagner (1992)
H. Wise, W.S., University of California, Santa Barbara, unpublished data, 2007
I. Henry, C.D., Nevada Bureau of Mines and Geology, unpublished data, 2007
J. McKee and John (1987)
K. John and others (1989)
L. Faulds and others (2000)
M. Chesterman and Gray (1975)
N. Smailbegovic (2002)
O. Smith, J.G., U.S. Geological Survey, unpublished data, 2008
P. Fleck, R.J., U.S. Geological Survey, unpublished data, 2008
Q. Kleinhampl and others (1975)
R. Garside and Silberman (1978)
S. Diggles and others (1989)
T. Pullman (1984)
U. Robinson and others (1968)
V. Crafford (2007)
W. Krauskopf and Bateman (1977)
X. Ashley and Silberman (1976)
Y. Gilbert and Reynolds (1973)
Z. Larsen (1979)
AA. Marvin and Cole (1978)
AB. Chesterman (1968)
AC. Dalrymple (1963)
AD. Huber and Rinehart (1967)
AE. Dalrymple (1964)
AF. Marvin and others (1977)
AG. Gilbert and others (1968)
AH. Morton and others (1977)
AI. Reheis and Block (2007)

geol_age

Radiometric ages have not been determined for most samples included in the database. However, identified age determinations and geologic and geochronologic reasoning were used to develop preferred geologic age estimates for many of the Tertiary igneous rock units in the study area. Geologic ages where given in years are rounded to the nearest million. No systematic effort was made to establish geologic ages for samples of dikes, sills, and other volumetrically insignificant intrusions. No entry is recorded in the “geol_age” column when the associated sample has been radiometrically dated.

geol_age_src

Estimates of geologic age for many of southern Cascades arc segment rocks rely upon geologic inference, correlations, and other diverse data sources; these sources are identified in the “geol_age_src” column of the database. Digits to the left of the “\” symbol identify the principal source used to establish geologic age. These digits are keyed to entries previously identified in either the “chem_src” or “age_src” discussions. Digits to the right of the “\” symbol identify the rationale used to establish geologic age. Entries coded as “\1” indicate that a correlation of map units figure or some discussion of age in the source provide the basis for the geologic age assignment. In contrast, entries coded as “\2” indicate that the radiometric age of sample(s) that are not part of the database, but representative of the same intrusion as sample(s) that are included in the database, was used to establish geologic age.

strat_name

Some sources associate either formal or informal stratigraphic nomenclature with samples for which they include geochemical data. These names were compiled in the database field titled “strat_name” in order to facilitate sorting of database contents by stratigraphic unit. Entries in this field are shortened from full stratigraphic designation (for instance, Eureka Valley Tuff) to entries that denote just the geographic feature included in the full stratigraphic designation (for instance, Eureka Valley). Coding samples by assigned stratigraphic name allows grouping of samples from a particular stratigraphic unit. Grouped in this way, geochemical characteristics of units can be identified and interpreted and comparisons to similar stratigraphic units can be made. Among the regionally most important stratigraphic designations of this sort are Kate Peak, Alta, Eureka Valley, Relief Peak, Table Mountain, Disaster Peak, Mehrten, Carson Pass, Stanislaus, Milltown, Lousetown, Coal Valley, Boca Ridge, Aurora, Warner Range, Pyramid, Potato Peak, Willow Springs, and Mt. Biedeman. Unfortunately, many data sources do not assign specific formal or informal stratigraphic names; these sources assign samples names that are entirely lithologic, such as basalt, basaltic andesite, or andesite.

Hudson and others (2009) have refined stratigraphic nomenclature for Tertiary volcanic rocks in the Virginia City, Nev., area. Stratigraphic designations compiled in the “strat_name” column for samples collected during their geologic mapping in the Virginia City area are in accord with their new nomenclature for the sampled units. Their stratigraphic refinements also affect names assigned to previously collected and analyzed samples from this area. Entries in the “strat_name” column of the form Kate Peak (Flowery Peak) give the stratigraphic name of the sampled unit, as assigned by the individual who collected the sample, followed (in parentheses) by the new stratigraphic name, as defined by Hudson and others (2009), for the sampled unit.

Isotopic Data

Stable and (or) radiogenic isotope data are available for a relatively small fraction of southern Cascades arc segment geochemical database samples. Data of this sort provide additional geologic framework information that can help constrain magma sources and the processes that contributed to the petrogenesis of these rocks. Compiled isotopic data pertain to ratios of various isotopes of oxygen, strontium, lead, and neodymium, as described next.

δO18

Stable isotope ratio of ^{18}O to ^{16}O relative to the same ratio in a standard (usually SMOW, standard mean ocean water).

87Sr/86SrI

Initial isotope ratio of ^{87}Sr (generated by radioactive decay of ^{87}Rb) to ^{86}Sr; except data from Ormerod (1988) (source=74), which are measured $^{87}Sr/^{86}Sr$ ratios. Initial ratios are calculated from measured $^{87}Sr/^{86}Sr$ ratios and determined sample ages.

206Pb/204Pb

Isotope ratio of ^{206}Pb (generated by radioactive decay of ^{238}U) to ^{204}Pb.

207Pb/204Pb

Isotope ratio of ^{207}Pb (generated by radioactive decay of ^{235}U) to ^{204}Pb.

208Pb/204Pb

Isotope ratio of ^{208}Pb (generated by radioactive decay of ^{232}Th) to ^{204}Pb.

143Nd/144Nd

Isotope ratio of ^{143}Nd (generated by radioactive decay of ^{147}Sm) to ^{144}Nd.

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