Re-Os dating of three samples of hydrothermal molybdenite collected from the Pueblo Viejo Au-Ag-Cu district (5.5 Moz gold, past production, 16.2 Moz proven plus probable gold ore reserves) yields ages of 112.1 ± 0.4, 112.0 ± 0.4, and 111.5 ± 0.4 Ma. These Re-Os dates confirm an Early Cretaceous age for mineralization, coeval with tholeiitic, intraoceanic island arc volcanism and, in particular, with an episode of felsic magmatism and extension across the Early Cretaceous arc (110–118 Ma). Re-Os dating of a sample of hydrothermal molybdenite collected from the Douvray porphyry Cu-Mo deposit (with inferred resources of 1,257 Mlb Cu, 0.276 Moz Au, 6.84 Moz Ag, and 4,367 tons Mo) yields an age of 93.3 ± 0.3 Ma, coeval with calc-alkaline magmatism along the Greater Antilles island arc.

Abstract

The age and geologic setting of Au-Ag-Cu mineralization in the Pueblo Viejo district of the Dominican Republic have long been subjects of controversy. Kesler et al. (1981, p. 1096) published the first detailed description of the ore deposits and concluded that they formed in a hot spring environment, “during sedimentation in a small basin in the upper part of the Los Ranches Formation.” Sillitoe and Bonham (1984) proposed that the basin was the product of a maar-diatreme eruption, a geoetic setting subsequently embraced by Russell and Kesler (1991). Galbraith (unpub. report, Rosario Dominicana, 1973) proposed a volcanicogenic massive sulfide (VMS) origin for Pueblo Viejo. The link to VMS deposits was also advocated by Sillitoe et al. (1996, p. 204), who described the deposits as having formed in “an environment that is transitional between those of terrestrial epithermal and deep-water volcanogenic massive sulfide systems.” Nelson (2000) presented evidence for a volcanic dome field at Pueblo Viejo, a setting consistent with a transitional (shallow water) VMS. Although their descriptions vary in detail, these authors all describe mineralization at Pueblo Viejo as an Early Cretaceous event, coeval with volcanism and epigenetic sedimentation within the Los Ranchos Formation.

Hollister (1978) was the first to describe Pueblo Viejo as a porphyry copper deposit. More recently, the porphyry copper model has been advocated by Sillitoe et al. (2006, p. 1427), who concluded that “there is no genetic relationship between the gold-silver orebodies and either a maar-diatreme system or volcanic dome complex.” Instead, “this new model for Pueblo Viejo assigns the deposit to a well-defined Late Cretaceous to Early Tertiary calc-alkaline magmatic arc.” This paper presents Re-Os dates for molybdenite collected from the Pueblo Viejo district and from the Douvray porphyry copper deposit located 200 km west of Pueblo Viejo (Fig. 1A). Our Re-Os dates for the Pueblo Viejo district are consistent with an Re-Os isochron age on pyrite reported by Kirk et al. (2014) and with U-Pb dates on zircon reported by Kesler et al. (2005) and Mueller et al. (2008). These Re-Os and U-Pb dates confirm an Early Cretaceous age for mineralization in the Pueblo Viejo district, coeval with tholeiitic island arc volcanism and some 20 m.y. older than the Late Cretaceous onset of calc-alkaline magmatism and related porphyry copper mineralization.

Mining History

The Pueblo Viejo district produced a total of 5.5 Moz of gold and 25.2 Moz of silver during a quarter-century of operation (1975–1999). Rosario Dominicana, a subsidiary of Amax that was later (1979) nationalized by the government, recovered gold from a blanket of near-surface oxidized ore that, by the early 1990s, was largely mined out. The underlying sulfide resource, drilled by Amax in the 1980s, was estimated to contain 25.8 Moz Au at an average grade of 2.5 g per metric tonne (g/t; Nelson, 2000). However, poor gold recovery as mining moved from oxide into sulfide ore forced the mine to close in 1999.

Despite then-prevailing low gold prices, the size and grade of the sulfide resource led to a successful international tender won in 2001 by Placer Dome. Barrick Gold Corporation purchased Placer Dome in 2006, added significantly to the resource at Pueblo Viejo, and decided in 2007 to reopen the...
mine in a 60–40 joint venture with Goldcorp Inc. Construction began on a new plant, including an autoclave circuit, and mining resumed in 2012. As of March 2012, proven plus probable ore reserves for Pueblo Viejo totaled 285.4 Mt at 2.8 g/t Au, 17.5 g/t Ag and 0.09% Cu for a total of 25.3 Moz gold, 160.2 Moz silver, and 590.5 Mlb copper (Borst et al., 2012). In the face of falling gold prices, proven plus probable ore reserves have since been reduced to 16.2 Moz gold, 101 Moz silver, and 379 Mlb copper (Evans et al., 2014).

Regional Geology

The Los Ranchos Formation, host to the ore deposits in the Pueblo Viejo district, is composed of basalt and basaltic andesite flows and pyroclastic units, plutons of diorite,
carbonaceous epiclastic sedimentary rocks, rhyodacitic volcanic dome fields, and tonalite stocks (Escuder-Viruete, 2007a). These rock units accumulated in an intraoceanic island arc of tholeiitic composition that formed in the Early Cretaceous as a result of SW-dipping subduction of Proto-Caribbean lithosphere (Pindell et al., 2006; Pindell and Keenan, 2009). Volcanogenic massive sulfide deposits of the bimodal mafic type (e.g., Cerro de Maimon, Fig. 1B) formed during this time interval both in Cuba and in the Dominican Republic (Nelson et al., 2011). Early Cretaceous volcanism evolved in the Late Cretaceous to calc-alkaline composition (Lewis and Draper, 1990; Lewis et al., 1991; Escuder-Viruete et al., 2006). Late Cretaceous to Paleogene calc-alkaline plutons host porphyry copper deposits, such as Douvray, in the Massif du Nord district of Haiti (Fig. 1A) and along the length of the Greater Antilles island arc (Nelson et al., 2011). For a more detailed description of the metallogenic evolution of the Greater Antilles the reader is referred to Kesler et al. (1990) and Nelson et al. (2011). For a description of Au-Ag-Cu mineralization at Pueblo Viejo and the local geologic setting, the reader is referred to Kesler et al. (1981), Russell and Kesler (1991), and Nelson (2000).

The Los Ranchos Formation consists of boninites, light rare earth element (LREE)-depleted, tholeiitic island arc basalts and normal, island arc tholeiites (Escuder-Viruete et al., 2007a). Within the tholeiitic island arc, these authors describe an interval dated at 110 to 118 Ma of felsic volcanism and coeval, geochemically equivalent, tonalite intrusion (Fig. 1B). Escuder-Viruete et al. (2007b) go on to describe the Maimon Formation (Fig. 1B) as the metamorphic equivalent of the Los Ranchos Formation.

The Maimon Formation is characterized by numerous VMS occurrences (Fig. 1B), one of which (Cerro de Maimon) is currently in production. Bedded VMS is also present in the Los Ranchos Formation, at the La Lechoza deposit, 6 km northeast of Pueblo Viejo (Fig. 2). Inferred resources at La

![Figure 2](image-url)

**Fig. 2.** Location map for molybdenite samples reported in this study. Samples were collected from diamond drill holes APV11-36, APV11-39A, and APV11-40. The extent of advanced argillic alteration within the Los Ranchos Formation is shown in gray. Low-angle reverse faults limit the extent of advanced argillic alteration but not of hydrothermal alteration and mineralization. Mineralization was fed by high-angle, northerly striking hydrothermal conduits, shown in red; nearby gossans and VMS deposits are also shown in red.
Lechoza are 1.23 Mt at 0.57 % Cu, 5.03 g/t Ag, 0.2 g/t Au in sulfides plus 0.98 Mt at 17.72 g/t Ag, 0.86 g/t Au in oxides (Dupéré and Paiement, 2012). Research underway at the University of Barcelona aims to describe the volcanic and magmatic evolution of the Los Ranchos and Maimon Formations in more detail and to further address the question of whether the two rock units are correlative.

Geochronology of Rock Units

The age of the Los Ranchos Formation, estimated from lead isotope ratios for seventeen rock samples, is 130 to 110 Ma (Cumming et al., 1982; Cumming and Kesler, 1987; Kesler et al., 1991). The age of the Los Ranchos Formation is further constrained by late lower Albian (Albian: 113–100 Ma) invertebrate fauna reported from the overlying Rio Hatillo Formation by Myczynski and Iturralde-Vinent (2005).

Within the Los Ranchos Formation, felsic volcanic dome fields (Fig. 1B) occur between a lower section characterized by boninites and LREE-depleted basalt, recording initiation of the subduction zone, and an upper section characterized by normal island arc tholeiitic basaltic volcanism (Escuder-Viruete et al., 2006, 2007a). Two of these felsic volcanic dome fields have been dated. Zircon from a rhyodacite dome in the Bayaguana district (Fig. 1A) yields a U-Pb age of 116.0 ± 0.8 Ma (Escuder-Viruete et al., 2007a). Similar volcanic domes mapped by Nelson (2000) in the Pueblo Viejo district have been dated (U-Pb on zircon) at 111.4 ± 0.5 Ma (Kesler et al., 2005).

Escuder-Viruete et al. (2007a) argue that tonalite plutons were the source for felsic volcanic dome fields of the Los Ranchos Formation (exposed in the Pueblo Viejo and Bayaguana districts) based on their similar age and trace element geochemistry. Nelson (2000) provides evidence that these Early Cretaceous volcanic dome fields were coeval with the hydrothermal cells that formed the Pueblo Viejo Au-Ag-Cu deposits. Back-arc basin basalts of the nearby Rio Verde Formation (Fig. 1B) were deposited at 110 to 118 Ma (Escuder-Viruete et al., 2009), indicating that this time interval was one of extension across the arc. Porphyry copper deposits in the Greater Antilles, on the other hand, are associated with Late Cretaceous to Eocene calc-alkaline magmatism (Nelson et al., 2011). Douvray is a good example; host rocks include calc-alkaline diorite, granodiorite, and tonalite that intruded a Late Cretaceous section of basaltic and dacitic tuffs, breccias, and flows (Bosc and Barrie, 2013).

Sillitoe et al. (2006) present convincing evidence that the Rio Hatillo Formation is conformable with the underlying Los Ranchos Formation and that the Rio Hatillo Formation was altered by the same hydrothermal system that was responsible for mineralization at Pueblo Viejo. However, the presence of altered limestone does not imply the presence of a limestone cover at the time of alteration and mineralization.

On the contrary, field observations in the pits (Kesler et al., 1981; Russell and Kesler, 1991; Nelson, 2000) demonstrate that the host rocks at Pueblo Viejo were exposed to erosion during the mineralization event. Rather than the limestone cap advocated by Sillitoe et al. (2006) or the unconformity reported by Russell and Kesler (1991), Nelson et al. (2011) describe the Rio Hatillo Formation as a fringing reef that formed marginal to an emergent stratovolcanic edifice (Loma la Cuaba), volcanic dome field and shallow marine sedimentary basin—host rocks to the ore deposits at Pueblo Viejo (Fig. 2).

Geochronology of Mineralization

Radiometric dating, particularly if that dating can be carried out on ore-related sulfide minerals, offers a means for resolving the controversy over the age of mineralization at Pueblo Viejo. Consequently, a brief review of previous radiometric dating at Pueblo Viejo is in order. Kesler et al. (1991) favor a mineralization age of 130 to 110 Ma based on the similarity of lead isotope ratios for ore-related galena, enargite, and pyrite and the host Los Ranchos Formation. These authors also report much younger ⁴⁰Ar/³⁹Ar ages (61.6 ± 0.9 and 67.8 ± 0.8 Ma) from a pyrite-alumite vein at Pueblo Viejo. Kesler et al. (1981) interpret younger ⁴⁰Ar/³⁹Ar ages on alumite as the result of thermal resetting, possibly by a nearby Eocene quartz diorite intrusion.

Citing the well-documented observation that Early Cretaceous tholeiitic magmatism in the Dominican Republic was succeeded by Late Cretaceous calc-alkaline magmatism (Lewis and Draper, 1990; Lewis et al., 1991, 2000; Escuder-Viruete et al., 2006), Sillitoe et al. (2006) interpret the ⁴⁰Ar/³⁹Ar dates reported by Kesler et al. (1981) as evidence for a Late Cretaceous age for mineralization at Pueblo Viejo and infer a genetic association with calc-alkaline magmatism.

Arribas et al. (2011), reporting both previously published and new ⁴⁰Ar/³⁹Ar data, show that ⁴⁰Ar/³⁹Ar dates on alumite
from Pueblo Viejo span 40 m.y. (80–40 Ma) and point out that “alunite samples collected within even meters to centimeters of one another yield different ages.” Arribas et al. (2011) conclude that the 40 m.y. range in $^{40}$Ar/$^{39}$Ar dates from alunite at Pueblo Viejo is the result of a complex thermal history.

Mueller et al. (2008) interpret $^{40}$Ar/$^{39}$Ar dates on alunite from the Pueblo Viejo district as a record of postmineral and postburial cooling history related to uplift and erosion. The Pueblo Viejo district was overridden by a package of oceanic lithosphere and overlying island arc volcanic rocks (Mueller et al., 2008). This cover generated temperatures higher than the ~300°C blocking temperature for Ar loss from alunite.

Field observations at Pueblo Viejo reported by Kesler et al. (1981), Russell and Kesler (1991), and Nelson (2000) provide strong evidence for coeval Early Cretaceous volcanism and mineralization. Corroborating evidence for an Early Cretaceous age includes Kesler et al. (2005), who presented a U-Pb date of 111.56 ± 0.45 Ma on zircon from dacite porphyry in the Moore pit, a rock unit that Nelson (2000) mapped as an intermineral volcanic dome. Mueller et al. (2008) cite additional corroborating evidence for Early Cretaceous mineralization with U-Pb dates of 112.2 ± 0.8 Ma and 109.6 ± 0.6 Ma on prismatic zircons from an intermineral andesite dike in the Monte Negro pit. Both the volcanic dome (dacite porphyry) and the andesite dike are demonstrably coeval with mineralization; they contain mineralized lithic fragments and are themselves hydrothermally altered and locally mineralized.

Kirk et al. (2014) report the results of Re-Os dating of gold-bearing sulfide from Pueblo Viejo. Combining pyrite separate and concentrate samples from the Moore and Monte Negro pits, Kirk et al. (2014) report an Re-Os isochron age of 111.9 ± 3.7 Ma. This Early Cretaceous age, the first reported direct date for mineralization in the Pueblo Viejo district, is in agreement with the U-Pb dates cited above for intermineral domes and dikes and is in agreement with our more precise Re-Os ages for in situ molybdenite, as reported below.

The Re-Os Chronometer

The Re-Os chronometer provides a tool for directly dating the age of ore mineralization, as both Re and Os are stored in sulfide, rather than in silicate minerals (see review in Stein, 2014). Molybdenite, in particular, provides a nearly infallible Re-Os clock, as this mineral routinely incorporates ppm levels of Re and takes in essentially no Os during crystallization; essentially all of the Os in molybdenite is radiogenically derived $^{187}$Os (Stein et al., 2001). In addition, studies have shown that the Re-Os chronometer in molybdenite is unaffected by later thermal and hydrothermal events (e.g., Stein et al., 1998; Stein and Bingen, 2002). Provided that molybdenite can be geologically and paragenetically tied to ore minerals, Re-Os dating of molybdenite can be used to precisely date mineralization.

Sampling

Molybdenite was first recognized in the Pueblo Viejo district by Carrasco (2011) who reported it in three diamond drill holes (APV11-36, APV11-39A, APV11-40) located on the flanks of Loma la Cuaba, less than 2 km west of the ore deposits (Fig. 2). Molybdenite occurs as fracture coatings and as coatings on the wall of quartz veinlets in samples that exhibit a phyllic (sericite after plagioclase) alteration assemblage (Fig. 3). Drill holes on Loma la Cuaba penetrate pervasively altered tholeiitic basalt and basaltic andesite flows mapped by Kesler et al. (1981, 2005) as the Platanal member of the Los Ranchos Formation. Torró et al. (2013), working with a suite of samples collected from these and other drill holes on Loma la Cuaba, describe hydrothermal alteration as a blanket of advanced argillic alteration measuring up to 300 m in thickness and zoned from dominant kaolinite + dickite near the surface to deeper pyrophyllite + diaspore. The advanced argillic blanket overlies (with some offset by low-angle reverse faults) phyllic and propylitic mineral assemblages. Propylitic alteration includes chlorite after mafic minerals and as
veinlets, and locally abundant vein and disseminated epidote (Torró et al., 2013). In addition, local potassic and sodic-calcic alteration has been observed. Potassic alteration (orthoclase plus magnetite) occurs at a depth of 267 to 293 m in drill hole APV11-33, 480 m northeast of APV11-39A (Fig. 2). Tourmaline, part of a sodic-calcic alteration assemblage, has been observed (Torró et al., 2012) at depths greater than 650 m in drill hole APV11-38, which is located 460 m northwest of APV11-40 (Fig. 2).

Thirty-nine diamond drill holes for a total of 12,000 m (one to depth of a km) have been completed on Loma la Cuaba. The best intercept (from drill hole APV11-36) is 39.65 m @ 0.25 g/t Au, 0.18% Cu (at a depth of 297.4–337.05 m); the highest grade intercept (from drill hole APV04-12 located 300 m southwest of APV11-36) is 12 m @ 0.05 g/t Au, 0.78% Cu (at a depth of 42–54 m). Mineralized intervals consist of quartz vein stockworks containing pyrite and chalcopyrite filling cracks and voids in pyrite grains. The Cu-Au mineralized intervals are separate from but are located close to the drill-hole intervals that were sampled for molybdenite (Fig. 2). Molybdenite has not been reported from the ore deposits at Pueblo Viejo; trace amounts of chalcopyrite and chalcocite are present (Évans et al., 2014), although the bulk of the copper occurs as enargite.

It is important to emphasize that our molybdenite samples, although collected from outside the limits of the known ore deposits, were collected from within the limits of the Pueblo Viejo hydrothermal alteration system (Fig. 2). Geologic mapping shows that advanced argillic alteration extends from the ore deposits west across the three diamond drill holes sampled for this study and continues, interrupted only by postmineral low-angle reverse faults, as far as the Hatillo Reservoir, a distance of over 5 km (Fig. 2). Drill holes on Loma la Cuaba and an alteration study by Torró et al. (2013) shows that hydrothermal alteration is continuous at depth. Although our results show that the hydrothermal system was episodic, hydrothermal alteration in the pits at Pueblo Viejo is spatially continuous with hydrothermal alteration on Loma la Cuaba.

Geologic mapping (Nelson, 2008) shows that previously published limits of advanced argillic alteration (Sillitoe et al., 2006) do not represent the limits of the hydrothermal system. Alteration and mineralization extend north from Pueblo Viejo, beyond the limits of advanced argillic alteration, to the La Lechoza VMS deposit (Fig. 2). To the south, the limits of alteration are obscured by low-angle reverse faults that offset the contact with the overlying Río Hatillo Formation.

One sample of molybdenite from the Douvray porphyry copper deposit was collected from diamond drill hole DDH D-002 at a depth of 194.6 m (Figs. 4, 5). The molybdenite is from a quartz stockwork with 1% Cu, 3.9 g/t Au, 0.38 g/t Au, and 1390 ppm Mo. The host rock is weakly magnetic, nonporphyritic tonalite containing primary plagioclase, hornblende, and quartz. Inferred resources at Douvray are 189.5 Mt at 0.3% Cu, 0.05 g/t Au, 1.12 g/t Ag, and 23.05 g/t Mo (Bosc and Barrie, 2013). A production decision has yet to be reached.

**Analysis and Results**

Molybdenite was extracted by a small hand-held drill as a powdered separate. Samples were equilibrated with a mixed Re-Os double spike in a sealed Carius tube. Isotopic ratios were measured by negative thermal ion mass spectrometry (NTIMS) through the AIRIE Program, Colorado State University. Samples were blank corrected and mass fractionation corrected for Os. Results are reported in Table 1 and are presented graphically in Figure 6. For more information on Re-Os analysis and interpretation, the reader is referred to a review article by Stein (2014).

For Pueblo Viejo, molybdenite collected from APV11-36 (38.5 m) provides an age of 112.1 ± 0.4 Ma. Molybdenite collected from APV11-39A (532 m) provides an age

**Table 1. Re-Os Data for Three Molybdenite Samples from the Pueblo Viejo Au-Ag District, Dominican Republic, and One Sample from the Douvray Porphyry Copper Deposit, Haiti**

<table>
<thead>
<tr>
<th>AIRIE Run no.</th>
<th>Drill hole number, Sample depth</th>
<th>Re (ppm)</th>
<th>(^{187}\text{Os} \text{ (pph)} )</th>
<th>Age, Ma (with (^{187}\text{Re}) decay constant uncertainty)</th>
<th>Age, Ma (analytical error only)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pueblo Viejo</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>MD-1317</td>
<td>APV11-36, 38.5 m</td>
<td>6191 (10)</td>
<td>7.276 (6)</td>
<td>112.1 ± 0.4</td>
<td>112.12 ± 0.20</td>
</tr>
<tr>
<td>MD-1395</td>
<td>APV11-39A, 530.15–532.70 m</td>
<td>105.7 (1)</td>
<td>124.1 (1)</td>
<td>112.0 ± 0.4</td>
<td>112.02 ± 0.14</td>
</tr>
<tr>
<td>MD-1398</td>
<td>APV11-40, 210.75–212.25 m</td>
<td>346.2 (3)</td>
<td>404.5 (3)</td>
<td>111.5 ± 0.4</td>
<td>111.47 ± 0.12</td>
</tr>
<tr>
<td><strong>Douvray</strong></td>
<td></td>
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<tr>
<td>MD-1333</td>
<td>DDH-002, 194.6 m</td>
<td>36.42 (4)</td>
<td>35.62 (3)</td>
<td>93.3 ± 0.3</td>
<td>93.31 ± 0.13</td>
</tr>
</tbody>
</table>

Samples equilibrated with double Os spike by Carius tube dissolution; sample weights 5, 30, 21, 17 pg for MD-1317, MD-1395, MD-1398, MD-1333, respectively; double Os spike allows for mass fractionation correction and check for common Os; no common Os found.

MD-1317 estimated 80% MoS\(_2\) with 20% silicate dilution; MD-1395 is barely visible MoS\(_2\) coincident with pervasive pyrite in a circular area; MD-1398 molybdenite extracted from a slickenside fault surface and is about 50% MoS\(_2\); MD-1333 is from a fracture coating, with about 20% silicate dilution in the molybdenite separate.

All uncertainties reported at 2σ with concentration uncertainties in parentheses for last stated digit; uncertainty in Re-Os ages shown with and without 187\(^{Re}\) decay constant uncertainty; for Re-Os age calculation, assumed initial 187\(^{Os}/188\(^{Os}\) is 0.2 (though here insensitive to age calculation).

For MD-1317, measured blanks are Re = 5 ± 1 pg, Os = 1.86 ± 0.03 pg with 187\(^{Os}/188\(^{Os}\) = 0.322 ± 0.010; for MD-1395 and MD-1398, measured blanks are Re = 3.18 ± 0.04 pg, Os = 0.17 ± 0.01 with 187\(^{Os}/188\(^{Os}\) = 0.313 ± 0.017; for MD-1333 measured blanks are Re = 7.9 ± 1.5 pg, Os = 1.86 ± 0.03 with 187\(^{Os}/188\(^{Os}\) = 0.32 ± 0.01; although insignificant for these samples, data reported are blank corrected.

APV11-36, UTM coordinates: 373432, 2094656, collar elevation: 232 m, azimuth: 40°, inclination: minus 70°

APV11-39A, UTM coordinates: 373633, 2095696, collar elevation: 374 m, azimuth: 315°, inclination: minus 70°

APV11-40, UTM coordinates: 373666, 2094922, collar elevation: 211 m, azimuth: 51°, inclination: minus 65°
of 112.0 ± 0.4 Ma. Molybdenite collected from APV11-40 (211 m) provides an age of 111.5 ± 0.4 Ma. Two Pueblo Viejo molybdenites have notably similar ages (112 Ma). The third molybdenite (111.5 Ma) on a slickenside surface is distinctly younger when, appropriately, only analytical uncertainties are compared (Table 1 and black inset rectangles on Fig. 6). Molybdenite collected from diamond drill hole DDH-002 (194.6 m) at Douvray (Fig. 4) yields an age of 93.3 ± 0.3 Ma.

**Discussion**

Molybdenite samples analyzed for this study provide Re-Os dates of 112.1 ± 0.4, 112.0 ± 0.4, and 111.5 ± 0.4 Ma, consistent
with a Re-Os isochron age of 111.9 ± 3.7 Ma reported by Kirk et al. (2014). These results confirm a previously proposed (Kesler et al., 1981; Russell and Kesler, 1990; Nelson, 2000) Early Cretaceous age for mineralization in the Pueblo Viejo district.

The small analytical uncertainties associated with molybdenite Re-Os ages (Fig. 6; Table 1) permit recognition in our samples of two episodes of mineralization closely spaced in time at ~112.0 and ~111.5 Ma. The younger of the two Re-Os model ages reported here is consistent with a previously reported U-Pb date of 111.4 ± 0.5 Ma (Kesler et al., 2005) on zircon from dacite porphyry in the Moore pit that was mapped by Nelson (2000) as an intermineral volcanic dome. Mueller et al. (2008) report an age of 112.2 ± 0.8 as well as a younger age of 109.6 ± 0.6 Ma for an intermineral andesite dike in the Monte Negro pit. Together, these dates provide documentation for pulsed hydrothermal alteration and mineralization during the period 109 to 112 Ma.

$^{40}$Ar/$^{39}$Ar dates on alunite from the Pueblo Viejo district span a 40-Ma age range from 40 to 80 Ma (Arribas et al., 2011) and, given the ~300°C blocking temperature of Ar in alunite, are reasonably interpreted (Mueller et al., 2008) to have been modified by metamorphism related to Late Cretaceous obduction of ophiolite. A proposed unconformity at the base of the Rio Hatillo Formation (Kesler et al., 1991) is contradicted by field evidence for a conformable contact presented by Sillitoe et al. (2006) and by the age of mineralization at Pueblo Viejo (109–112 Ma based on radiometric dating, this study), which is essentially the same as the age of the Rio Hatillo Formation (late lower Albian based on fossil fauna assemblages, Myczynski and Iturralde-Vinent, 2005).

Re-Os dating of molybdenite from the Douvray porphyry copper deposit (93.3 ± 0.3 Ma) confirms a Late Cretaceous age for porphyry copper mineralization at this and, quite probably, at other porphyry copper deposits in the Massif du Nord region of Haiti.

Potassic alteration (K-feldspar plus magnetite) and subeconomic Cu-Au stockwork mineralization have been encountered by drilling on Loma la Cuaba (Carrasco, 2011; Torró et al., 2013). Cu-Au stockwork mineralization has also been encountered by drilling at the Doña Amanda deposit in the Bayaguana district (Chenard, 2006; Torró et al., 2014). This has led some to conclude that there is good potential for porphyry copper mineralization at Pueblo Viejo and elsewhere across the Los Ranchos Formation. However, 32 drill holes for a total of 11,500 m, one to a depth of a km, have so far failed to encounter economic porphyry copper mineralization on Loma la Cuaba. These results suggest, to us, that this intra-oceanic tholeiitic island arc is not prospective for porphyry copper mineralization. Instead, we see potential in the Los Ranchos Formation for hybrid epithermal-VMS deposits like those of the Pueblo Viejo and Bayaguana districts. Monecke et al. (2014) describe submarine hydrothermal systems associated with arc rifting, modern analogs, in our view, to Pueblo Viejo. If our model is correct, exploration in the Los Ranchos Formation should focus on transitional epithermal-VMS rather than porphyry copper deposits.

Conclusions

This study reports the first Re-Os dates for molybdenite from the Pueblo Viejo Au-Ag-Cu district, Dominican Republic, and the Douvray porphyry copper deposit, Haiti. Precise Re-Os dates of 112.1 ± 0.4, 112.0 ± 0.4, and 111.5 ± 0.4 Ma for the Pueblo Viejo district agree with a previously reported Re-Os isochron age derived from representative samples of
pyrite from the Moore and Monte Negro pits (Kirk et al., 2014). Combining the Re-Os dates with previously reported U-Pb dates on zircon from an intermineral (coeval with meralization) quartz porphyry volcanic dome (111.4 ± 0.4 Ma reported by Kesler et al., 2005) and an intermineral andesite dike (109.6 ± 0.6 Ma, reported by Mueller et al., 2008) results in an age of 109 to 112 Ma for Au-Ag-Cu mineralization in the Pueblo Viejo district. Molybdenite from the Douvray porphyry copper deposit yields an Re-Os age of 93.3 ± 0.3 Ma.

The Re-Os dates reported here provide documentation for an Early Cretaceous age of mineralization at Pueblo Viejo, consistent with field observations reported by Kesler et al. (1981), Russell and Kesler (1991), and Nelson (2000). At Pueblo Viejo, the ore deposits formed at 109 to 112 Ma in a volcanic dome field and sedimentary basin during a period of extension and tonalitic magmatism across an Early Cretaceous tholeiitic, intracratonic island arc (Nelson et al., 2011). Similar deposits have been described in the Bayaguana district (Chenard, 2006; Nelson et al., 2011; Torró et al., 2014). Re-Os dates reported here are consistent with the observations reported by Sillitoe et al. (2006) but are inconsistent with a model that attributes mineralization at Pueblo Viejo to Late Cretaceous to Tertiary calc-alkaline intrusive activity. True porphyry copper deposits in the Greater Antilles, such as Douvray, formed after the Late Cretaceous onset of calc-alkaline island arc volcanism.

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REFERENCES


Toloczyki, M., and Ramirez, I., 1991, Geologic map of the Dominican Republic 1:250,000: Ministry of Industry and Commerce, Department of Mining, Geographic Institute of the University of Santo Domingo. (in Spanish)