Time-Space Development of an External Brine-Dominated, Igneous-Driven Hydrothermal System: Humboldt Mafic Complex, Western Nevada

David A. Johnson1 and Mark D. Barton

Center for Mineral Resources, Department of Geosciences, University of Arizona, Tucson, Arizona 85721

Abstract

The Humboldt mafic complex, west-central Nevada, is a large composite Middle Jurassic basaltic-composition volcano-plutonic center that has exceptionally extensive (>900 km³), intense (nearly complete leaching of many elements) sodium-rich hydrothermal alteration. Mapping of exposures at multiple structural levels allows assessment of the time-space development of hydrothermal alteration and cogenetic magnetite and hematite ± copper sulfide mineralization.

Alteration varies from early, deep and proximal mafic-plagioclase-hornblende to shallow and distal albite-actinolite-chlorite and chlorite-carbonate assemblages. These associations reflect large compositional changes in host rocks (mass-transfer), whereas distal and deep propylitic assemblages are less intensely modified. Substantial quantities of iron are present in massive, breccia-form, and stratabound magnetite and hematite bodies at intermediate and shallow depths. Lower amounts of copper, cobalt, and other metals are sporadically enriched at shallow levels.

Field, petrological, and geochemical constraints require that the fluids were dominantly or entirely non-magmatic, external brines that circulated in response to the heat and permeability increases associated with repeated basaltic intrusion. The Humboldt system represents a mafic end-member among iron oxide-rich copper-bearing hydrothermal systems (Barton and Johnson, 1996) and, in the larger context, an end-member in the spectrum of igneous-related hydrothermal systems.

Introduction

Igneous-related iron oxide-rich hydrothermal systems are common throughout western North America in Jurassic rocks (Barton et al., 1988; Barton, 1996). This kind of system has attracted attention globally because some occurrences host large concentrations of Cu, Au, and other elements (e.g., Hitzman et al., 1992). The origin of these hydrothermal systems is controversial and revolves around the source of the hydrothermal fluids, magmatic versus externally derived (Barton and Johnson, 1996; Hitzman et al., 1992; Williams, 1994).

Fe oxide-rich deposits occur with igneous rocks that range from mafic to felsic (Barton and Johnson, 1996). In this and other respects, they contrast to many other kinds of igneous-related mineral deposits which occur with narrow ranges of igneous compositions. Alkali-dominated hydrothermal alteration is voluminous and large volumes of magnetite- or hematite-rich rock (replacement and open space) typify generally sulfide-poor mineralization.

The hydrothermal system associated with the Humboldt mafic complex (Fig. 1) represents an exceptionally large, compositional end-member within the Fe oxide group. In aggregate, the system covers parts of three mountain ranges in the western Great Basin over an area approximately 40 by 70 km in present exposure. This basalt-related hydrothermal system provides an important contrast with other Great Basin Jurassic Fe oxide-rich districts that are associated with intermediate- to felsic-composition igneous rocks. The comparison of Fe oxide-rich systems associated with different kinds of igneous rocks and with other styles of mineralization, as at Yerington, allows better assessment of the roles that igneous rocks play in the hydrothermal system.

This study grew out of recognition that regionally extensive sodium-rich hydrothermal alteration in the western United States typically had associated Fe oxide-rich mineralization (Barton et al., 1988; Battles and Barton, 1995). Work in the Humboldt mafic complex was undertaken as part of a comparison of compositionally diverse systems in the Jurassic of the Great Basin (Johnson, 2000). The Humboldt mafic complex is favorable for study due to good exposure of multiple structural levels and a good pre-existing geologic framework. This was critical to building an understanding of the characteristics and origin of the widespread iron oxide ± copper mineralization in this complex and its implications for similar systems elsewhere.

This study draws upon earlier work on the complex and provides part of the framework for geochemical studies in progress. Early studies concentrated on descriptive information on the iron oxide occurrences in the Mineral basin district (Reeves and Kral, 1955; Nickle, 1968). These early studies were complemented by regional geologic and petrographic work of Speed (1962, 1976), who covered the entire complex. Geologic maps of the region were published by Page (1965) and Speed (1976). Vanko (1982) and Vanko and Bishop (1982) studied aspects of the petrology of the igneous and scapolitized rocks.

Mining history and Fe-Cu-Co-Ni resources

Copper and cobalt-nickel-copper mineralization within the Humboldt mafic complex was discovered early in Nevada’s mining history. Most copper occurrences are high in the volcanic section and found in the central part of the complex in the Stillwater Range. The Boyer Copper mine was found prior to 1860, and in 1861 shipped several wagon trains of rich copper sulfide ore to Sacramento for treatment (Lincoln, 1923). Early observers suggested that these copper occurrences

1 djohnson@geo.arizona.edu
were similar in grade and extent to porphyry copper deposits such as Ely, Bingham, and Yerington (Carpenter, 1911). Nickel-cobalt-copper occurrences in Cottonwood Canyon were located in 1882 and shipped ores to Swansea, Wales (Lincoln, 1923; Ferguson, 1939).

Igneous and sedimentary rocks related to the Humboldt mafic complex contain more than 50 occurrences of iron oxide mineralization (Johnson, 1977; Moore, 1971; Willden and Speed, 1974), ranging from small prospects to deposits exceeding 100 Mt of resource. Production of iron began in the late 1880s and continued intermittently through World War II (Reeves and Kral, 1955; Willden and Speed, 1974). After World War II, Japanese steel companies contracted with Nevada mines to supply iron ore. In addition to shipments made to Japan, small quantities of ore were shipped to the Ford Motor Company in Dearborn, Michigan. Production continued until 1968, when contracts expired. Small shipments, mainly from stockpiled ore, have continued on and off until the present mainly for use in the cement industry. Total production to 1971 is at least 4 Mt of iron ore. Published resource estimates for 15 of the 31 largest mines and prospects is greater than 170 Mt of measured and indicated reserves at an average grade of 33 wt percent iron (Moore, 1971). Total resource estimates for all evaluated occurrences are probably greater 500 Mt (unpub. reports, United States Steel). In addition to metals, small amounts of gypsum were produced from Jurassic sedimentary rocks in the West Humboldt Range and Mopung Hills (Willden, 1974).

Geologic Framework

The Humboldt mafic complex and related host rocks are exposed in the West Humboldt, Stillwater, and Clan Alpine ranges and in the Buena Vista Hills covering an area of approximately 1800 km². The outcrop pattern forms a crude ellipse elongated east-west with a two to one axis ratio (Fig. 2; Speed, 1976). Stratigraphic relations and major structural relationships are summarized in Figure 3.

The Humboldt mafic complex was emplaced at ~170 Ma into an extending back-arc trough (Saleeby et al., 1992; Johnson, 2000) in the mildly alkaline Jurassic arc (Miller, 1978). The mafic rocks intrude and overlie Late Triassic to Early Jurassic pelitic assemblages of the Lovelock assemblage (Speed, 1976). The lowest portion of the complex consists of numerous intrusive bodies which intrude and feed the overlying volcanic pile. Plutonic rocks are dominantly gabbroic. West-northwest-oriented mafic dikes are abundant and locally form sheeted dike swarms. These are best exposed in the central portions of the complex. The overlying volcanic pile is mainly composed of basaltic lavas and tuffs with interbedded volcaniclastic and other sedimentary rocks (Johnson, 2000). Volcanic rocks overlie or interfinger with sandstones and evaporites of the Middle Jurassic Boyer Ranch Formation (central areas) and the carbonates and evaporites
of the Lovelock and Muttlebury Formations (western areas; Speed and Jones, 1969; Johnson, 2000).

Structural relationships within the Humboldt mafic complex are complex. These include (1) compressional, pre-Humboldt mafic complex structures (Elison and Speed, 1988; Oldow et al., 1990; Wyld and Wright, 2000), (2) extensional and possible compressional structures, syn-Humboldt mafic complex (Johnson, 2000; Speed, 1966, 1976; Speed and Page, 1964), (3) compressional, post-Humboldt mafic complex thrusting along the Lunning-Fencemaker thrust belt (Oldow et al., 1990, Wyld and Wright, 2000), and (4) mid-Tertiary and Basin and Range extension (Hudson and Geissman, 1991; John, 1995; Johnson, 2000). These relationships have led previous workers to a variety of interpretations for the origin of the Humboldt mafic complex (Speed, 1966, 1976; Speed and Page, 1964), (3) compressional, post-Humboldt mafic complex thrusting along the Lunning-Fencemaker thrust belt (Oldow et al., 1990, Wyld and Wright, 2000), and (4) mid-Tertiary and Basin and Range extension (Hudson and Geissman, 1991; John, 1995; Johnson, 2000). These relationships have led previous workers to a variety of interpretations for the origin of the Humboldt mafic complex (Speed, 1966, 1976, Dilek et al., 1988, Dilek and Moores, 1995). Herefore largely undescribed, Tertiary extension within the Humboldt mafic complex complicates the structural and lithologic story in the pre-Tertiary rocks (Johnson, 2000).

Pre-Humboldt complex folding and thrusting are exposed in Triassic and lower Jurassic rocks throughout the complex (Oldow et al., 1990; Wyld and Wright, 2000). These compressional structures die out up section and are missing in the Middle Jurassic sediments (Oldow et al., 1990). Igneous rocks were probably initially emplaced into multiple centers as demonstrated by the distribution of mafic dike swarms. Volcanic rocks were erupted into the shallow basin, eventually building a topographic high, as shown by (1) interfingering of the lower volcanic flows with the basin margin Boyer Ranch Formation, (2) the presence of rare pillow structures in the lower portions of the volcanic pile and the absence of these features in higher stratigraphic sections, and (3) the high abundance of debris flows sourced from topographic highs preserved throughout the volcanic section. Dike swarms feeding the overlying volcanic pile developed in a number of locations, such as the Buena Vista Hills and the White Rock Canyon area, commonly with a west-northwest orientation (Fig. 4). Orientations of dike swarms and Jurassic faults are roughly parallel to each other. Other faults composing the contacts between the mafic complex and host rocks as well as contacts within the Middle Jurassic sedimentary units place younger rocks on top of older rocks (Speed, 1976) and likely have normal displacement. These observations are consistent with emplacement of the complex into a northeast-southwest extending Jurassic basin. Similar Jurassic extension is documented for the Dunlap Formation in western Nevada, a roughly correlative unit to the Boyer Ranch Formation (Oldow and Bartel, 1987). This interpretation contrasts with earlier interpretation of emplacement of the complex as a single lopolithic mass which displaced surrounding mid-Jurassic sedimentary rocks outward along a number of thrust faults (see Speed, 1966; and Speed and Page, 1964).
Large degrees of mid-Tertiary extension in west central Nevada is documented in a number of areas in the western Great Basin (Proffett, 1977; Seedorff, 1991; Hudson and Geissman, 1991; John, 1995). At least two episodes of extension are recorded in the Humboldt mafic complex. Young tilting is represented by Basin and Range (<13 Ma?) normal faulting which controls range fronts and tilts Miocene and younger basalts and sediments (John, 1995). Older is an earliest Miocene (~24 Ma) extensional event documented in the southern Stillwater Range (south of the Humboldt mafic complex; Hudson et al., 1993; Hudson and Geissman, 1991), which tilts volcanic units of the Job Canyon caldera up to 90° (John and Silberling, 1994, John, 1995). Hudson et al. (1993) estimate that Cenozoic extension in this region is between 70 and 100 percent.

In the complex, the maximum possible Cenozoic extension is not well constrained because the older units of the Tertiary volcanic sequence which occur to the south in the Stillwater Range are missing. It is likely at least 50 percent, compatible with 45° dips on many of the Tertiary volcanic rocks, but it could be 100 percent or more (Johnson, 2000). Tertiary volcanic rocks dip up to 75°; Jurassic volcanic and sedimentary rocks also have variable dips and in a few places, such as in the Buena Vista Hills, they are overturned (Fig. 4). Tertiary tilting of various fault blocks within the Humboldt

Igneous Rocks

Basaltic volcanic rocks and gabbroic intrusions constitute most of the complex (Fig. 2). Gabbroic rocks are exposed in all three ranges and compose the largest portion of complex at intermediate and deep structural levels. Volcanic and volcanioclastic rocks are exposed in the Stillwater Range, Buena Vista Hills, and in drill core at the western edge of the Carson Sink. A third type, composed of mafic dike swarms, is volumetrically subordinate to other types, but are important at intermediate structural levels in many locations throughout the complex.

Hornblende gabbro, olivine gabbro, and microgabbro constitute the majority of intrusive rocks. A wide range of textures are found within this group ranging from fine- to coarse-grained, from equigranular to strongly porphyritic, and from nonfoliated to strongly foliated varieties. The largest portion of the plutonic rocks consists of hornblende- and olivine-bearing equigranular gabbros with subdivide coarse-grained picrites and anorhanites, and variably porphyritic fine-grained gabbros and dikes. Equigranular gabbros are subophitic in texture with 0.5–2 cm plagioclase and augite with variable amounts (10–20%) of amphibole (magnesiohastingsite to hornblende) and olivine (<1–5%; Fh75–82). Minor minerals include magnetite and ilmenite (0.5–1.5%), minor chromite in the olivine-rich rocks, and accessory apatite and titanite. The latter is magmatic and rims ilmenite. Orthopyroxene is commonly present only in olivine-bearing gabbros.

Equigranular gabbros commonly grade outward into finer-grained (0.1–0.3 cm) diabasic microgabbro, which is commonly exposed near the periphery of the complex, possibly as a border phase or as small bodies intruding the sedimentary host rocks, and near the plutonic-volcanic contact throughout the complex (Speed, 1976). Microgabbros typically contain hornblende, augite, and minor olivine. Accessory minerals include magnetite (~1%),apatite intergrown with the hornblende, and igneous biotite (Phl75–95). Contacts between equigranular and the finer-grained gabbros are commonly gradational. Where crosscutting relationships are exposed, the microgabbro is typically older.

Strongly porphyritic rocks occur at intermediate to shallow levels and intrude the volcanic pile. These rocks are commonly trachytic textured and are composed of 5–20 percent plagioclase phenocrysts 1–2 cm in size 5–20 percent and groundmass (0.2–0.5 cm) plagioclase, augite and hornblende. Rarely, these bodies can be shown to feed overlying porphyritic volcanic flows. Due to their relatively shallow distribution, these rocks are commonly strongly altered (Fig. 6b). Where contacts are exposed, strongly porphyritic rocks cut equigranular varieties.

Minor picritic gabbros are distributed throughout the periphery of the complex at deeper levels and are commonly over lain by anorhanitic rocks. Picritic gabbros commonly have magmatic foliations defined by plagioclase (1–4 cm)
Structural Data

- Orientation of Jurassic mafic dikes
- Strike & dip of foliation
- Strike & dip of beds
- Horizontal beds
- Normal fault
- Thrust fault

Lithology

- Qal: Alluvium & sediments of Lake Lahontan
- QPh: Post-Humboldt rocks
- Rd: Mafic to intermediate intrusive rocks of the Humboldt mafic complex
- Jv: Mafic to intermediate volcanics of the Humboldt mafic complex
- Tc: Undivided Jurassic sediments, carbonates, evaporites, coarse clastics Lovelock, Murtlebury, & Boyer Ranch Fm
- Pre-Humboldt pelitic and carbonate rocks

FIG. 4. Structural orientations of Jurassic mafic dikes, iron oxide bodies, and igneous foliations in the Humboldt mafic complex. Data from Johnson (2000), Reeves and Kral (1955), and Wilden and Speed (1974).

Tertiary & Quaternary Structural Domains

- Representative orientation of Tertiary units
- Oldest and youngest units shown where exposed
  - Oldest (large symbol)
  - Youngest (small symbol)
  - Oldest unit used where undivided

FIG. 5. Tertiary tilting domains within the Humboldt mafic complex. Data from Johnson (1977), Johnson (2000), Page (1965), Speed (1976), and Wilden and Speed (1974).
which is intergrown with large kaersutitic amphiboles (1–6 cm) and shows nice orthocumulate textures with olivines (<1 cm, with chromite inclusions) and large poikilitic orthopyroxenes. Anorthositic gabbros are also coarse grained (>2 cm) and equigranular with a magmatic foliation defined by tabular plagioclase (An$_{40-60}$) and hornblende.

At higher levels, small stocks, individual dikes, and sheeted dike swarms intrude fine-grained gabbroic and overlying volcanic rocks. Dikes within the swarms have both single- and double-sided chilled margins. The majority of these rocks are fine-grained basalts with chilled margins and sparse, small (0.2–0.4 cm) plagioclase ± augite phenocrysts in a fine-grained (<0.1 cm) groundmass. Up section, the dikes and hy-babyssal intrusions become less abundant and, in a few places, can be demonstrated to feed lava flows (White Rock Canyon). Dike swarms occur within a number of separate centers, commonly at least several kilometers long. These areas tend to localize the most intense hydrothermal alteration and provide some of the best evidence for synmagmatic alteration within the complex (e.g., in the Anderson Ranch–Buena Vista mine area; see Johnson and Barton, 2000).

The volcanic pile comprises predominantly mafic lavas, pyroxclastic, and volcaniclastic rocks. Lower and upper sequences in the pile differ based upon the proportion of massive lavas and well-bedded volcaniclastic rocks. The best preserved volcanic section is exposed on the eastern side of the Stillwater Range. There, the lower sequence consists of massive basaltic lava flows, volcanic-derived debris flows, minor lapilli tuffs, and reworked volcaniclastic rocks. These rocks are commonly composed plagioclase and augite phenocrysts. Olivine and magnetite are minor and not always present. Individual flows commonly have vesiculated flow tops which may be strongly altered (Fig. 6d). In Cottonwood Canyon these rocks are interpreted to conformably overlie and interfinger with the Boyer Ranch Formation (Speed and Jones, 1969, Riehle, 1969). Overlying the lower sequence is a dominantly stratified sequence composed of basalt and basaltic andesite lavas and tuffs, reworked tuffs, and bedded volcaniclastic rocks. The upper sequence typically contains a smaller volume of dikes. The presence of lapilli tuffs and other pyroclastic units and the lack of subaqueous sediments indicate that most of the volcanic rocks were erupted subaerially or in very shallow bodies of water. Pillow structures are rare; they have been found only in lower sequence rocks in a few areas within the Stillwater Range (Dilek and Moores, 1995; Johnson, 2000).

Igneous development began with intrusion of basaltic magma into a shallow, evaporite-bearing basin as recorded by the Boyer Ranch and correlatable Lovelock and Muttlebury Formations. Basaltic volcanic rocks interfinger with parts of the Boyer Ranch Formation. Continued eruption in an active tectonic environment led to a volcanic pile 1–2 km thick which periodically shed debris flows incorporated within the volcanic section. Synmagmatic alteration, described later, began shortly after the first magmatic input into the system. The most strongly altered areas centered upon zones of sheeted dikes and resulting structural zones. These areas provide the best evidence for the evolving system. In addition to multiple crosscutting magmatic and hydrothermal relationships, other evidence for a coeval hydrothermal system in an active tectonic environment includes the incorporation of high-temperature-alteration clasts within the debris flows that are in turn altered to other assemblages or overlain by later syngenetic hematite.

Fresh igneous rocks within the Humboldt mafic complex are rare. The least-altered analyzed igneous rocks range from calc-alkaline to slightly alkaline basalts and trachybasalts. Igneous rocks range in SiO$_2$ from 45.8 to 53.7 wt percent, with the majority of the samples between 48.6 and 51.9 wt percent SiO$_2$ excluding picritic rocks and moderately chloritized samples. The content of sodium and potassium varies between 2.0–5.5 wt percent Na$_2$O and 0.3–2.5 wt percent K$_2$O. Rocks demonstrating higher alkali contents are weakly altered (Fig. 7). Major and trace element contents and neodymium isotopic compositions of these rocks are consistent with magmatism in an evolving arc to back-arc environment (Gleason et al., 2000; Johnson, 2000).

**Hydrothermal Alteration and Fe oxide (-Cu) Mineralization**

Sodium-rich hydrothermal alteration and Fe oxide and Cu sulfide mineralization are distributed widely and systematically throughout the Humboldt mafic complex. The complex is characterized by >900 km$^3$ of sodium-rich alteration that consists of deep and proximal scapolite-rich mineral assemblages that are overlain and/or overprinted by shallow or distal albite/oligoclase-dominated assemblages (Fig. 8). Magnetite and hematite mineralization occurs at intermediate and shallow levels. Cu sulfide ± hematite assemblages are rare within the deeper, mainly magnetite-rich, mineralization but

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**FIG. 7. Total alkali-silica igneous rock classification grid after Le Bas et al. (1986). Composition of fresh and altered rocks is shown.**
are widespread at shallow levels. In addition to copper-sulfide mineralization, rare “five-element-suite” (Co-Ni-Ag-As-U) sulfide and arsenide assemblages with accessory Cu occur in two areas near the edge of the complex.

Alteration associations

Hydrothermal alteration assemblages are conveniently divided into five major groups reflecting mineralogy and bulk composition changes. These groups are (1) scapolite-hornblende sodic or sodic-calcic alteration, (2) albite/oligoclase-actinolite sodic-calcic alteration, (3) albite-chlorite sodic alteration, (4) carbonate-chlorite alteration, and (5) propylitic alteration (Table 1, Fig. 9). The terminology of sodic-calcic alteration follows that used in the Yerington district (Carten, 1986; Dilles and Einaudi, 1992; Dilles et al., 2000) and by Battles (Battles, 1990; Battles and Barton, 1995) for other occurrences in the western United States.

Early, virtually ubiquitous proximal alteration is characterized by scapolite-dominated sodic-calcic alteration composed of scapolite-hornblende ± clinopyroxene-titanite ± magnetite ± apatite assemblages exposed in deeper parts of the complex (Fig. 8). These assemblages replace both intrusive and volcanic rocks (Fig. 6a, b and Table 1) (Vanko and Bishop, 1982; Johnson, 2000). In most cases, marialitic scapolite (ca. Na₄Al₃Si₉O₂₄Cl) replaces igneous plagioclase, volcanic groundmass, and mafic minerals whereas paragasitic hornblende ± diopside pyroxene replaces igneous augite and hornblende. Minor titanite ± magnetite forms in the original Fe-Ti-oxide sites. Based upon petrography and textures, scapolitic alteration is subdivided into several assemblages for mapping (Table 1, Fig. 9). Strong scapolitization (Sp-2, SP-2a assemblages) is pervasive and commonly texture destructive, transforming fine-grained rocks into coarse-grained equigranular rocks (cf. Fig. 6a). Strong scapolitic alteration is spatially concentrated near the plutonic-volcanic contact in the central portions of the complex (e.g. Mineral basin district) along structurally complex zones, and/or associated with dike swarms (e.g. Buena Vista mine area, Fig. 8). Magnetite is commonly destroyed in deep exposures containing strong, pervasive scapolitic alteration (Fig. 6b; see map in field guide). Strong scapolitic alteration consists of greater than 80 vol percent of hydrothermal minerals in mapped exposures. In contrast, incipient to moderate scapolitic alteration typically preserves igneous textures. Igneous feldspars and groundmass minerals are partially replaced and/or mantled by scapolite and mafic minerals are converted to hornblende, actinolite, and chlorite. Exposures mapped as moderate scapolitic alteration contain between 15 to 80 vol percent of the above assemblages. Distal to SP-2 and SP-2a assemblages are SP-1 scapolitic assemblages. These assemblages consist of a lower volume of scapolite in conjunction with higher abundance of epidote and are commonly less texture destructive than SP-2 assemblages. Other scapolitic assemblages are volumetrically minor in the mapped portions of the complex and occur near iron oxide mineralization (Fig. 9; Table 1; see Johnson, 2000).

Sodic plagioclase-actinolite (sodic-calcic) assemblages are restricted in distribution. These assemblages are characterized by the replacement of igneous plagioclase or hydrothermal scapolite by combinations of albite, oligoclase and epidote, mafic minerals by actinolite ± pyroxene, and iron-titanium oxides by titanite. Plagioclase-rich sodic ± calcic alteration is divided into two assemblages based upon the modal mineralogy, mode of occurrence, and the spatial distribution of the assemblage. Albite (without oligoclase)-actinolitic...
<table>
<thead>
<tr>
<th>Alteration type</th>
<th>Symbol used in figures</th>
<th>Pervasive replacement</th>
<th>Vein/open space iron oxide/sulfide mineralization</th>
<th>Relict Minerals</th>
<th>Spatial/host</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scapolitic</td>
<td>SP-1 Scap+Ep+Hbld+Ti+Mt±Ap</td>
<td>Ep, Scap-Hbld±Mt</td>
<td>P/Plag cores, Hbld, Cpx</td>
<td>Deep-Int/I-V</td>
<td>Pervasive to weak; distal to SP-2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SP-2 Scap+Hbld+Ti+Mt±Ap+Cal±All</td>
<td>Mt±Ap+Hbld±Scap, ms Mt±Ap+Scap+Hbld</td>
<td>P/Plag cores, Hbld, Cpx</td>
<td>Deep-Int/I-V</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SP-2a Scap+Hbld+Ti±Ap+Cal±Ep±Mt(r)</td>
<td>Scap+Hbld+Ti+Ap</td>
<td>P/Plag cores in bx fragments</td>
<td>Deep-Int/I-V</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SP-3 Scap+Pt+Hbld±Ep+Mt±</td>
<td>Mt±Ap</td>
<td>P/Plag, Hbld</td>
<td>Int/I-V</td>
<td>Locally developed in WRC, NBVH</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SP-4 Scap±Ab+Act+Cal+Ti±Ep±Mt±Ap</td>
<td>Mt±Act+Ap+Ti-Ab±Cpy(r)</td>
<td>H/Scap</td>
<td>Deep-Int/I-V</td>
<td>Widespread with Ep, occurs as vug filling and replacements w/in ms repl bodies</td>
<td></td>
</tr>
<tr>
<td>Albite-actinolite</td>
<td>SC-1 Ab+Act+Mt+Ap+Ti+Rut±Ep</td>
<td>Mt/Hm+Act+Ap</td>
<td>H/Scap, Hbld, textures</td>
<td>Int/I-V</td>
<td>Overprints scapolitic alteration, coarsening grain size, rare Ep at BVH</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SC-2 Ab/Olig+Ep+Act+Ti+Chl+Mt±Py</td>
<td>Ab+Act+Ep+py</td>
<td>P/Plag cores, Hbld, Cpx</td>
<td>Int/I-V</td>
<td>Widespread</td>
<td></td>
</tr>
<tr>
<td>Albitic</td>
<td>S-1 Ab+Chl+Mt/Hm±Ti±Rut</td>
<td>Mt±Ab+Chl; Hm±Cpy±Bn</td>
<td>H/Mt redistributed</td>
<td>Shal-Int/V-I-B</td>
<td>Overprints scapolitic alteration, Ap stable</td>
<td></td>
</tr>
<tr>
<td></td>
<td>S-2 Ab+Chl+Ank±Hm±Py±Cpy±Rut±Trnl</td>
<td>stratabound Hm±Qtz, Hm±Cpy±Bn+Chl, Qtz±Ab+Co+Ni+Cu+As+U</td>
<td>P/Plag, (Hbld, pyx)</td>
<td>Shal-Int/V-V-I-B</td>
<td>texture and mineral sites preserved, Ank after mafic sites, Hm±Cpy±Bn veins; 5 element suite hosted by Boyer Ranch sediments, Trnl in B</td>
<td></td>
</tr>
<tr>
<td>Carbonate-chlorite</td>
<td>C-1 Ank±Ab+Chl±Hm+Py</td>
<td>Ank±Hm+Py</td>
<td>P/Plag, (mafic)</td>
<td>H/Ab, Chl,</td>
<td>Shal-Int/V-I-B</td>
<td>Distal; texture and mineral sites preserved</td>
</tr>
<tr>
<td></td>
<td>C-2 Ank±Chl+Ab±Hm</td>
<td>Ank±Brt±Qtz±Py</td>
<td>P/Plag, (mafic)</td>
<td>H/Ab, Chl,</td>
<td>Shal-Int/V-I-B</td>
<td>Distal; texture and mineral sites preserved</td>
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<tr>
<td></td>
<td>C-3 Cal+Chl±Ep±Ab+Act+Hm±Mt</td>
<td>Cal±Hm</td>
<td>P/Plag, Hbld, Cpx</td>
<td>Deep-Int/I</td>
<td>Locally well developed in SWR and WHR</td>
<td></td>
</tr>
<tr>
<td>Propylitic</td>
<td>P-1 Act+Chl+Ab+Ep+Cal+Ser±Preh+Py±Mt</td>
<td>Ep±Ab, Act±Ab, Chl</td>
<td>P/Plag, (mafic)</td>
<td>Deep-Shal/I-V</td>
<td>Widespread at all structural levels</td>
<td></td>
</tr>
<tr>
<td>Propylitic(?)</td>
<td>P-2 Ab+Anal+Cal+Ser+Preh+Rut</td>
<td>Cal, Anal</td>
<td>P/Plag</td>
<td>Int/I-V</td>
<td>Proximal; hydrothermal texture preserved/ replaces scapolitized rocks</td>
<td></td>
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</table>

Alteration assemblages include widespread replacement and vein envelopes; alteration assemblages are divided by the respective mineralogy, mineral abundance, timing, and associated textures; mineralization assemblages include both open-space filling and replacement.

Abbreviations: (host rock): I = intrusive rock, V = volcanic sequence, B = Boyer Ranch Fm; (spatial): Int = intermediate levels, Shal = shallow; (occurrence): ms = massive, repl = replacement, bx = breccia; (minerals): Ank = ferroan dolomite, All = allanite; (locality abbreviations in addition to abbreviations used in text): WHR=West Humboldt Range, SWR=Stillwater Range, BVH=Buena Vista Hills, NBVH=northern BVH, WRC=White Rock Canyon.
hornblende-titanite ± epidote ± magnetite (SC-1) assemblages sporadically overprint magnetite-rich scapolitic alteration in the Buena Vista Hills and eastern Stillwater Range and are commonly associated with iron oxide mineralization (Fig. 9). The second assemblage consists of albite/oligoclase-epidote-actinolite ± pyroxene (SC-2) assemblages and is similar to plagioclase-rich sodic-calcic assemblages described elsewhere in the Great Basin (Carten, 1986; Dilles and Einuadi, 1992; Battles and Barton, 1995). These assemblages are exposed throughout deeper plutonic rocks, especially near the margin of the complex and at shallower levels within hydabyssal intrusive rocks. These sodic-calcic assemblages grade from pervasive replacements in deep portions of the system along epidote-actinolite-albite veins to weakly developed assemblages along epidote-albite veins and lithologic contacts in hydabyssal rocks.

Distal and/or later albite-chlorite (sodic) alteration types constitute the second most common hydrothermal assemblages
(Fig. 8). Sodic assemblages are defined by the presence of abundant albite and chlorite without actinolite (Table 1, Fig. 9). Feldspathic minerals are totally replaced by albite (An<10) and mafic minerals are replaced by chlorite ± iron oxides. Other common minerals include the replacement of titanite by rutile and the introduction of ferroan dolomite giving altered rocks an orange color in outcrop. Strong albite alteration was mapped where mineral assemblages replaced both groundmass and phenocryst sites and the abundance of secondary hydrothermal minerals is greater than 70 vol percent. Weak albite assemblages are widespread, affecting nearly all volcanic rocks. Weak assemblages were mapped where the abundance of hydrothermal minerals was between 10 to 70 vol percent of the outcrop.

Sodic alteration in the mapped areas is divided into an albite-chlorite-magnetite-stable assemblage (S-1) and an albite-chlorite-hematite ± ankeritic dolomite assemblage (S-2). Albite-chlorite assemblages overprint all sodic-calcic assemblages. Sodic assemblages mostly occur at shallow to intermediate levels within the complex where they replace volcanic, volcanioclastic, and shallow level intrusive rocks. Both pervasive and fracture-controlled types are common; the character depends upon the rock type and structural level (Fig. 6c). Where pervasive, igneous and earlier hydrothermal textures are typically preserved, except near structures and other highly permeable zones (Fig. 6d). At deeper levels, sodic assemblages occur along the margins of the complex and are dominantly structurally controlled, overprinting high-temperature assemblages.

Carbonate-chlorite alteration grades outward from albite assemblages and consists of ferroan dolomite-chlorite ± albite ± hematite ± rutile ± sulfides. It is locally divided into two assemblages based upon the volume of associated albite (C-1, C-2 assemblages; Table 1, Fig. 9). Both varieties are distal to and overprint albitic and sodic (-calcic) alteration in volcanic rocks and gabbroic rocks. At these shallow levels carbonate-chlorite alteration is widespread and pervasive, especially near structures and along favorable lithologic contacts. At deeper levels the assemblages are commonly fracture-controlled and occupy small volumes (see alteration map in field guide for the Buena Vista mine area). In the most intensely altered rocks, ferroan dolomite replaces plagioclase phenocrysts, groundmass, and matrix minerals; chlorite ± ferroan dolomite ± hematite replace mafic minerals, and rutile replaces igneous and hydrothermal titanite (Table 1, Fig. 9). Early ankerite-carbonate veins have albitic envelopes. Assemblages lacking albite commonly are associated with a variety of carbonate ± quartz ± sulfide ± barite veins. These veins are best developed at shallow levels within the volcanic pile (White Rock Canyon area).

Propylitic alteration assemblages are common throughout the complex at all stratigraphic levels, affecting both intrusive and volcanic rocks. Propylitic alteration is divided into two distinct assemblages: P-1 and P-2 (Table 1, Fig. 9). P-1 assemblages consist of minerals typical of propylitic alteration as defined by Meyer and Hemley (1967): plagioclase is variably replaced by epidote, carbonate, prehnite, chlorite ± sericite and is commonly mantled by albite plagioclase. Mafic minerals are replaced by actinolite-chlorite ± pyrite. Magnetite is typically stable although other oxides may be replaced by pyrite. 

Veins of chlorite ± actinolite and epidote with albite ± actinolite ± pyrite selvages, and calcite-prehnite are common within propylitized rocks. At shallow structural levels, greater than 75 percent of nonalbitically altered volcanic rocks are pervasively altered to these assemblages. At deeper levels, the freshest rocks are also propylitized. There, propylitic P-1 assemblages are interpreted to grade into weak sodic ± calcic assemblages in deeper settings based upon spatial relationships. The other assemblage, P-2, consists of calcite-analcite ± sericite ± chlorite assemblages replacing scapolitized rocks and is included here with propylitic due to the probable lack of chemical exchange. P-2 assemblages occur at intermediate to deep levels of the complex replacing scapolitized gabbroic and volcanic rocks. These assemblages occur as selvages to analcite-calcite veins. In these rocks scapolite is replaced by analcite, calcite, and sercite and hydrothermal amphibole is commonly weakly replaced by chlorite ± actinolite (Fig. 9). Propylitic assemblages represent formation of new hydrous and carbonate minerals by volatile addition from higher temperature igneous and hydrothermal assemblages and results in, at most, minor changes in the major elements and variable changes in trace elements such as copper (Johnson, 2000).

Fe oxide (-Cu-Co) mineralization

Hydrothermal iron oxides and sulfides are widespread in the complex and have systematic vertical and lateral distribution patterns (Fig. 8). They consist of four main types: (1) massive to breccia-hosted bodies of magnetite-rich mineralization; (2) replacement and stratabound bodies of hematite-rich mineralization; (3) minor but widespread copper sulfide mineralization; and (4) rare nickel-cobalt sulfide and arsenide mineralization.

At intermediate structural levels, iron oxide mineralization consists of discordant massive to disseminated magnetite-apatite and various silicate minerals replacing scapolitized shallow level intrusions and volcanic rocks and as open-space filling in veins and breccia bodies (Fig. 6e, f). Magnetite-rich mineralization follows the transition between scapolitic and albritic alteration. Early magnetite mineralization commonly consists of magnetite-scapolite-hornblende ± titanite ± apatite assemblages. These assemblages generally replace pervasively scapolitized rocks including scapolitized breccias forming disseminated to massive bodies.

Early magnetite mineralization is commonly cut by magnetite-apatite ± hornblende-rich assemblages where scapolite is volumetrically less significant (Fig. 9) forming massive replacement bodies (Fig. 6e) and open-space veins and breccias (Fig. 6f). The bodies are composed of both fine-grained (< 0.1 cm) and coarse-grained (0.5–3 cm) magnetite and common dendritic, hopper-shaped apatite that displays crustiform textures in both veins and replacement bodies. Multiple generations of these mineralized assemblages are demonstrated by crosscutting mineralized and nonmineralized dikes and the incorporation of early magnetite-rich mineralization into later breccia bodies containing mineralized clasts cemented by magnetite.

Late magnetite-rich assemblages consist of magnetite-hornblende-chlorite ± apatite that are interpreted to be part of the transitional (scapolite-albite) SP-4 assemblages and later SC-1 assemblages. Early albitic alteration is magnetite
stable and commonly redistributes magnetite locally, coarsening the grain size. It is not known if there is significant newly added magnetite during these stages as these assemblages are only identified overprinting magnetite-rich rocks. Later albite-chlorite assemblages largely overprints silicate gangue and oxidizes magnetite to hematite. Magnetite-rich bodies commonly lie up section from strong, magnetite-poor, scapolitic (SP-2, 2a) assemblages and down section from strong albitic alteration (Johnson and Barton, 2000).

Up section from the magnetite-rich mineralization in the Stillwater range are large (> 50 m × 100 m) hematite-rich replacement bodies in volcanic and volcaniclastic rocks and small, laminated, stratabound bodies composed of hematite ± fine-grained quartz (Fig. 6h). Hematite replacement bodies are best developed in volcaniclastic rocks and along flow tops within the mafic lavas. These assemblages are composed of hematite ± chlorite ± albite. Magnetite is sometimes found as euhedral grains within the volcaniclastic units but is largely oxidized to hematite. These bodies are spatially associated with albitic alteration, typically lying above pervasive alteration. Good cross cutting relationships have not been seen within these bodies so that exact timing and relations to other assemblages is not well established. Small, laminated, stratiform bodies of hematite crop out discontinuously for less than 150 m and are commonly less than 1 m thick, interbedded with volcaniclastic rocks (Fig. 6h). These bodies are composed of fine-grained, finely laminated hematite intergrown with variable amounts of quartz. Fine layering within these bodies is conformable with layering seen in the clastic rocks both above and below exposures and often shows draping around clasts and soft sediment deformational features. Many of these occurrences lack hematite mineralization in the surrounding rocks. It is our belief that some of these bodies may be syngenetic in origin having formed on the paleosurface from exiting hydrothermal fluids due to their stratigraphic location, unaltered nature of surrounding units, and the finely laminated sedimentary textures preserved within the hematite and quartz.

Sulfide mineralization is minor but relatively widespread within albitic and carbonate-chlorite altered portions of the volcanic sequence. Mineralization occurs as discontinuous veinlets and cement within local breccia bodies and consists of iron-copper sulfides, dominantly pyrite, chalcopyrite, and bornite, along with hematite, ferroan dolomite, and rare quartz and barite (Fig. 6g). Copper sulfide mineralization is best developed at the Boyer Copper mine and the Bradshaw, Anaconda, and unnamed prospects in the Stillwater Range and at small prospects in the Copper Kettle area. In these areas, chalcopyrite and bornite occur in abundant large veins, in breccia cement, and as vein and vesicle filling in flow tops. Grades and tonnages are not known, but copper mineralization at the Anaconda and Boyer Copper mines is exposed over areas of 0.5 and 1 km², respectively.

In addition to the dominantly copper-rich mineralization, nickel-cobalt-copper sulfide and arsenide mineralization associated with high silver contents and reported uranium mineralization occurs in Cottonwood Canyon at the Lovelock and Nickel mines (Ransome, 1999; Elevatorski, 1978). These occurrences are typical of five-element-suite deposits described elsewhere (Ruzicka and Thorpe, 1996). The Ni-Co-Cu mineralization occurs as quartz-carbonate-sulfide-arsenide veins in strongly albitized and carbonated quartz arenites of the Boyer Ranch Formation and basaltic volcanic rocks (Willden and Speed, 1974; Johnson, 2000).

**Mass Transfer and Sources of Components in the Hydrothermal System**

Geologic, geochemical, and mass balance evidence require external derivation of the Na- and Ca-bearing brines from the surrounding evaporite-bearing wall rocks and/or coeval surface fluids. Hydrothermal circulation of these brines led to large metasomatic changes, primarily gain of sodium with some calcium, chlorine and water but with the loss of most other constituents.

**Nature of fluids and sources of components**

The fluids involved in the hydrothermal system are moderately saline Na-Ca brines as indicated by fluid inclusions, many of which are halite-bearing, and by the stability relationships of marialitic scapolite and other minerals in the hydrothermal system (M.D. Barton, D.A. Johnson, J.D. Gleason, unpub. data). Three lines of evidence indicate much or all of the water and dissolved salts came from external sources: (1) mass balance—the amount of sodium and chlorine added during alteration exceeds by a factor of at least 10 the maximum amount that could plausibly have been available from the original basaltic magma; (2) hydrogen, oxygen, and strontium isotope data point to large scale-exchange with nonmagmatic sources; and (3) evaporites (presumably with coeval surface or connate brines) constitute a significant part of the Jurassic stratigraphy, complete with solution-collapse features in sections near the intrusion (Speed and Clayton, 1974; Speed, 1975). Most salinities are compatible with a low-temperature, halite-saturated source. It is easy to envision how other more dilute and locally high saline inclusions can form by fluid flow paths that intersect the vapor-brine solvus or, for dilute cases only, mix with local, relatively fresh, near-surface waters.

Other constituents in the hydrothermal system, notably first-row transition metals and the rare earth elements, are mobilized in large quantities during alteration of the igneous rocks and need not be sourced elsewhere by other mechanisms (see below). Neodymium isotopic data supports multistage mobilization and concentration of the rare earth elements from a primary igneous source (Gleason et al., 2000; Johnson et al., 1995). Sulfide and sulfate sulfur is enriched in 34S (commonly >8 ‰ for sulfides) and is consistent either with reduction of an external sulfate or with the pronounced fractionation of sulfur that could take place in a sulfur-limited system such as this.

**Mass transfer**

Components are strongly redistributed in both shallow and deep parts of the hydrothermal system (Figs. 10 and 11). Gains and losses correlate with changes in mineralogy and give insight into the chemical environment during hydrothermal alteration. The most obvious changes are the large additions of sodium to altered rocks at all levels of the complex resulting from the conversion of igneous feldspars to scapolite or sodic plagioclase. Concurrent with the addition of sodium...
is the loss of iron from deep levels and the local redistribution of iron at shallow levels. The loss of iron in deep levels results from the replacement of mafic minerals by calcium- and magnesium-rich amphibole ± pyroxene, the loss of magnetite, and the conversion of iron-titanium oxides into titanite and rutile. Besides sodium and iron, other components such as potassium, magnesium, phosphorous, manganese, barium, and the base metals are strongly removed during sodic-calcic alteration at deeper levels (Fig. 10).

Reconstructions based on the mapped distribution of alteration allow estimates of the total mass transfer in the system (Johnson, 2000). Approximately 50 billion tonnes of sodium was added to the complex during sodic ± calcic and sodic alteration. Approximately 20 billion tonnes of calcium and 15 billion tonnes of magnesium were mobilized from some of the deep rocks but largely redistributed within the system at local to complex-wide scales. Iron and phosphorous are strongly depleted in deep and in many intermediate level rocks.

Metals such as Cu, Zn, Pb, Co and Ni are removed during sodic ± calcic alteration at deeper levels (Fig. 10; Johnson, 2000). The quantities of metals redistributed within or lost from the hydrothermal system are comparable to the amounts contained in world-class deposits (Fig. 12). Copper and zinc removed during sodic-calcic alteration total approximately 20 to 40 and 30 to 45 million tonnes, respectively. These changes have implications for the associated iron oxide, iron-copper sulfide, and five-element-suite mineralization. Rare earth and metal concentrations can be directly attributed to trapping of only a small fraction of the masses moved. In a sulfur-poor environment only the siderophile elements...
and the most chalcophile elements are precipitated. Considerable iron and phosphorous are reprecipitated at intermediate to shallow levels in upflow zones as focused and dispersed magnetite/hematite-apatite-rich mineralization. Copper with minor cobalt and nickel are present mainly in sulfide-bearing mineralization in shallow, distal settings. Less chalcophile elements such as zinc and lead appear to be lost from the hydrothermal system (Fig. 11).

**Time-Space Synthesis of Magmatic and Hydrothermal Events**

Figure 13 shows a geologically consistent interpretation of the development of the igneous and hydrothermal system near one of the dike swarms as a function of time and depth. The number of intrusive and crosscutting hydrothermal events is largely schematic, although all of the relationships and events shown can be demonstrated in a number of places throughout the complex and actually probably represent a minimum number of events for the complex. Temporal relationships between the magmatic and hydrothermal system are largely evidenced by the numerous dike events which can be used as time lines to document timing of various assemblages, especially where mid-Tertiary tilting reveals contiguous sections demonstrating a large paleovolcanic component (see the field guide, Buena Vista mine area). Separate intrusive bodies show similar overall relations, but are generally limited in the number of magmatic pulses seen. Time-space relationships on the margin of the complex and, perhaps, on the margin of individual intrusive centers would be different (cf. diagrams for Yerington in Dilles et al., 2000). Although generalized, this figure highlights the demonstrable intimate link between magma emplacement, formation of voluminous hydrothermal alteration, and the more restricted development of iron oxide and sulfide mineralization.

The mid-Jurassic record begins with the accumulation of evaporitic sedimentary rocks, likely in an extending, restricted basin. These sediments compose the reworked eolian sandstones of the Boyer Ranch Formation to the east, and the carbonate-rich Lovelock and Muttlebury Formations to the west. These features are part of the broader Jurassic evaporite-eolian sand package that was a response to monsoon-driven aridity on the western margins of the Americas following the breakup of Pangea (Parrish, 1993).

Mafic magmas intruded and were erupted on these sediments, probably from a number of distinct centers. These centers are best evidenced by the presence of well-exposed, spatially distinct basaltic dike swarms. The number and size of these centers are not well established, but the best documented one is in the southern Buena Vista Hills, and stretches at least 8 km east-west (Johnson and Barton, 2000). This length is similar to volcanically active segments in modern back-arc basins. Sedimentation continued with volcanism but became dominated by volcanioclastic rocks and rare syndepoclastic hematite-rich chemical sediments.

A volcanic pile, ultimately about 2 km thick, was constructed by repeated eruption, surface reworking and, in deeper sections, intrusion by basaltic magmas. Thus, the top surface in Figure 13 moves upward with time. This is important to help understand the complex hydrothermal overprinting that obscures the earliest alteration record. Rare clasts of intensely scapolitized rocks in the oldest recognizable intrusions indicate that brines circulated soon after initiation of magmatism, yet initial hydrothermal alteration formed from a heating brine would have likely have contained sodic albite formed as the fluids and host rocks heated. If originally present, such assemblages were destroyed by higher temperature scapolitization as the oldest igneous rocks were buried and progressively heated.
Regardless of the precise time of its initiation, hydrothermal activity continued steadily throughout recognizable magmatic history, waxing and waning with individual intrusive pulses (Fig. 13). Even the youngest dikes have, at minimum, a propylitic overprint. Many examples of mutually crosscutting relations between dikes and sodic-calcic alteration demonstrate this at deeper levels (Buena Vista mine area; Johnson and Barton, 2000). At shallower levels in the complex, albite-bearing assemblages formed contemporaneously with the deep scapolite as demonstrated by the mafic dikes that are scapolitized at depth and albitized at shallower levels (for example in White Rock Canyon, eastern Stillwater Range). Intermittently (between intrusive events) retrograde albitization (lower-temperature assemblages) collapse to deeper levels and overprints scapolitic alteration only to be cut in turn by younger scapolitic veins and associated dikes. In the central portions of the complex, only in the waning stages of the system (the last few percent of intrusive rocks) are dikes altered incompletely to albitic or chloritic assemblages (Fig. 13).

Fluid flow lines can not be fully illustrated on Figure 13 given the evidence for external derivation of the Na- and Ca-bearing brines. External fluids must flow in from outside the diagram. During inflow, fluids would heat and create some of the distal and shallow sodic plagioclase-stable alteration assemblages.

FIG. 13. Time-space diagram showing the evolution of the Humboldt mafic complex and summarizing magmatic and hydrothermal events.
Magnetite (-hematite-sulfide) mineralization formed at the same time as the sodic alteration. It too shows repetitive formation associated with diking and brecciation events. Magnetite-rich veins, replacements, and breccias are concentrated in and over the major dike complexes, where evidence for repeated brecciation, remineralization and intrusion is common (e.g., Buena Vista mine area). Shallower types—syngenetic hematite-silica, bedding-parallel replacement hematite-magnetite, and Cu-Fe sulfide-hematite veins and replacements—are more clearly associated with dikes, but likely formed concurrently with the magnetite-rich types through much of the history. This is demonstrated by the location of syngenetic bodies within the volcanic pile, the association of some hematite-sulfide mineralization with albite-dominated alteration in veins and breccia bodies, and the general overlap with albite and chlorite-carbonate-style alteration. In addition to crosscutting relationships demonstrated by the dikes, high-temperature magnetite and lower-temperature, syngenetic hematite-silica mineralization occur at clasts in debris flows. These flows are in turn covered by later flows and altered to albic assemblages. This demonstrates an active tectonic environment where higher temperature parts of the systems become exposed at the surface and are subsequently buried and are overprinted by later alteration assemblages. (Johnson, 2000).

Concluding Remarks

The Jurassic Humboldt mafic complex represents an end-member in the spectrum of intrusion-related hydrothermal systems. It is part of a broader pattern in the western United States that includes multiple styles of iron oxide-rich hydrothermal systems, including districts such as Yerington, Nevada, Eagle Mountains, California, and the Cortez Mountains, Nevada (Fig.1). Excellent exposures in tilted fault blocks of the otherwise undeformed and unmetamorphosed complex allow study of deep and shallow, proximal and distal parts of the Humboldt magmatic and hydrothermal systems, and interpretation of its temporal and spatial development.

The Humboldt system reflects protracted fluid convection driven by heat of repeated basaltic intrusions. Externally derived brines circulated to depths of at least 4 km and achieved temperatures of at least 500°C. Accompanying sodic-calcic hydrothermal alteration and iron oxide-dominated, locally Cu-bearing mineralization resulted from the interaction between these brines and the hot mafic rocks. Profound leaching of many constituents from large volumes of this complex is only partly reflected in the metals and other constituents that precipitated in identified upwelling zones or at the paleosurface. Some elements, such as zinc, were likely lost due to the lack of suitable traps. Others, like iron, may mass balance over larger volumes.

The Humboldt complex shares characteristics with many Fe oxide (-Cu-Au) systems. These features include voluminous sodic (calcic) alteration, iron oxide-rich sulfide-poor mineralization and copper as the principal base metal. These systems may have multiple origins; they certainly have many differences. In this particular example, as with some other Phanerozoic examples (Salton Sea, California; Danakil Depression, Ethiopia; Siberian traps; Newark Supergroup, Pennsylvania), basaltic magmatism in evaporitic basins results in a common and geochemically sensible type and style of mineralization (Barton and Johnson, 1996). The links to the intermediate and felsic variations on this theme deserve further exploration.

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DEVELOPMENT OF A HYDROTHERMAL SYSTEM: HUMBOLDT MAFFIC COMPLEX, W. NV


