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The metallogenic evolution of the Greater Antilles

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ABSTRACT

The Greater Antilles host some of the world's most important deposits of bauxite and lateritic nickel as well as significant resources of gold and silver, copper, zinc, manganese, cobalt and chromium. Beginning in Jurassic time, sedimentary exhalative base metal deposits accumulated in marine sedimentary rift basins as North and South America drifted apart. With the onset of intraoceanic subduction during the Early Cretaceous, a primitive (tholeiitic) island arc formed above a southwesterly-dipping subduction zone. Podiform chromite deposits formed in the mantle portion of the supra-subduction zone, directly above subducted Proto-Caribbean oceanic lithosphere. Within the nascent island arc, bimodal-mafic volcanogenic massive sulfide deposits formed in a fore-arc setting; mafic volcanogenic massive sulfide deposits formed later in mature back-arc basins. The Pueblo Viejo gold district, with five million ounces in production and twenty million ounces in mineable reserves, formed at 108-112Ma, in an apical rift or back-arc setting. By Late Cretaceous time, calc-alkaline volcanism was well established along the entire length of the Greater Antilles. Volcanogenic massive sulfide deposits including shallow submarine deposits characteristic of the primitive island arc gave way to porphyry copper and epithermal precious metal deposits typical of the mature island arc. Oblique collision of the Greater Antilles with North America began in the Late Cretaceous in Cuba and migrated eastward. Orogenic gold and tungsten deposits that formed during the collision event are preserved in ophiolites and in metamorphic core complexes. Since the Eocene, regional tectonism has been dominated by strike-slip motion as the North American continent moved westward relative to the Caribbean Plate. Large nickel-cobalt laterite deposits were formed when serpentinites were exposed to weathering and erosion during the mid-Tertiary. Bauxite deposits were derived from the weathering of volcanic ash within a carbonate platform of Eocene to Miocene age.

KEYWORDS **Caribbean. Metallogeny. Mineral deposit. Tectonic evolution.**

INTRODUCTION

This paper assembles grade and tonnage information for metallic mineral deposits of the Greater Antilles and relates mineral deposit formation to the tectonic evolution of the northern margin of the Caribbean Plate. Tables are used to compile past production and current (as of 2010) resource information for economically significant examples of each deposit type along with references to the literature. Resource information is from a continually-updated GIS database for mineral occurrences of the Caribbean Basin (CBMap, www.cbmap.net). Other summaries of regional metallogeny for the Greater Antilles include Kesler (1978), Kesler et al. (1990), and Proenza and Melgarejo (1998). Summaries of the tectonic evolution of the Greater Antilles can be found in Lewis et al. (1990, 2000), Mann (2007) and García-Casco et al. (2008). Plate tectonic models are discussed by Pindell and Barrett (1990), Lewis and Draper (1990), Iturralde-Vinent (1998), Meschede and Frisch (1998), Kerr et al. (1999), Pindell et al. (2006) and Pindell and Kennan (2009) among others and will not be reviewed here.

Currently, the mineral endowment (past production plus known resources) of the Greater Antilles totals 36 million ounces (Moz) gold, 277Moz silver, 7 million metric tonnes (Mt) copper, 1Mt lead, 3Mt zinc, 14Mt nickel, 1Mt cobalt, 2Mt chromium, 3.5Mt manganese, and 706Mt aluminium (Tables 1 through 9).

For the purposes of this regional overview, we recognize the following deposit types, each of which is associated with a particular episode in the tectonic evolution of the Greater Antilles volcanic arc. Resource information and references to the literature for deposits with production and/or resources are provided in Tables 1 to 9. Representative examples of each deposit type are described in the text. Readers interested in detailed descriptions for individual deposits should consult the references provided in the text and in the tables.

1. Sediment-hosted deposits formed in extensional basins during the Jurassic and Early Cretaceous separation of North and South America including:
    a. Sedimentary exhalative Cu-Zn-Pb deposits of the Guaniguanico Terrane, western Cuba
    b. Sedimentary exhalative Cu-Zn-Pb deposits of the Escambray Terrane, central Cuba
    c. Stratiform barite deposits and sediment-hosted manganese occurrences
2. Bimodal mafic (Kuroko-type) volcanogenic massive sulfide deposits formed in extensional (fore-arc) basins during the earliest stages of island arc volcanism including:
    a. Cu-Zn-Au-Ag volcanogenic massive sulfide deposits of the Early Cretaceous arc of the central Dominican Republic
    b. Cu-Zn-Au-Ag volcanogenic massive sulfide deposits of the Early Cretaceous arc of the Villa Clara district, central Cuba
    c. Cu-Zn-Au-Ag volcanogenic massive sulfide deposits of the Cretaceous arc of eastern Cuba
    d. Cu-Zn-Au-Ag volcanogenic massive sulfide deposits of the Paleogene arc of the Sierra Maestra, eastern Cuba
3. Mafic (Cyprus-type) volcanogenic massive sulfide deposits formed in mature back-arc basins
4. Epithermal deposits of the Early Cretaceous tholeiitic island arc including:
    a. Au-Ag-Cu deposits of the Pueblo Viejo district, Dominican Republic
    b. Au-Ag-Cu deposits of the Bayaguana district, Dominican Republic
5. Epithermal deposits of the Late Cretaceous to Eocene calc-alkaline island arc including:
    a. Au-Ag-Cu deposits of the Restauración district, Dominican Republic
    b. Au-Ag-Cu deposits of the Massif du Nord, Haiti
    c. Au-Ag-Cu deposits of the Camagüey district, Cuba
6. Porphyry copper and skarn deposits associated with Late Cretaceous to Tertiary calc-alkaline plutons including:
    a. Cu-Au porphyry deposits of the Utuado district, Puerto Rico
    b. Cu-Au porphyry deposits of the Massif du Nord district, Haiti
    c. Cu-Au porphyry deposits of the Restauración district, Dominican Republic
    d. Cu-Au skarn and porphyry deposits of the Terre Neuve district, Haiti
    e. Cu-Au porphyry and iron skarn deposits of the Camagüey and Villa Clara districts, Cuba
    f. Cu-Au porphyry deposits of the Bellas Gate district, Jamaica
    g. Iron skarn deposits of the Hierro Santiago district, Sierra Maestra, Cuba
    h. Iron skarn deposits of the Maimón-Hatillo district, Dominican Republic
7. Volcanogenic (Cuban type) manganese deposits of the Sierra Maestra, Cuba
8. Orogenic deposits formed during collision of the Greater Antilles with North America:
    a. Orogenic gold deposits
    b. Listvenite gold deposits
    c. Tungsten deposits
9. Orthomagmatic (podiform chromite) deposits formed in supra-subduction zones and hosted by ophiolites
10. Bauxite (aluminium) and lateritic nickel-cobalt deposits formed by weathering and supergene enrichment of favorable host rocks:
    a. Bauxite deposits
    b. Lateritic Ni-Co deposits
11. Alluvial and beach placer deposits

The following sections describe each of these tectono-metallogenic events and their associated metallic mineral deposits. Figure 1 shows deposits (with production and/or resources) and mineral occurrences (prospects) on a regional tectonostratigraphic map; additional geologic detail is provided in figures 2 and 3. Figure 4 provides a geologic map for the Pueblo Viejo Au-Ag-Cu district, Dominican Republic. Figure 5 locates each mineral deposit type on a series of cross sections summarizing the tectonic and metallogenic evolution of the northern Caribbean margin.

SEDIMENT-HOSTED DEPOSITS

The oldest metallic mineral deposits to form in the Greater Antilles date to the Jurassic breakup of Pangea. Sedimentary exhalative base metal deposits, stratiform barite deposits and stratiform manganese deposits formed in rift-related terrestrial and marine sedimentary basins that developed along the passive margin of North America as North and South America drifted apart (Proenza and Melgarejo, 1998 and references therein). Host rocks are Jurassic to Cretaceous siliciclastic and carbonate sedimentary rocks exposed in western and central Cuba (Millán, 1996; Iturralde-Vinent, 1998, 2006; Pszczólkowski, 1999; García-Casco et al., 2008). Sedimentary basins of similar age and origin host sedimentary exhalative and Mississippi Valley-type (MVT) ore deposits in northeastern México (González-Sánchez et al., 2009; Camprubí, 2009).

Past production and resource information for sediment-hosted deposits is provided in Table 1; deposit locations are shown on Figs. 1 and 2. The classification of sediment-hosted deposits followed in this paper is that of Leach et al. (2005). Although the Matahambre sedimentary exhalative base metal deposit is an important past producer, no sedimentary exhalative deposits are currently being mined in the Greater Antilles.

Sedimentary exhalative Cu-Zn-Pb deposits of the Guaniguanico Terrane, western Cuba

Sedimentary exhalative deposits are found in Early (?) to Late Jurassic terrestrial syn-rift sedimentary rocks of the San Cayetano basin in western Cuba (Zhidkov et al., 1975; Feoktistov et al., 1983; Lavandero et al., 1988; Kesler et al., 1990; Valdés-Nodarse et al., 1993, 1998; Simón, 1995; Maynard and Morton, 1995; Whitehead et al., 1996; Elswick and Maynard, 1998; Pérez-Vázquez and Melgarejo, 1998; Rojas-Agramonte et al., 2008). The San Cayetano basin (Fig. 2A) belongs to an unmetamorphosed fragment of the Maya Block borderland named the Guaniguanico Terrane by Iturralde-Vinent (1994).

Sedimentary exhalative deposits of the San Cayetano basin are hosted in lenticular black shales interbedded with quartz-feldspar sandstone and siltsone. The main deposits (Table 1) include Matahambre (Cu stockwork with Zn-Pb), La Esperanza (Cu stockwork), Castellanos (Zn-Pb-Ba with Cu stockwork), and Santa Lucía (Zn-Pb-Ba). Some of these deposits (e.g. Mantua and Unión) were interpreted as Besshi-type volcanogenic massive sulfide deposits by Kesler et al. (1996) and by Russell et al. (2000). However, these deposits occur in limestone and calcareous schist, with intercalations of sandstone, mudstone and carbonaceous schist, and could also be tentatively included in the sedimentary exhalative category.

The Matahambre mine (Fig. 2A) reached a depth of 1553 meters on level 45 (Pérez-Vázquez and Melgarejo, 1998). A total of 561,000 tons of copper was produced (Rodríguez-Romero, 2003) during the lifetime of the mine (1916 to 1997). The ore deposit consists of two types of mineralization (Pérez-Vázquez and Melgarejo, 1998). High-grade copper veins up to 10 meters in width cut the sandstone section and are interpreted as hydrothermal conduits. These veins account for the bulk of production to date and for the bulk of the remaining resource. Polymetallic stratiform deposits hosted by black shales (e.g. the Cuerpo 70 ore body) are interpreted as the result of hydrothermal venting on the seafloor (Whitehead et al., 1996) and account for less than 10% of the remaining resource.

Sedimentary exhalative deposits of the Escambray Terrane, central Cuba

Sediment-hosted Cu-Zn-Pb deposits occur within Jurassic metamorphosed carbonate rocks of the Escambray Terrane in central Cuba (Iturralde-Vinent, 1998; Proenza and Melgarejo, 1998; Russell et al., 2000; García-Casco et al., 2008; López-Kramer et al., 2008a). The Escambray Terrane was part of a sedimentary prism that extended southeastward from the Maya Block, named Caribeana by García-Casco et al. (2008). The Escambray and Guaniguanico Terranes represent fragments of the North American passive margin.

Sedimentary exhalative deposits of the Escambray Terrane were interpreted by Russell et al. (2000) as Cyprus-type volcanogenic massive sulfide deposits. However, their occurrence in carbonate rocks, the lack of evidence for volcanism and an extensional setting suggest that they may instead be sedimentary exhalative deposits (Lavandero and Bravo, 1994; Batista-González et al., 1998; Montano-Pérez et al., 1998; Proenza and Melgarejo, 1998). The main deposits are Carlota, Victoria and Guachinango (Table 1, Fig. 2B).

Host rocks for sediment-hosted deposits of the Escambray Terrane include locally graphitic limestone

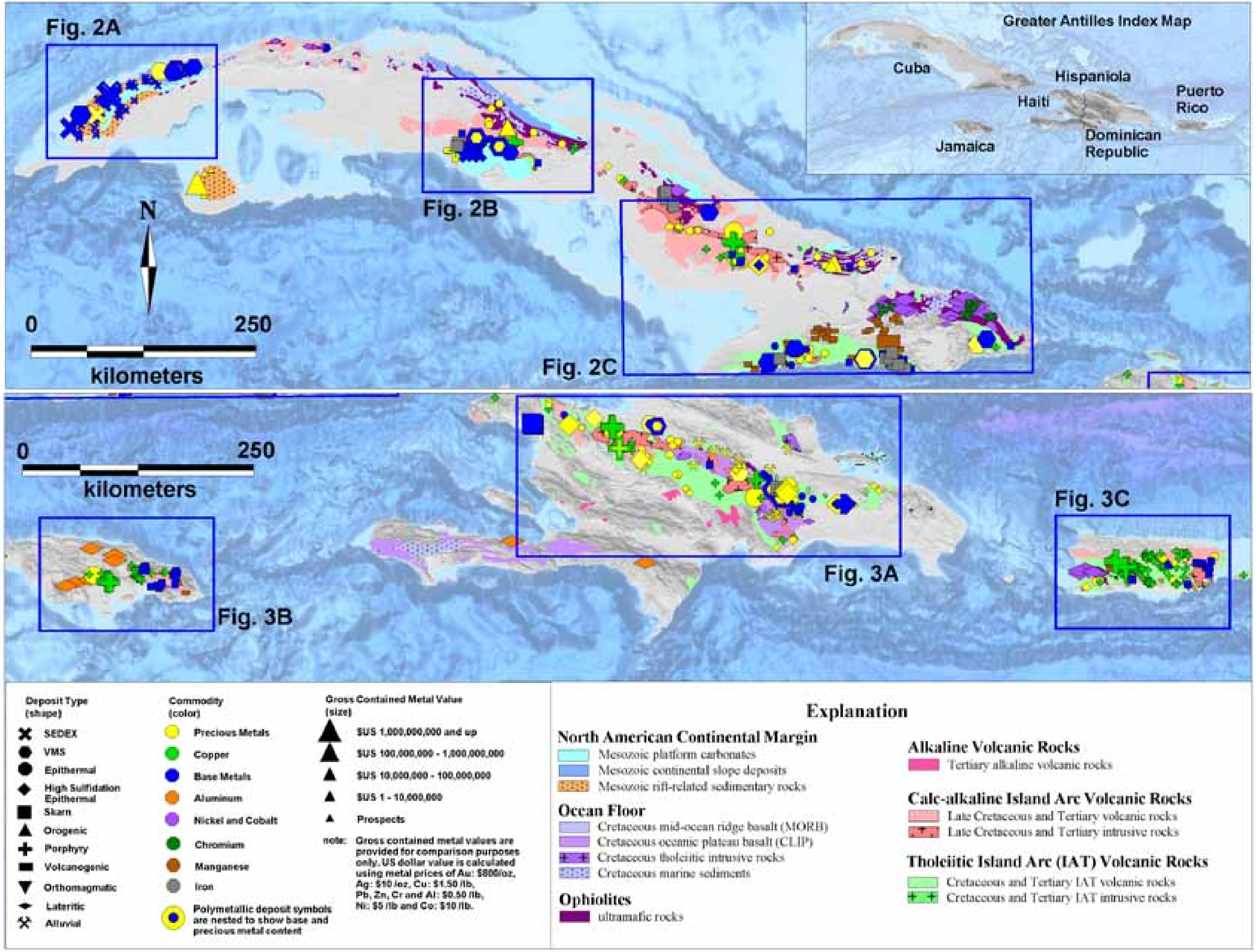

FIGURE 1 | **Metallogenic map of the Greater Antilles showing the location of more detailed maps displayed in Figs. 2 and 3. Mineral occurrences are shaped according to deposit type, color coded according to commodity and sized according to gross contained metal value. The geologic base map is from Case and Holcombe (1980), modified to display tectonostratigraphic rock units.**

and marble, and lesser limey siltstone and graphitic schist with interbedded, conformable lenses of massive and disseminated sulfide mineralization (Tolkunov et al., 1974a). Locally-colloform pyrite, pyrrhotite and marcasite (80%) are present along with lesser chalcopyrite, sphalerite, quartz and ankerite (Hill, 1958; Cabrera, 1986). Minor galena, melnikovite, bornite, enargite and tennantite are also present (Tolkunov et al., 1974a). Batista-González et al. (1998) and Montano-Pérez et al. (1998) report locally elevated gold and silver.

Stratiform barite deposits and sediment-hosted manganese occurrences

Stratiform barite deposits are found in the San Cayetano basin of western Cuba where they are spatially associated with sedimentary exhalative deposits (Whitehead et al., 1996). The main deposits include Isabel María, El Indio, Santa Gertrudis and Jagua. The barite deposits lack base metals but they are distinctively bedded and are interpreted to have formed in an environment similar to the nearby, barite-bearing, Castellanos, Santa Lucía and Matahambre sedimentary exhalative deposits.

A number of small sediment-hosted manganese mineral occurrences are found in the Guaniguanico and Escambray Terranes. They exhibit short lateral continuity, are thin (<1m), and are composed primarily of Mn oxides (Park, 1942; Simons and Straczek, 1958; Batista-González et al., 1998; Montano-Pérez et al., 1998; Cazañas and Melgarejo, 1998).

BIMODAL MAFIC VOLCANOGENIC MASSIVE SULFIDE DEPOSITS

Southwestward-dipping subduction of Proto-Caribbean lithosphere began in Early Cretaceous time and was responsible for the formation of the Greater Antilles volcanic arc (e.g. Pindell et al., 2006; Pindell and Kennan, 2009). Arc-related volcanism and plutonism extended from Cuba across Jamaica, Hispaniola, Puerto Rico and the Virgin Islands (Iturralde-Vinent, 1998; Kerr et al., 1999; Jolly et al., 2001, 2006; Lewis et al., 2002; Escuder-Viruete et al., 2006, 2007; Proenza et al., 2006; Marchesi et al., 2007). During the Early Cretaceous, the Greater Antilles volcanic arc was dominated by tholeiitic volcanic rocks (e.g. Donnelly and Rogers, 1981; Lewis et al., 1995). Tholeiitic island arc volcanic rocks in the Greater Antilles (Figs. 1, 2, and 3) include the Los Pasos Formation (Fm.) (central Cuba), the Téneme Fm. (eastern Cuba), the Amina, Los Ranchos and Maimón Formations (Hispaniola), and the Water Islands Formation (Virgin Islands). In the Greater Antilles, tholeiitic island arc volcanic rock suites include boninites as well as typical oceanic arc tholeiites.

According to the classification scheme of Franklin et al. (2005), volcanogenic massive sulfide deposits can be divided into five lithostratigraphic types: i) bimodal-mafic, ii) mafic, iii) pelite-mafic, iv) bimodal-felsic, and v) siliciclastic-felsic. Deposits of the first two types are found in the Greater Antilles arc. Bimodal-mafic (also known as Kuroko-type) deposits occur in rifted bimodal volcanic arcs above intraoceanic subduction zones. Mafic (also known as Cyprus-type) deposits form in mature back-arc basins (Franklin et al., 2005 and references therein) and will be discussed separately.

Bimodal-mafic volcanogenic massive sulfide deposits are found in Lower Cretaceous formations of the Dominican Republic (Maimón and Amina Formations, Lewis et al., 2000), central Cuba (Los Pasos Formation) and eastern Cuba (Purial Complex) (Proenza and Melgarejo, 1998; Russell et al., 2000; Bottrill et al., 2000). Another belt of bimodal-mafic volcanogenic massive sulfide deposits occurs in the Paleogene El Cobre Formation (Cazañas et al., 1998a, 2008), part of the Sierra Maestra volcanic arc of eastern Cuba (Fig. 2C). Volcanic host rocks in these belts show the characteristic features of intraoceanic island arc tholeiites (Díaz de Villalvilla, 1997; Cazañas et al., 1998b; Lewis et al., 2000; Kysar-Mattietti, 2001; Proenza et al., 2006). Past production and current resources for volcanogenic massive sulfide deposits of the Greater Antilles are provided in Table 2; deposit locations are shown on figures 1, 2 and 3.

Cu-Zn-Au-Ag volcanogenic massive sulfide deposits of the Early Cretaceous arc of the central Dominican Republic

The principal host rocks for volcanogenic massive sulfide deposits in the Dominican Republic include the Maimón Formation, a northwest-striking belt of low-grade metamorphosed volcanic and volcaniclastic rocks of pre-Albian age (Bowin, 1966; Draper and Lewis, 1991; Lewis et al., 2000; Childe, 2000) and the Amina Formation, a strongly deformed volcanic rock unit of similar composition (Draper and Lewis, 1982; Escuder-Viruete et al., 2007). The Maimón and Amina Formations share the same geochemical, isotopic and petrogenetic signature (Horan, 1995; Escuder-Viruete et al., 2007) suggesting that they were part of the same primitive island arc.

Basaltic rocks of the Maimón Formation range from low-Ti tholeiites with boninitic affinities to typical oceanic island arc tholeiites (Lewis et al., 2000; Escuder-Viruete et al., 2007). Felsic rocks are quartz-feldspar tuffs and porphyries that exhibit a similar depleted trace element signature indicating a common source. The presence of depleted basalts with boninitic affinities in oceanic island arc tholeiites is a characteristic feature of the Izu-Bonin fore-arc in the Western Pacific (Bloomer et al., 1995).

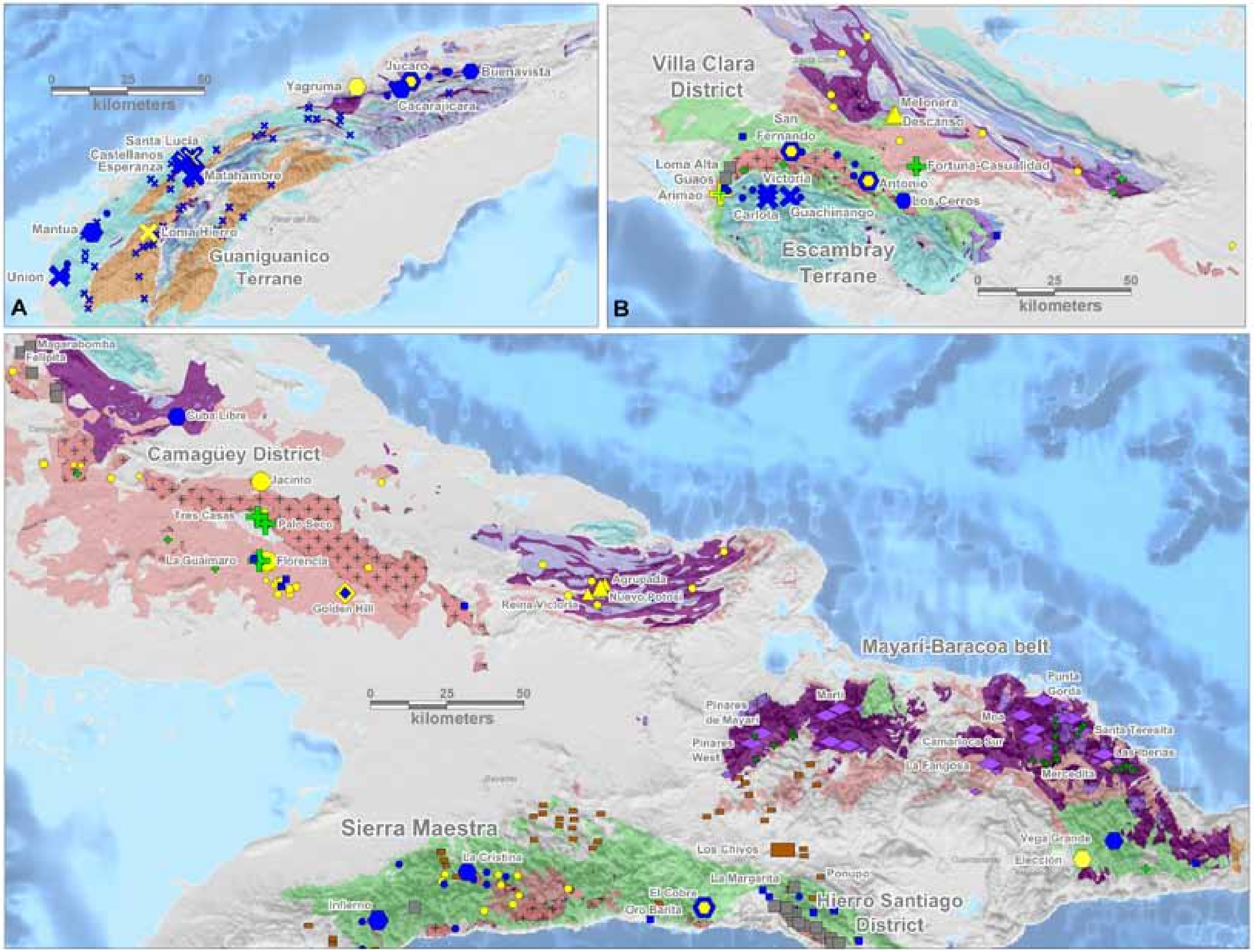

FIGURE 2 | **Detailed metallogenic maps for Cuba. A) Sediment-hosted base metal and volcanogenic massive sulfide deposits of the Guaniguanico Terrane, western Cuba. B) Orogenic gold, porphyry-related copper-gold, sediment-hosted base metal, and volcanogenic massive sulfide deposits of the Villa Clara district and the Escambray Terrane, central Cuba. C) Lateritic nickel-cobalt, orthomagmatic chromite, orogenic gold, porphyry copper, epithermal gold-silver, volcanogenic massive sulfide, volcanogenic manganese and iron skarn deposits of the Camagüey district, the Mayarí-Baracoa belt and the Sierra Maestra, eastern Cuba. The geologic base map for Figure 2 is from Lavandero et al. (1988) modified to display tectonostratigraphic rock units. A legend for rock units and deposit types is provided on Fig. 1.**

TABLE 1 **Sediment-Hosted Deposits**

Deposit	Past production	Current resource	Observations	References
Matahambre, Cuba	560,938 tons Cu (1916-1997)	13 Mt at 4% Cu	Cu stockwork with Zn and Pb	Rodríguez-Romero (2003), Valdés-Nodarse (1998), Pérez-Vázquez and Melgarejo (1998)
Santa Lucía, Cuba	none	18 Mt at 1 g/t Au, 52 g/t Ag, 0.5% Cu, 1.83% Pb, 5.7 % Zn	Zn, Pb and Ba	Valdés-Nodarse (1998)
Castellanos, Cuba	126,964 ozs (1994-2003)	12 Mt at 2.4% Zn, 43 g/t Ag, 1.28 % Cu, 3.23 % Pb	Zn, Pb, and Ba with Cu stockwork	Whitehead et al. (1996), Valdés-Nodarse (1998), Rabchevsky (1994), Bermudez-Lugo (2004)
Unión, Cuba	none	20 Mt at 0.7% Cu		Russell et al. (2000)
Guachinango, Cuba	none	5.1 Mt at 0.81% Cu, 0.84% Zn	Carbonate hosted	Sherlock and Michaud (2000), Russell et al. (2000)
Mantua, Cuba	none	7.5 Mt at 3.03% Cu	Carbonate hosted, sulfide	Kesler et al. (1996), Russell et al. (2000), Torres (1995, 1999)
Hierro Mantua, Cuba	14,764 ozs Au (1998-2000)	2 Mt at 1.44 g/t Au, 11.65 g/t Ag	Carbonate hosted, oxide cap	Kesler et al. (1996), Russell et al. (2000), Torres (1995, 1999)
Carlota, Cuba	none	2.35 Mt at 1.13% Cu, 3.23% Pb	Carbonate hosted	Sherlock and Michaud (2000)
La Esperanza, Cuba	none	2.5 Mt at 1.55 % Cu	Cu stockwork	Valdés-Nodarse (1998)
Loma Hierro	none	0.8 Mt at 310 g/t Ag	Oxide cap	Krason (1999), Lastra and Lara (1998)
Victoria, Cuba	none	0.536 Mt at 0.86% Cu, 0.19% Pb, 0.2% Zn	Carbonate hosted	Russell et al. (2000)

This observation led Lewis et al. (2000) to suggest that the Maimón Formation and associated volcanogenic massive sulfide deposits formed in a nascent primitive island arc, probably in a fore-arc basin. On the other hand, Horan (1995) concluded that both the Maimón Formation and associated deposits were formed in a back-arc basin, based on geochemical similarity to the Lau Basin in the southwestern Pacific.

Since there is an overlap among some trace elements between the Los Ranchos, Maimón and Amina Formations it has been suggested that these three formations are co-genetic (Escuder-Viruete et al., 2007). However, Lewis (written communication) argues that the mineral deposits in the Maimón and Amina Formations differ strongly in almost all aspects from those in the Los Ranchos and could not have been formed under the same conditions from the same magma system.

Pb isotope ratios help to distinguish among the geochemically similar Maimón-Amina Formations, the Los Ranchos Formation, and the primitive island arc rock units studied so far in Puerto Rico and the Virgin Islands (Cumming et al., 1982; Cumming and Kesler, 1987; Horan, 1995; Frost et al., 1998; Jolly and Lidiak, 2006; Jolly et al., 2008). The $^{206}Pb/^{204}Pb$ ratios for the Maimón and Amina Formations and also the Los Pasos Formation, the volcanogenic massive sulfide-bearing unit of Lower Cretaceous age from central Cuba, cluster at a low value (18.3-18.4) indicating a common source for the host rocks of these three formations (Horan, 1995; Blein et al., 2003). Lead isotope ratios for massive sulfide mineralization exhibit slightly lower $^{206}Pb/^{204}Pb$ ratios (18.2-18.25) than the Maimón Formation host rocks. Maimón Formation lead isotope ratios are lower than those of the Los Ranchos Formation and are also distinct from island arc tholeiites in Puerto Rico where considerably higher $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ ratios indicate a more evolved source (Cumming and Kesler, 1987; Jolly et al., 2008).

Bimodal-mafic volcanogenic massive sulfide deposits in the Maimón Formation include Cerro de Maimón and Loma Pesada; those in the Amina Formation are Anomaly "B" and Cerro Verde (Table 2, Fig. 3A). Bimodal-mafic volcanogenic massive sulfide occurrences in the Maimón Formation include Loma Barbuito, Río Sin, Loma la Mina, and San Antonio (Childe, 2000; Lewis et al., 2000; Holbeck and Daubeny, 2000).

The Cerro de Maimón volcanogenic massive sulfide open pit mine (Fig. 3A) went into production in 2008. Ore is drawn from a massive sulfide lens that measures 200 meters in width, 800 to 1000 meters along strike and, near the surface, is up to 40 meters in thickness. The average thickness of the massive sulfide lens is approximately 12 meters and the dip is 30° to the southwest. The orebody, which plunges southeast at 25°, narrows and its dip flattens down plunge. The hanging wall section of intermediate tuffs, mafic flows and thin chert horizons is metamorphosed and exhibits less evidence of hydrothermal alteration than the footwall section. Dominant lithologies in the hanging wall include epidote-chlorite mafic schist intercalated with minor felsic (sericite-pyrite) layers. Exhalites are best developed in the western hanging wall and consist of thin graphitic and hematitic chert horizons (Watkins, 1990; Lewis et al., 2000). Footwall rocks exposed in the western and central part of the deposit are quartz-sericite-pyrite schists, formed by metamorphic recrystallization of pervasively altered host rocks. Alteration in the eastern footwall, where lithologies are mainly mafic to intermediate chlorite schists with minor quartz sericite lenses, is less intense (Watkins, 1990; Astacio, 1997; Lewis et al., 2000).

The Cerro de Maimón orebody is zoned, bottom to top, from primary mineralization, where the Cu:Zn ratio is close to 1:1, through a supergene enrichment zone that contains up to 12% Cu, into a near-surface oxidized zone formed by weathering and leaching of primary mineralization. The primary sulfide mineralogy is pyrite with interstitial chalcopyrite, sphalerite and tennantite (Andreu et al., 2010). Galena and Au-Ag tellurides (altaite, hessite and kernerite) are present as trace minerals (<1%) with a grain size up to 10μm. The supergene sulfide mineralogy is characterized by finely intergrown chalcocite and covellite replacing sphalerite, chalcopyrite and pyrite (Andreu, 2010). Gold in the oxide zone is extremely pure (99% Au). Silver occurs as iodargyrite (AgI) in botryoidal aggregates (Andreu et al., 2010).

Cu-Zn-Au-Ag volcanogenic massive sulfide deposits of the Early Cretaceous arc of the Villa Clara district, central Cuba

The Los Pasos Formation of the Villa Clara district (Fig. 2B) is a bimodal suite of basalt and rhyolite (Díaz de Villalvilla, 1997; Díaz de Villalvilla et al., 2003) with lesser dacite and intercalations of pyroclastic, epiclastic and sedimentary rocks (Iturralde-Vinent, 1998). Chondrite-normalized Rare Earth Element (REE) patterns for both the basalts and the rhyolites are flat with values typical of island arc tholeiites (Díaz de Villalvilla et al., 2003). Bimodal-mafic volcanogenic massive sulfide deposits of the Los Pasos Formation include San Fernando, Antonio and Los Cerros (Table 2, Fig. 2B). Other mineral occurrences include Los Mangos, Independencia, La Ceiba and Minas Ricas (Tolkunov et al., 1974b; Cabrera, 1986; Lavandero et al., 1988; Batista-González et al., 1998; Montano-Pérez et al., 1998; Bottrill et al., 2000; Russell et al., 2000). Alfonso et al. (2007) described stratiform, stratabound and stockwork copper and zinc mineralization at the San Fernando deposit. San Fernando was mined intermittently from its discovery in 1827 to its closure in 1961. Stratiform and stockwork mineralization occur near the contact between basaltic flows and felsic pyroclastic rocks.

Cu-Zn-Au-Ag volcanogenic massive sulfide deposits of the Cretaceous arc of eastern Cuba

Bimodal-mafic volcanogenic massive sulfide deposits in the Cretaceous volcanic arc of eastern Cuba (Fig. 2C) include the Elección deposit and the La Cruzada, Aníbal and Panchita mineral occurrences (Tolkunov et al., 1974b; Lavandero et al., 1988). Host rocks are greenschist facies, volcaniclastic metasedimentary rocks of the Purial Complex (Tolkunov et al., 1974b; Millán, 1996; Iturralde-Vinent, 2006). The occurrences are spatially associated with porphyritic diorite and quartz diorite intrusions. Elección, the most important deposit in the district, went into production in 1938 (Tolkunov et al., 1974b) and produced ore locally in excess of 15% copper from veins that measured up to 30 meters in length and 2.5 meters in width. Ore consists of pyrite, chalcopyrite, quartz with lesser sphalerite, galena, pyrrhotite, cubanite and local gold and silver (Tolkunov et al., 1974b).

Cu-Zn-Au-Ag volcanogenic massive sulfide deposits of the Paleogene arc of the Sierra Maestra, eastern Cuba

Bimodal-mafic volcanogenic massive sulfide deposits are also well developed in the Paleogene (Thanetian to Early Middle Eocene) Sierra Maestra volcanic arc in eastern Cuba. The Sierra Maestra arc is dominated by the El Cobre Group, a volcanic rock sequence more than 4,000m thick (Iturralde-Vinent, 1996; Cazañas et al., 1998a; Kysar-Mattietti, 2001; Rojas-Agramonte et al., 2006b). Volcanic rocks in the lower and middle sequences of the El Cobre Group are low-K island arc tholeiites similar to Early Cretaceous island arc tholeiitic series from elsewhere in the Greater Antilles (Cazañas et al., 1998b). Kysar-Mattietti (2001) suggested that island arc tholeiitic volcanism in the Sierra Maestra represents a very immature intraoceanic arc environment (an "infant arc") that never evolved beyond the first stages of subduction. Pindell et al. (2005) and García-Casco et al. (2008) suggested that arc-related magmatism in the Sierra Maestra formed as a result of low-angle, intra-arc detachment. The Sierra Maestra volcanic arc was intruded, during the final stages of volcanism, by low- to medium-K tonalites and trondhjemites derived from the same mantle source as the volcanic rocks (Kysar-Mattietti, 2001; Rojas-Agramonte et al., 2006b).

El Cobre (Fig. 2C) is the largest volcanogenic massive sulfide deposit in the Sierra Maestra (Cazañas et al., 1998a, 2008) and the oldest copper mine in the Americas. More than 1 million tons of high grade (>14%) copper ore and over 2 million tons of >3% copper ore has been extracted since the deposit was discovered in 1530 (Tolkunov et al., 1974b). Production began in 1544 and continued intermittently until the most recent mine closure in 2000.

The El Cobre and adjacent Oro Barita deposits are located along the El Cobre fault which extends for over 40 kilometers (Fig. 2C). Three main styles of mineralization are distinguished: i) stratiform manganese, anhydrite and Au-bearing barite deposits; ii) stratabound Zn–Cu–Pb–(Au) mineralization; and iii) Cu-rich veins and stockworks (Cazañas et al., 2008). The deposits are stratigraphically controlled and are underlain by stockworks of disseminated sulphides and quartz (Cazañas et al., 1998a; Russell et al., 2000). Other volcanogenic massive sulfide deposits in the Paleogene Sierra Maestra island arc include El Infierno, La Cristina, El Pino, El Roble, Limoncito, and Precaución.

MAFIC (CYPRUS-TYPE) VOLCANOGENIC MASSIVE SULFIDE DEPOSITS

Extension across the Greater Antilles volcanic arc resulted in the development of back-arc basins and associated mafic volcanogenic massive sulfide deposits. Several of these deposits are preserved in the Northern Cuban Ophiolite Belt (Tolkunov et al., 1974b; Feoktistov et al., 1983; Lavandero et al., 1988; Cruz and Simón, 1994; Russell et al., 2000). The best examples are the Júcaro and Buena Vista deposits of the Bahía Honda region (Fig. 2A). Ore assemblages consist of pyrite, marcasite and chalcopyrite, with minor sphalerite. Other mafic volcanogenic massive sulfide occurrences are located in the Habana-Matanzas region within the Margot Formation (e.g. Margot and America) and near Camagüey (e.g. Cuba Libre deposit, Fig. 2C) (Russell et al., 2000). In addition, the Las Lajas, María Antonieta and La Más Buena mineral occurrences are hosted within Sagua La Chica ophiolitic basalt (Rivero-Manzano, 1998) and can be tentatively classified as mafic volcanogenic massive sulfides.

Sabana Potrero is a mafic volcanogenic massive sulfide mineral occurrence hosted by basaltic rocks including pillow lavas and minor hyaloclastites of the Late Cretaceous Peralvillo Formation, Dominican Republic (Fig. 3A). The basalts show a mid-ocean ridge (MORB) signature with a small negative Nb-Ta anomaly (Espaillat et al., 1989; Lewis et al., 2000) similar to the chemical signature of back-arc basalts in the Lau basin. These data indicate a back-arc basin setting for the Sabana Potrero basalts and associated volcanogenic massive sulfide mineralization.

EPITHERMAL DEPOSITS OF THE EARLY CRETACEOUS THOLEIITIC ISLAND ARC

The Cordillera Central in the Dominican Republic and Massif du Nord in Haiti represent the trace of the Greater Antilles volcanic arc across Hispaniola. Epithermal deposits are known from the entire length of the Greater Antilles volcanic arc and formed throughout its volcanic history. Early Cretaceous tholeiitic volcanic rocks host the Pueblo Viejo and Bayaguana districts in the Dominican Republic. Epithermal deposits characterized by high sulfidation mineral assemblages are best developed in the older, tholeiitic portion of the arc. Deposits characterized by low sulfidation mineral assemblages are much less important economically and are better developed in the younger, calc-alkaline portion of the arc. Epithermal deposits are plotted relative to tholeiitic and calc-alkaline volcanic and intrusive rocks on Figures 1, 2 and 3. Production and resource figures are provided in Table 3.

Au-Ag-Cu deposits of the Pueblo Viejo district, Dominican Republic

The Pueblo Viejo district (Fig. 3A, 4) has produced 5.3Moz of gold and 24.4Moz of silver from oxide ore (1975-1996) and is host to an additional 35Moz of refractory mineralization at a one gram per metric tonne (g/t) gold cutoff grade (Ruiz, 1997). Construction on a new plant facility designed to process the refractory sulfide resource began in 2008. The mine is scheduled to reopen in 2011 at a yearly production rate of one million ounces gold plus by-product silver and copper. Mineable reserves are 20.0Moz gold, 97.9Moz silver, and 388 million pounds (Mlbs) copper (Smith et al., 2008).

The Early Cretaceous Los Ranchos Formation, which hosts mineralization at Pueblo Viejo, is composed of boninites, LREE-depleted tholeiitic island arc basalts, and normal island arc tholeiites with an interval of felsic volcanism dated at 110-118Ma (Kesler et al., 2005a, b; Escuder-Viruete et al., 2007). This felsic volcanic interval which includes volcanic domes is coeval with the extrusion of tholeiitic back-arc basin basalts of the Río Verde Formation (Escuder-Viruete et al., 2010). These felsic domes consist of both intrusive and extrusive facies, both of which are well exposed in the Moore pit (Fig. 4). Field observations reported by Nelson (2000a, b) supporting an intrusive origin for dacite porphyry include: i) cross-cutting contacts between dacite porphyry

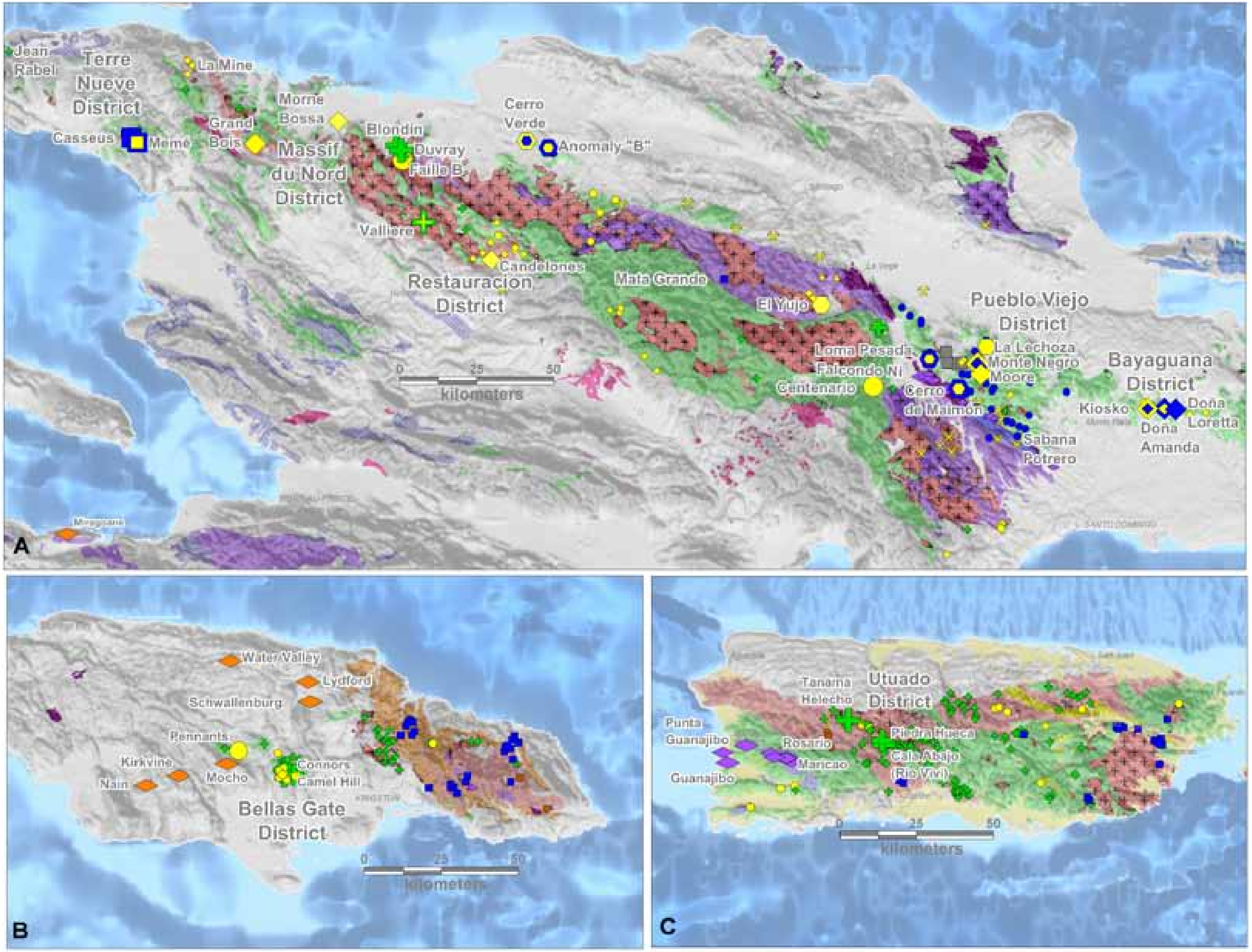

FIGURE 3 | **Detailed metallogenic maps for Hispaniola, Jamaica and Puerto Rico. A) Lateritic nickel-cobalt, volcanogenic massive sulfide, porphyry copper, skarn and epithermal deposits of the Terre Neuve, Massif du Nord and Restauración districts of the Cordillera Central and the Pueblo Viejo and Bayaguana districts of the Dominican Republic. B) Porphyry copper, epithermal gold-silver, sediment-hosted base metal and bauxite deposits of Jamaica. C) Porphyry copper, epithermal gold and lateritic nickel deposits of Puerto Rico. The geologic base map for the Dominican Republic is from Toloczyki and Ramírez (1991) modified to reflect contributions by the ongoing IGME-BGRM Sysmin mapping project. The geologic base maps for Haiti, Jamaica and Puerto Rico are from Vila et al. (1985), McFarlane (1977), and Cox and Briggs (1973), respectively. Each of the geologic maps has been modified to display tectonostratigraphic rock units. A legend for rock units and deposit types is provided on Fig. 1.**

TABLE 2 | **Volcanogenic Massive Sulfide (VMS) Deposits**

Deposit	Past Production	Current resource	Observations	References
El Cobre (Mina Grande), Cuba	300,000 tons Cu (1544 – 1998)	10 Mt at 1.5 g/t Au, 3 g/t Ag, 1.83% Cu	Bimodal mafic type, inactive mine	Krason (1999), Sherlock and Michaud (2000), Russell et al.(2000)
Cerro de Maimón, Dominican Republic	(2008 – present)	4.9 Mt at 1.2 g/t Au, 38 g/t Ag, 2.5 % Cu	Bimodal mafic type, active mine	Lewis et al. (2000)
Antonio, Cuba	50,000 tons Cu at 1.2 to 2.5% Cu (1956-1957)	2.7 Mt at 0.3 g/t Au, 18 g/t Ag, 0.64 % Cu, 3.89 % Zn	Bimodal mafic type	Krason (1999), Russell et al. (2000)
San Fernando, Cuba	38,580 ozs Au, 2,636,444 ozs Ag, 11,000 tons Cu, 28,000 tons Zn (1827 – 1961)	2 Mt at 2.3% Cu, 3.5% Zn	Bimodal mafic type	Childe (2000), Bottrill et al. (2000), Krason (1999), Sherlock and Michaud (2000), Alfonso et al. (2007)
Jucaro, Cuba	62 tons Cu	2.6 Mt at 1 g/t Au, 1.9 % Cu	Mafic type	Russell et al. (2000), Anonymous (1996)
Loma Pesada, Dominican Republic	none	1.09 Mt at 0.16 g/t Au, 4.36 g/t Ag, 2.22 % Cu, 0.77 % Zn	Bimodal mafic type	Lewis et al. (2000), Chenard (2006)
Oro (Zona) Barita, Cuba	none	1.66 Mt at 1.64 g/t Au, 5 g/t Ag, 1.55 % Cu	Bimodal mafic type	Luna (1994), Anonymous (1996)
Yagruma, Cuba	none	1.5 Mt at 2 g/t Au	Mafic type, oxide cap	
La Cristina, Cuba	none	0.8 Mt at 1.15% Cu	Bimodal-mafic type	Russell et al. (2000)
Cacarajicara, Cuba	none	0.6 Mt at 1.2% Cu	Mafic type	Russell et al. (2000)
Cerro Verde (El Anon), Dominican Republic	none	0.23 Mt at 0.15% Cu, 2.18 g/t Au, 3.84 g/t Ag	Bimodal mafic type	Chenard (2006), Childe (2000)
Anomaly “B” (El Anon), Dominican Republic	none	0.3 Mt at 1.81% Cu, 1.34% Zn, 1.1 g/t Au, 12.37 g/t Ag	Bimodal mafic type	Chenard (2006), Childe (2000)
La Lechosa, Dominican Republic	none	0.03 Mt at 2 g/t Au	Bimodal mafic type, oxide cap	unpublished estimate by RosarioResources
Los Cerros, Cuba	750 tons Cu, 2,750 tons Zn (1954-1957)		Bimodal mafic type	Russell et al. (2000)
Buena Vista, Cuba	none	0.1 Mt at 2.58% Cu	Mafic type	Russell et al. (2000)
Infierno, Cuba	none	28 Mt at 2.27% Zn, 0.63% Pb	Bimodal-mafic type	Russell et al. (2000)

and carbonaceous epiclastic sedimentary host rocks, ii) hornfels development adjacent to the dacite porphyry contact, iii) tilting of carbonaceous epiclastic sedimentary host rocks away from the dacite porphyry contact, and iv) a funnel-shaped root in cross section, also documented by Smith et al. (2008). Volcanic domes, by definition, intrude their host rocks but breach the surface and are exposed to erosion. Evidence that the dacite porphyry in the Moore pit breached the paleosurface includes a halo of quartz phenocrysts that appear as clasts in the surrounding epiclastic sedimentary rock section and, adjacent to the dome margin, slump breccias of dacite porphyry that fill channels in the epiclastic sedimentary rock section.

Volcanic domes are also reported (Nelson, 2000a) from the Monte Negro pit. Evidence includes i) development of hornfels at intrusive (dome and dike) margins, ii) multiple intrusive phases within intrusive (dome) facies, and iii) accumulation of unsorted crumble breccia aprons at extrusive (dome) margins. Photos of rock units and their structural relationships in the Moore and Monte Negro pits are provided in Kesler et al. (1981), Nelson (2000a, b) and Mueller et al. (2008).

There is abundant evidence at Pueblo Viejo that mineralization was coeval with volcanic dome emplacement and that dome emplacement was coeval with accumulation of carbonaceous epiclastic sedimentary host rocks. Massive sulfide beds accumulated in carbonaceous epiclastic sedimentary rocks adjacent to the Moore dacite porphyry dome. This same dome contains hydrothermally altered fragments and is itself hydrothermally altered and locally-mineralized (Nelson, 2000a, b). Similarly, in the Monte Negro pit, a hydrothermally altered and locally mineralized andesite dike contains hydrothermally altered and mineralized fragments (Nelson, 2000a; Mueller et al., 2008). Finally, in both pits, hydrothermally altered and mineralized clasts occur in hydrothermally altered and mineralized epiclastic sedimentary host rocks (Kesler et al., 1981; Nelson, 2000a, b).

Detailed U-Pb dating on zircon supports an Early Cretaceous age for mineralization at Pueblo Viejo. Mueller et al. (2008) dated zircon from an inter-mineral dike in the Monte Negro pit at 109±0.6Ma. Inter-mineral intrusions refer to intrusive rocks that contain mineralized fragments and are also mineralized, indicating that intrusion occurred during the mineralization event. Nelson (2000a) assigned this 109Ma inter-mineral dike to the Early Cretaceous Los Ranchos Formation in spite of its much younger K-Ar ages (46.1±1.2Ma on illite and 63.1±1.7Ma on feldspar). Early Cretaceous U-Pb ages (average of 111.56±0.45Ma) are also reported by Kesler et al. (2005a, b) for zircon from an inter-mineral dacite porphyry in the Moore pit. Mueller et al. (2008), reinterpreting the U-Pb data of Kesler et al. (2005a), proposed an age of 108.7±0.6Ma for the Moore dacite porphyry. These U-Pb dates along with the geologic observations summarized above argue for an Early Cretaceous age (108 to 112Ma) for precious metal mineralization in the Pueblo Viejo district, coeval with emplacement of volcanic domes and deposition of epiclastic sedimentary host rocks. The younger K-Ar ages at Pueblo Viejo are best understood as cooling ages reflecting slow uplift and erosion after burial metamorphism (Mueller et al., 2008).

The Pueblo Viejo deposit has long been a subject of debate as far as its origin is concerned. Published models refer to Pueblo Viejo as a Tertiary porphyry copper deposit (Hollister, 1978), a Cretaceous epithermal deposit (Kesler et al., 1981, 2005a), a Cretaceous maar-diatreme (Sillitoe and Bonham, 1984; Russell and Kesler, 1991), a Cretaceous high sulfidation deposit (Sillitoe et al., 1996), a shallow subaqueous epithermal deposit in a Cretaceous volcanic dome field (Nelson, 2000a), and a Tertiary porphyry copper lithocap (Sillitoe et al., 2006). In addition, Hannington (1993), Hannington et al. (1999) and Sillitoe et al. (1996) describe Pueblo Viejo as a high sulfidation volcanogenic massive sulfide deposit. In this review, Pueblo Viejo is interpreted to have formed in an extensional environment, on or immediately adjacent to an Early Cretaceous, tholeiitic, intraoceanic island arc. Pueblo Viejo is best described as a "hybrid deposit", with both epithermal and volcanogenic massive sulfide characteristics, in effect, a volcanogenic massive sulfide deposit that formed at shallow depth.

Mineralized epiclastic carbonaceous sediments at Pueblo Viejo are overlain by carbonate reefs of the Late Lower Albian Hatillo limestone (Myczynski and Iturralde-Vinent, 2005). Russell and Kesler (1991) described the contact as an unconformity. Sillitoe et al. (2006) described the contact as conformable and cited evidence for hydrothermal alteration in the Hatillo limestone that they attributed to the same hydrothermal system that was responsible for mineralization at Pueblo Viejo. If this observation is correct, the Late Lower Albian Hatillo limestone must have been in place during gold mineralization. The unconformity reported by Russell and Kesler (1991) may instead be interpreted as the locally-fragmental base of a fringing reef, offshore of an emerging Early Cretaceous island arc.

Modern analogs to Pueblo Viejo are reported from the western Pacific. Massive sulfide mineralization is accumulating at the Valu Fa ridge in the Lau back-arc basin, behind the Tonga-Kermadec subduction zone (Herzig et al., 1998) and in the PACMANUS hydrothermal field in the Manus back-arc basin, off the east coast of Papua New Guinea (Binns et al., 2007). At PACMANUS, precious metal-bearing massive sulfide mineralization is forming in a series of pull-apart rifts between the inactive Manus trench to the north and the active New Britain trench to the south. Pyrophyllite-bearing acid sulfate alteration and massive sulfide (precious metal-bearing chalcopyrite and sphalerite) chimneys (black smokers) occur in no fewer than five locations along a submarine ridge dominated by dacitic volcanic rocks (Binns et al., 2007). Paulick et al. (2004) interpret some of the dacitic volcanic rocks as originating from a nearby eruption center. Mineralization collected from the seafloor at PACMANUS is remarkably similar in terms of texture, composition and alteration mineralogy to disseminated and massive sulfide mineralization at Pueblo Viejo.

Au-Ag-Cu deposits of the Bayaguana district, Dominican Republic

The Bayaguana District is located approximately 60km east of Pueblo Viejo (Fig. 3A). Epithermal gold, silver and

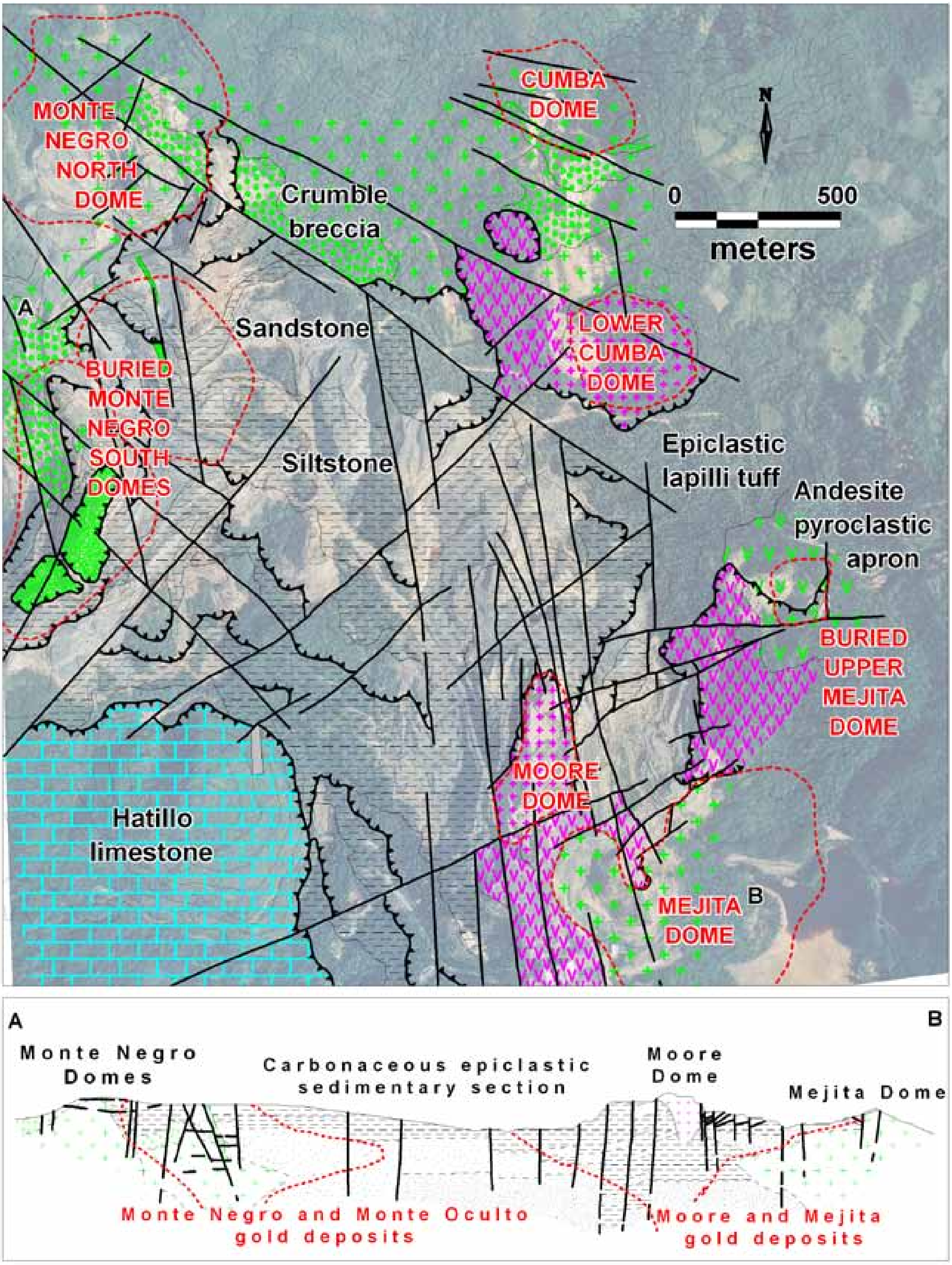

FIGURE 4 | **Simplified geologic map and cross section of the Pueblo Viejo district, Dominican Republic, plotted on an aerial photographic base showing the Moore and Monte Negro pits. Based on 1:2000 scale mapping by Nelson (2000a). Carbonaceous epiclastic sedimentary rocks are shown in grey and labelled as “siltstone” and “sandstone.” Basaltic andesite of the Los Ranchos Formation is shown in green; dacite of the Los Ranchos Formation is shown in pink. The Hatillo limestone appears in blue. Volcanic domes are outlined in red.**

copper mineralization is related to a volcanic dome field (Chenard, 2006). A large hydrothermal alteration system, similar in size to the alteration system at Pueblo Viejo, covers over 50 square kilometers and is hosted by the same Early Cretaceous tholeiitic island arc volcanic rocks of the Los Ranchos Formation. Mineralization consists of hydrothermal disseminations and stringers of sulfides dominated by pyrite, chalcopyrite and bornite and locally enriched in gold and silver. Three epithermal deposits (Kiosko, Doña Amanda, and Doña Loretta) have been identified and tested by drilling (Fig. 3A). Resources are listed in Table 3.

Kiosko (Cerro Kiosko) is a silicified, tabular quartz vein swarm hosted by altered mafic volcanics that has been traced for 1.1km along strike. Mineralization consists of disseminations and stringers of pyrite and chalcopyrite with local chalcocite, bornite and enargite. At Doña Amanda, a supergene enrichment blanket (chalcocite and covellite) approximately 100 meters thick overlies strongly silicified and mineralized mafic volcanic rocks that are intruded by porphyritic dacite. Hypogene disseminated and stockwork mineralization at Doña Amanda consists of pyrite and chalcopyrite with local enargite and pyrophyllite (Chenard, 2006). Mineralization at Doña Loretta (also known as Ceja del Coco) consists of a broad zone of hydrothermal alteration associated with silicified and argillized volcanic rocks. At all three deposits, mineralization is associated with volcanic domes of felsic composition (Chenard, 2006). The volcanic domes consist of porphyritic (quartz and feldspar phenocrysts) dacite and/or rhyolite. A U-Pb date on zircon from a dacite dome at Ceja del Coco returned an age of 116 ± 0.8Ma (Escuder-Viruete et al., 2006). Volcanic dome emplacement at Bayaguana apparently occurred a few million years earlier than volcanic dome emplacement at Pueblo Viejo (108 to 112Ma).

Throughout the Bayaguana district, host rocks closely resemble those of the Pueblo Viejo district. Similar sequences of thin- to medium-bedded epiclastic carbonaceous siltstones and sandstones with minor conglomerates accumulated in a basin marginal to a volcanic dome field. As at Pueblo Viejo, terrestrial plant fossils are common. The Hatillo limestone that overlies the epiclastic carbonaceous sedimentary section at Pueblo Viejo also overlies the epiclastic carbonaceous section in the Trinidad area of the eastern Bayaguana district. Although no large metallic mineral deposits have been discovered, hydrothermal alteration and mineralization in the Bayaguana district is similar to that encountered at Pueblo Viejo. High sulfidation mineral assemblages occur with epithermal vein and disseminated Au-Ag-Cu mineralization in both districts. The Bayaguana district indicates that felsic volcanic dome fields and related gold-, silver- and copper-bearing epithermal systems developed at more than one location along the length of the Early Cretaceous tholeiitic island arc rocks of the Los Ranchos Formation.

EPITHERMAL DEPOSITS OF THE LATE CRETACEOUS TO EOCENE CALC-ALKALINE ISLAND ARC

Early Cretaceous tholeiitic volcanism evolved in Late Cretaceous and Paleogene time to calc-alkaline composition (Lewis and Draper, 1990; Lewis et al., 1991, 2000; Escuder-Viruete et al., 2006). Today, the axis of the Late Cretaceous Greater Antilles volcanic arc is marked by a chain of calc-alkaline plutons that extends from Cuba to Puerto Rico (Fig. 1). These plutons have associated porphyry copper mineralization and intrude suites of Late Cretaceous calc-alkaline volcanic arc rocks. Epithermal deposits are strongly developed in these Late Cretaceous volcanic arc rocks in the western Cordillera Central (Restauración district) of the Dominican Republic and its extension into the Massif du Nord district in Haiti, and also in the Late Cretaceous volcanic arc rocks of the Camagüey district of east-central Cuba (Fig. 2 and 3).

Au-Ag-Cu deposits of the Restauración district, Dominican Republic

The Restauración district is located in the western Cordillera Central of the Dominican Republic along the border with Haiti (Fig. 3A). Mineral deposits and prospects in the district have been described by Amarante et al. (1989) and Amarante and Lewis (1996). The mineralization, which is typically polymetallic (Cu-Zn-Pb-Au-Ag), occurs in volcanic and pyroclastic rocks of the Upper Tireo Formation (Jiménez and Lewis, 1989; Louca, 1990; Lewis et al., 1991). Its association with dacitic rocks (quartz-plagioclase porphyries) and the occurrence of barite and massive barite-sulfide mineralization is a characteristic feature of the epithermal mineralization in this district and westwards into Haiti. Barite and sulfides occur together in various mineral associations, textures and proportions, with sulfides forming up to 70% by volume in massive ore. An intimate association of precious metals with barite is a typical feature of the deposits. At Candelones, the largest deposit discovered to date (Fig. 3A, Table 3), vuggy quartz veins containing gold along with pyrite, enargite and barite are surrounded by a gold-bearing vein stockwork and by disseminated mineralization. At shallow levels, gold-barite veins and barite breccias grade into massive, structurally-controlled, barite replacements. Multiple phases of alteration include an early illite-pyrite stockwork accompanied by dickite, kaolinite and alunite within or in close proximity to the orebody. The Savanne La Place prospect, located eight kilometers northwest of Candelones on the Haitian side of the border shows similar features at the surface and likely belongs to the same hydrothermal system as Candelones.

The Cerro Montazo, Guano and Naranjo prospects are located four to eight kilometers east-northeast of Los Candelones (Fig. 3A). Hydrothermal alteration consists of pyrophyllite-bearing zones of massive chalcedonic silicification, vuggy silica, sulfide stockworks, massive barite and barite veins that grade outwards to dickite and illite at the margins. The hydrothermal system is cut by, at least, two well-defined northwest-striking structures. At Naranjo, gold has been confirmed by trenching across veins and lenses of dense silica-barite alteration. At Guano, gold has also been confirmed by trenching in alteration that consists of vuggy silica, quartz-chalcopyrite veins and massive barite. Gold at Montazo occurs in barite lenses and in argillically altered rock.

Au-Ag-Cu deposits of the Massif du Nord, Haiti

The epithermal mineral deposits in the Massif du Nord (Fig. 3A) have the same general characteristics, particularly the association with barite and barite sulfide mineralization, as seen in the Restauración district described above. Many of the individual deposits and prospects were described by Louca (1990).

Grand Bois is the largest epithermal deposit known to date from the Massif du Nord (Fig. 3A). The resource estimate (Table 3) is based on drilling conducted by the United Nations (1978-1984) which defined a tabular body of mineralized and oxidized volcanic rock with a thickness of approximately 20 meters. In recent years, drilling below the oxide zone has reportedly intersected chalcocite, covellite and chalcopyrite. Morne Bossa (Milot) located south of Cap-Hatien in the Milot-Grande Rivière area is also a gold oxide deposit (Table 3). Louca (1990) states that the mineralization took place on the edge of a dacite porphyry.

Faille B is a low sulfidation epithermal Au-Ag quartz vein deposit (Fig. 3A) that occurs along a major, northwest-striking fault zone. Host rocks include a tabular, wedge-shaped body of micro-tonalite which intrudes a section of metamorphosed mafic to ultramafic rocks (Morne Cabrit Series). Mineralization consists of lenticular veinlets, sheeted veins and five sets of quartz veinlets. Most veins strike northwest, parallel to the regional host fault. Quartz is the principal gangue mineral; the most abundant sulfide is pyrite which is accompanied by smaller amounts of chalcopyrite and sphalerite. Gold occurs as the native metal in quartz as grains that measure 2 to 50 microns in diameter.

La Mine prospect refers to three significant occurrences of epithermal gold, silver and base metal mineralization located in the northernmost exposures the Late Cretaceous volcano-sedimentary sequences of the La Mine Series in the Massif du Nord (Fig. 3A). The principal mineralization is a 3km long northwest trending stockwork vein system consisting of steeply dipping fault strands varying in width from a few meters to 100m wide (Louca, 1990). Polymetallic (Cu, Pb, Zn, Au, Ag) sulfide mineralization, confirmed by trenching, is associated with barite and with barite-sulfide replacements that, locally, cut across the argillically altered fault zone.

Au-Ag-Cu deposits of the Camagüey district, Cuba

Epithermal deposits exhibiting both low (e.g. Jacinto and Florencia) and high sulfidation (e.g. Golden Hill) sulfide mineral assemblages are found in the Camagüey district (Fig. 2C) of Cuba (Lavandero and Bravo, 1994; Barroso et al., 1998; Lugo-Primelles et al., 1998; Simon et al., 1999; Kesler et al., 2004; López-Kramer et al., 2006). The deposits are hosted by calc-alkaline volcanic rocks and surround the Camagüey batholith, a composite intrusion that consists of gabbro-tonalite, syenite, and granodiorite (see section on porphyry copper deposits described below).

Jacinto (Fig. 2C) is a typical epithermal vein deposit with adularia-sericite alteration and a low sulfidation sulfide mineral assemblage. Six crustiform-banded veins measuring up to a kilometer in length contain free gold and gold tellurides in a gangue of quartz, calcite, adularia and minor pyrite. An alteration halo of K-feldspar plus sericite envelops the veins. Host rocks are pillowed basalt, andesite and latite flows of the calc-alkaline Camujiro Formation (Simon et al., 1999; Kesler et al., 2004). Florencia is similar in terms of its gangue mineralogy (quartz, carbonate and chlorite) but is richer in base metal sulfides including chalcopyrite, sphalerite and galena (López-Kramer, 1988).

Golden Hill (Fig. 2C) consists of breccias cemented by two stages of quartz, pyrite and enargite. The first stage is accompanied by kaolinite, zunyite and diaspore. The second stage contains tungsten and bismuth and is accompanied by natroalunite, pyrophyllite and barite (Kesler et al., 2004). Golden Hill demonstrates that epithermal precious metal deposits with high sulfidation mineral assemblages are not restricted to the Early Cretaceous tholeiitic history of the island arc; they also occur in Late Cretaceous calc-alkaline volcanic rocks.

PORPHYRY COPPER AND SKARN DEPOSITS

Porphyry copper deposits of the Greater Antilles are small and, to date, none have been mined. All of the known deposits are associated with calc-alkaline plutons and many are surrounded by clusters of epithermal precious metal occurrences (e.g. Camagüey district of Cuba, Massif du Nord district of Haiti, Restauración district, Dominican Republic and Bellas Gate district of Jamaica). Porphyry copper and skarn deposits are plotted on Figs. 1, 2 and 3; resource information is provided in Table 4.

Whole rock geochemical data for the associated Late Cretaceous calc-alkaline intrusive rocks of the Greater Antilles exhibit low-K, medium-K and high-K signatures even in a single intrusive complex (Kesler et al., 1975; Lidiak and Jolly, 1996). Most radiometric dates published for plutonic rocks associated with porphyry copper mineralization in the Greater Antilles (Hollister, 1978; Kesler, 1978) are K-Ar dates from the 1970's. As is the case at Pueblo Viejo, K-Ar dates may, in some cases, reflect the age of uplift rather than the age of emplacement and should be interpreted with caution.

Cu-Au porphyry deposits of the Utuado district, Puerto Rico

The Tanamá-Helecho, Piedra Hueca, and Cala Abajo (Río Viví) porphyry copper deposits of Puerto Rico (Fig. 3C) are associated with the Utuado batholith which is zoned from a core of quartz monzonite and granodiorite outward into quartz diorite (Hollister, 1978) and tonalite porphyry (Cox, 1985). The Tanamá-Helecho deposit is associated with tonalite porphyry dikes and stocks that were intruded late in the history of the Maastrichtian Utuado batholith (Cox, 1985) or during a separate Eocene pulse of low-K magmatism (Barabas, 1982). Mineralization consists of stockworks of quartz, chalcopyrite and magnetite with associated potassic alteration, both as K-feldspar and as hydrothermal biotite.

Cala Abajo (Río Viví) and Piedra Hueca are hosted by quartz diorite stocks. The deposits exhibit feldspar-stable hydrothermal alteration along with secondary biotite. Magnetite-bearing quartz stockworks contain chalcopyrite and, locally, molybdenite. Most of the porphyry copper deposits of Puerto Rico were discovered in the late 1950's and drill tested in the early 1960's. None have been developed. Open pit mining has been precluded by law in Puerto Rico since 1996.

Cu-Au porphyry deposits of the Massif du Nord district, Haiti

Porphyry copper mineralization, closely associated with epithermal mineralization of the same Late Cretaceous age, is widespread in the Massif du Nord district of Haiti. Host rocks are plutons of quartz diorite to tonalite composition, the shallow-level expression of the Loma de Cabrera hornblende tonalite batholith that straddles the border between Haiti and the Dominican Republic. As pointed out by Louca (1990), porphyry copper deposits of the Massif du Nord district failed to develop the concentric shells of alteration and mineralization that are typical of porphyry copper deposits and they also lack strong feldspathic alteration. Porphyry copper deposits of the Massif du Nord are characterized by propylitic alteration (epidote, chlorite, albite, quartz and calcite).

The Blondin and Douvray porphyry copper deposits (Fig. 3A) fall on a northwest trending copper-rich zone about 7 kilometers long (Niccolini, 1977). Copper sulfides occur as disseminations and fracture fillings in volcanic rocks and in porphyritic to aplitic quartz diorite intrusive rocks. Sulfides include pyrite, chalcopyrite, bornite, enargite, chalcocite and smaller amounts molybdenite which are preserved beneath an oxide zone that averages about 20 meters in thickness but, locally, reaches 60 meters in thickness.

Two porphyry copper occurrences (Valliere and Mont Organisé) are located in the Massif du Nord, near the western margin of the Restauración district (Fig. 3A). Only the Valliere deposit has a (small) established resource (Table 4). Alteration and sulfide mineralization at the Mont Organisé porphyry copper prospect, 13km east-northeast of Valliere, appears to be confined to the contact zone between a porphyritic tonalite and rocks of the Upper Tireo Group (Louca, 1990). The Treuil porphyry copper prospect, located twelve kilometers south of the La Mine prospect (Fig. 3A), occurs in a quartz diorite stock.

Cu-Au porphyry deposits of the Restauración district, Dominican Republic

Three porphyry copper prospects occur in the northwest Restauración district (Fig. 3). At the El Corozo prospect, situated along the Lebon pluton on the border with Haiti, a multiphase chalcopyrite-pyrite-quartz-magnetite stockwork occurs in silicified granodiorite. Hydrothermal alteration at El Corozo includes secondary biotite and K-feldspar along with (later) epidote and chlorite. The Jiménez occurrence, located 2-3km northeast of the town of Restauración, is centered on three adjoining quartz-feldspar porphyry (dacite) domes (Jiménez, Poco Negro and a third unnamed dome) that intrude basaltic to andesitic flows, andesitic lapilli tuff, accretionary lapilli tuff and a calcareous sedimentary sequence. The mineralization occurs at the base of the domes and is characterized by gold-bearing high-grade chalcopyrite veins. Neita, located about 1km south of Jiménez, is a northwest trending copper-rich zone, the extent of which is based on anomalous values of Cu, Mo and Au in soils.

Several clusters of epithermal gold occurrences are peripheral to these porphyry copper prospects including a NW trending 3km long anomalous As-Ba-Cu-Zn-Au signature in soils located about 1km west of the Neita prospect.

TABLE 3 **Epithermal Deposits**

Deposit	Past production	Current resource	Observations	References
Moore, Pueblo Viejo District, Dominican Republic	3,521,705 ozs Au, 16,132,220 ozs Ag (1975-1999)	135.1 Mt at 2.9 g/t Au, 14.3 g/t Ag, 0.1 % Cu	High sulfidation, under construction	Ruiz (1997), Smith et al. (2008), Nelson (2000a, b)
Monte Negro, Pueblo Viejo District, Dominican Republic	1,760,852 ozs Au, 8,066,110 ozs Ag (1980-1999)	70.6 Mt at 3 g/t Au, 15.8 g/t Ag, 0.06 % Cu	High sulfidation, under construction	Ruiz (1997), Smith et al. (2008), Nelson (2000a, b)
Grand Bois, Haiti	none	4.5 Mt at 2.3 g/t Au	High sulfidation	Louca (1990), Sillitoe et al. (1996)
Morne Bossa, Haiti	none	2.0 Mt at 2.25 g/t Au	High sulfidation	Louca (1990), Sillitoe et al. (1996)
Candelones, Restauración District, D.R.	none	2.04 Mt at 1.1 g/t Au	High sulfidation	Lamouille et al. (1998), Amarante et al. (1989)
Doña Amanda, Bayaguana District, D.R.	none	43.2 Mt at 0.45% Cu, 0.23 g/t Au, 1.07 g/t Ag	High sulfidation	Chenard (2006)
Golden Hill, Camagüey District, Cuba	none	10.5 Mt at 0.22% Cu, 0.6 g/t Au	High sulfidation	Kesler et al. (2004), López-Kramer et al. (2007)
Centenario (El Higo), Dominican Republic	none	2.5 Mt at 5.5 g/t Au	Low sulfidation	Listin Diario, Santo Domingo, June 21, 1997
(Cerro) Kiosko, Dominican Republic	none	4.92 Mt at 2.01 g/t Au, 5.17 g/t Ag, 0.98 % Cu	High sulfidation	Chenard (2006)
Doña Loretta (Ceja del Coco), Dominican Republic	none	8.2 Mt at 0.5% Cu	High sulfidation	Chenard (2006)
Faille B, Haiti	none	0.5 Mt at 15.5 g/t Au	Low sulfidation	Louca (1990), Espaillat (1996)
Jacinto, Cuba Camagüey District, Cuba	none	1.1 Mt at 4.73 g/t Au	Low sulfidation	López-Kramer et al. (2007)
Florencia, Cuba Camagüey District, Cuba	none	0.837 Mt at 5.37 g/t Au	Low sulfidation	López-Kramer et al. (2006, 2007)
Pennants (Main Ridge), Jamaica	12,000 ozs Au (2001 – 2002)	75,500 tons at 20.4 g/t Au	Low sulfidation	Garrett et al. (2004)

Cu-Au skarn and porphyry deposits of the Terre Neuve district, Haiti

The Memé and Casseus copper-gold skarn deposits of Haiti (Fig. 3A) are found in limestone pendants within the Terre Neuve intrusion, a composite calc-alkaline pluton of medium to high potassium content (Lidiak and Jolly, 1996) with quartz monzonite, granodiorite and quartz diorite phases (Kesler, 1968; Harnish and Brown, 1986). Production dates back to the early 1700's; neither mine is currently active. Gangue minerals consist of garnet, diopside, tremolite, chlorite, wollastonite, epidote, magnetite and hematite. Sulfides include chalcopyrite, pyrite, chalcocite, digenite, covellite, bornite and, locally, molybdenite (Louca, 1990).

Terre Neuve intrusive rocks lie along a northwest trending structure in the Terre Neuve Massif separate from the Massif du Nord to the north. These intrusive rocks are distinctly more K-rich and have a higher content of large-ion lithophile elements (LILE) than those of the western Cordillera Central and Massif du Nord (Lidiak and Jolly, 1996). Their compositions are similar to plutonic rocks from central and eastern Jamaica, central Cuba and the Nicaraguan Rise (Lewis et al., this volume). A single K/Ar date of 66Ma has been published for the Terre Neuve intrusions (Kesler and Fleck, 1967), younger than most K/Ar and Ar/Ar dates for intrusive rocks in the Massif du Nord and Cordillera Central (Kesler et al., 1991; Escuder-Viruete et al., 2006). This evidence indicates that the magmatism responsible for the Terre Neuve intrusions and Cu-Fe skarn deposits is from a different source than that of the western Cordillera Central-Massif du Nord tonalite plutons, but that it is more evolved and younger in age.

The Jean Rabel (Vert de Gris) porphyry copper-molybdenum prospect is located on the northwest extension of the Terre Neuve massif in an anticlinal structure (Cheilletz, 1976; Cheilletz et al., 1978). Stockwork and disseminated mineralization occur in a complex of porphyritic stocks and dikes. The intrusive rocks include, from oldest to youngest, locally porphyritic hornblende-biotite tonalite, rhyodacite porphyry intrusions and intrusive breccias, and dikes of hornblende andesite porphyry. The sulfide mineral assemblage includes pyrite, bornite, chalcopyrite and minor molybdenite. Copper and molybdenum mineralization occurs with potassic alteration characterized by green to brown secondary biotite, potassium feldspar and apatite at the contact between intrusive rocks and andesite, and, in intrusive rhyodacite breccias. In addition to potassic alteration, phyllic alteration (quartz-sericite-pyrite) and propylitic alteration (chlorite and epidote) are also present. A whole-rock Rb/Sr isochron age of 67.3±4Ma is interpreted as the age of intrusion. A K/Ar isochron age of 57.7±5Ma on four biotite separates is interpreted as the age of mineralization (Cheilletz et al., 1978).

Cu-Au porphyry and iron skarn deposits of the Camagüey and Villa Clara districts, Cuba

Several small porphyry copper deposits are located in the Camagüey district, within a cluster of epithermal precious metal occurrences (Fig. 2C). Examples include the Tres Casas, Palo Seco and Guaimaro Cu-Mo-Au porphyry deposits (Torres et al., 2005), and La Union Au±Cu prospect (Ulloa-Santana et al., 2011). These porphyry deposits (Table 4) are related to a plutonic complex that, as originally defined by Pérez-Rodríguez and Sukar (1997) and modified by Hall et al. (2004), includes three main compositional phases. Recent U/Pb SHRIMP dating on zircons (Rojas-Agramonte, 2006a; Stanek et al., 2009) shows that syenite was the earliest intrusive phase (107-99Ma) followed by granodiorite (~85Ma). Acid magmas of the plagiogranite (trondhjemite) series (81-75Ma) were the last to crystallize. Comparison of the chemistry of the volcanic rocks with those of the plutonic rocks shows that the same magmas were the source of both intrusive and extrusive phases (Piñero et al., 1997; Mari, 1997). Hall et al. (2004) have explained the relatively young Ar/Ar ages, which have a narrow range of ca. 75–70Ma, for both the volcanic and intrusive rocks, as related to rapid cooling and uplift in the Late Cretaceous.

Skarns in the Villa Clara district (Fig. 2B) and in the Camagüey district (Fig. 2C) were formed by the recrystallization of limestone intervals within volcanic and volcaniclastic rocks of Cretaceous age near the contact with calc-alkaline plutons of intermediate composition (see Moreira et al., 2001 for a review). Skarn deposits in the Villa Clara district are found mainly on the western flank of a calc-alkaline batholith (Fig. 2B). Gangue minerals at the Guaos deposit include garnet, pyroxene, chlorite, epidote, wollastonite, calcite, siderite, and magnetite; sulfide minerals include pyrite, chalcopyrite, galena and sphalerite (Tolkunov et al., 1974b; Batista-González et al., 1998). Past producers from the Villa Clara district include Guaos (with up to 11.7g/t Au) and Loma Alta (Fig. 2B). The Felipita and Magarabomba iron deposits (Fig. 2C), in the Camagüey district, are composed of magnetite and hematite plus minor chalcopyrite and covellite with a gangue assemblage that includes epidote, garnet and calcite.

Cu-Au porphyry deposits of the Bellas Gate district, Jamaica

Two small porphyry copper deposits (Connors and Camel Hill) are known from the Central Inlier of Jamaica (Fig. 3B), an erosional window that exposes Cretaceous tholeiitic island arc (IAT) basalts, minor pyroclastic rocks and interbedded volcaniclastic sedimentary rocks. The volcanic rocks are intruded by a Late Early to Early Late Cretaceous suite of diorite, granodiorite and tonalite dikes, sills and stocks (Mitchell, 2003). A hornfels surrounding the granodiorite stock at Ginger Ridge (Porter, 1970) has given a K/Ar isochron age of 85±9Ma (Lewis et al., 1973). At Connors and at Camel Hill, the Ginger Ridge granodiorite stock is partially unroofed and is host to magnetite-bearing quartz veins and stockworks. Mineralization consists of vein and disseminated pyrite, chalcopyrite, and minor sphalerite locally enriched by secondary copper sulfide (chalcocite). The ore bodies occur within a zone of widespread propylitic alteration that surrounds two, northwest-striking, structurally-controlled corridors of phyllic alteration and hydrothermal biotite-bearing potassic alteration. The porphyry copper deposits are surrounded by a cluster of base- and precious metal-bearing quartz veins.

Iron skarn deposits of the Hierro Santiago district, Sierra Maestra, Cuba

Iron oxide deposits classified here as skarns are found in the eastern part of the Sierra Maestra volcanic arc (Lavandero et al., 1988; Cazañas et al., 1989;

TABLE 4 | **Porphyry Copper and Skarn Deposits**

Deposit	Past production	Current resource	Observations	References
Douvray, Haiti	none	180 Mt at 0.59% Cu	Cu-Au Porphyry	Espaillat (1996), Louca (1990)
Tanamá and Helecho, Puerto Rico	none	126 Mt at 0.64 % Cu	Cu-Au Porphyry	Hollister (1978), Cox (1985)
Cala Abajo (Río Viví), Puerto Rico	none	71 Mt at 0.82 % Cu	Cu-Au Porphyry	Hollister (1978), Barabas (1982)
Valliere, Haiti	none	84 Mt at 0.44% Cu, 1.5 g/t Ag	Cu-Au Porphyry	Espaillat (1996)
Blondin, Haiti	none	50 Mt at 0.56 % Cu	Cu-Au Porphyry	Espaillat (1996), Louca (1990)
Piedra Hueca, Puerto Rico	none	33 Mt at 0.82 % Cu	Cu-Au Porphyry	Hollister (1978), Barabas (1982)
Arimao, Cuba	none	60 Mt at 0.3 g/t Au, 18 g/t Ag, 0.31 % Cu	Cu-Au Porphyry	
Camel Hill, Jamaica	none	13.177 Mt at 0.17 g/t Au, 0.35 % Cu	Cu-Au Porphyry	Fenton (1981)
Connors, Jamaica	none	6 Mt at 0.5% Cu	Cu-Au Porphyry	Fenton (1981)
Palo Seco, Cuba	none	42 Mt at 0.15% Cu	Cu-Au Porphyry	
Guaimaro, Cuba	none	103 Mt at 0.1% Cu, 0.011% Mo	Cu-Au Skarn	
Memé, Haiti	97,000 ozs Au, 30,000 ozs Ag (1960-1971)	1.5 Mt at 2 g/t Au, 2 % Cu	Cu-Au Skarn	Louca (1990)
Casseus, Haiti	none	2 Mt at 1.35% Cu	Cu-Au skarn	Harnish and Brown (1986)
Daiquirí (Hierro Santiago) District, Cuba	6,577,457 tons Iron ore (1906-1912)	40 Mt at 40% to 45% Fe	Iron skarn district	Cazañas et al. (1989), Moreira et al. (2001)
Maimón-Hatillo District, Dominican Republic	700,000 tons iron ore (1950-1958)		Iron skarn distict	Bowin (1966)
Mata Grande, Dominican Republic	unknown (minor)		Cu skarn	

Pérez-Rodríguez and Santa Cruz, 1991; Méndez et al., 1994; Sánchez-Cruz et al., 1998; Moreira et al., 2001). Mineralization occurs in volcanic rocks near a contact with plutons of quartz diorite, tonalite and gabbro (Kysar-Mattietti, 2001). The main mining area is the Daiquirí or Hierro Santiago district, where the La Grande, Antoñica, Concordia, Folia, Yuca, El Norte, El Descanso, Vinent, Fausto, Falcón, Falconera, and Chalía mines are located (Fig. 2C). The deposits were mined from 1890 to 1947 with 6,577,457 tons of ore produced between 1906 and 1912 (Moreira et al., 2001); resources are in excess of 40Mt containing 40-45% total iron (Cazañas et al., 1989)

Skarn deposits of the Sierra Maestra have some affinity to iron oxide copper-gold (IOCG) deposits. Sillitoe (2003), Williams et al. (2005) and Pollard (2006) describe iron oxide copper-gold deposits in more detail. In the Sierra Maestra, host rocks are mainly volcanic and volcaniclastic (Pérez-Rodríguez and Santa Cruz, 1991; Moreira et al., 2001) but calc-silicate minerals are present. Iron oxide (magnetite-hematite) is the dominant ore mineral; copper sulfides are present but are uncommon; gold is present as native gold. Calc-silicate minerals include andradite-grossularite with a small amount of pyroxene, calcic amphibole and, in the more distal parts, epidote. Some skarn deposits of the Sierra Maestra contain rare earth minerals.

TABLE 5 | **Volcanogenic ("Cuban-type") Manganese Deposits**

Deposit	Past production	Current resource	Observations	References
Cristo, Ponupo, Los chivos	10 Mt of 35% Mn during the 1940's		Volcanogenic (Cuban-type) Mn	Mosier and Page (1998), Cazañas and Melgarejo (1998), Cazañas et al. (2003)
La Margarita	Included above		Volcanogenic (Cuban-type) Mn	Cazañas and Melgarejo (1998) Cazañas et al. (2003)

Iron skarn deposits of the Maimón-Hatillo district, Dominican Republic

Iron oxide deposits were mined from a dozen small deposits in the Maimón-Hatillo district between 1950 and 1958 (Bowin, 1966). These deposits are located between the Pueblo Viejo district and the Cerro de Maimón deposit (Figs. 1, 3A). In situ mineralization is reported from two deposits, Sabana Grande and Las Lagunas; the others consisted of magnetite boulders (weighing up to twelve tons) embedded in lateritic clay (Bowin, 1966). The in situ deposits consisted of pod-shaped replacements of magnetite (90%) and hematite (10%) in massive limestone. All of the deposits are close to exposures of diorite. At Las Lagunas, magnetite mineralization occurs at the contact between limestone and dikes of diorite. Koschmann and Gordon (1950), Bowin (1966) and Muntean et al. (2007) interpret these deposits as skarns. The age of mineralization is Late Eocene (Kesler et al., 1981) to Early Oligocene (Nelson, 2000a) based on K-Ar dating of associated diorite.

VOLCANOGENIC (CUBAN-TYPE) MANGANESE DEPOSITS

Important manganese deposits formed in the Paleocene to Middle Eocene Sierra Maestra volcanic arc of eastern Cuba (Park and Cox, 1944; Simons and Straczek, 1958; Sokolova et al., 1974; Lavandero et al., 1988; Cazañas and Melgarejo, 1998; Cazañas et al., 2003). Production during the 1940's is estimated at 10Mt at an average grade of 35% Mn (Mosier and Page, 1998; Cazañas et al., 1998, 2003). Manganese deposits of the Sierra Maestra are shown on Fig. 2C; production and resources are listed in Table 5.

Manganese mineralization occurs at several stratigraphic levels in the volcano-sedimentary El Cobre Group, but is best developed at the top of the sequence, near the contact with overlying sedimentary rocks deposited in post-volcanic basins. Manganese ore consists predominantly of botryoidal todorokite and other oxides. According to Cazañas et al. (2003), the mineralization can be interpreted as volcanogenic-exhalative in origin, and was formed in short-lived intra-arc basins. Mosier and Page (1998) use Cuban manganese deposits as a reference model for volcanogenic manganese mineralization. In these deposits, the following lithofacies have been established from the bottom to the top (Cazañas et al., 2003): i) hydrothermal alteration zones at the wall ("green rocks"), ii) jasperoids, iii) massive Mn oxides mineralization ("rich ores"), iv) pyroclastic rocks cemented by Mn mineralization, and v) hematitic hydrothermal alteration bodies.

OROGENIC DEPOSITS

Accretion of the Greater Antilles volcanic arc to the North American margin began in the Late Campanian (García-Casco et al., 2008). Collision may have also triggered the emplacement of metamorphic core complexes (e.g. the Pinos and Escambray terranes). During the suturing process, orogenic deposits formed and were later exposed by erosion. Emplacement of ophiolites in eastern Cuba occured during the latest Cretaceous and Early Danian (Iturralde-Vinent et al., 2006). In western and central Cuba, thrusting of ophiolite onto the Bahamian borderlands took place during the Paleocene to early Late Eocene (Iturralde-Vinent, 1998; Iturralde-Vinent et al., 2008).

Three types of orogenic deposits are recognized: i) orogenic gold deposits, ii) "listvenites" or gold veins deposited in silica-carbonate-altered ultramafic rock, and iii) tungsten deposits. None are in production and only the orogenic gold deposits are known to host substantial resources. Deposits are located on Figs. 1 and 2; past production and resources appear in Table 6.

Orogenic gold deposits

Orogenic gold deposits are known from the entire length of the suture zone that marks the northern margin of the Caribbean Plate. Delita, located in the Pinos Terrane on the Isla de la Juventud off the south coast of western Cuba (Fig. 1) is classified by Bortnikov et al. (1989, 1993)

TABLE 6 | **Orogenic Deposits**

Deposit	Past production	Current resource	Observations	References
Delita, Cuba	unknown (1950's)	18.9 Mt at 2.87 g/t Au, 22.7 g/t Ag	Orogenic Au	López-Kramer et al. (2008a, 2008b), Bermudez-Lugo (2004), Torres (1995), Robertson (1996)
Nuevo Potosí, Cuba	102,724 ozs Au (1904-1990)	83,330 tonnes at 7.8 g/t Au	Listvenite Au	López-Kramer et al. (1998, 2008b), Anonymous (1997)
Melonera, Cuba	none	61,450 tonnes at 28.3 g/t Au, 7.3 g/t Ag	Listvenite Au	López-Kramer et al. (1998, 2008b), Anonymous (1997)
Descanso, Cuba	none	13,840 tonnes at 49.5 g/t Au, 11.8 g/t Ag	Listvenite Au	López-Kramer et al. (1998, 2008b)
Agrupada, Cuba	none	14,200 tonnes at 13 g/t Au	Listvenite Au	López-Kramer et al. (2008b), Anonymous (1997)
Reina Victoria, Cuba	none	1,420 tonnes at 1.42 g/t Au	Listvenite Au	López-Kramer et al. (2008b), Anonymous (1997)
Mina Lela, Cuba	none	0.8 Mt at 0.6% WO_3	orogenic W	Page and McAllister (1944)

as mesothermal. Mineralization consists of quartz veins (0.2-0.5 meters thick) and sulfidic, silicified breccias (Bortnikov et al., 1989) that fill a fault zone within the metamorphic host rocks (López-Kramer et al., 2008a, 2008b). The main gold-bearing mineral is arsenopyrite containing between 5.4 and 56ppm gold (Bortnikov et al., 1993) but native gold is also present. Other sulfides present in minor amounts include sphalerite, tetrahedrite, boulangerite, jamesonite, galena, silver sulfosalts and stibnite (López-Kramer, 1988; López-Kramer et al., 1998).

Listvenite gold deposits

Gold deposits hosted by altered serpentinite in Cuba have been described as listvenites (Cabrera and Tolkunov, 1979; Cabrera, 1986; Lavandero et al., 1988; López-Kramer et al., 1998; Montano-Pérez et al., 1998). These gold deposits have also been referred to as ophiolite-hosted mesothermal gold-quartz veins (Lefebure, 1997). Listvenite is a rock type formed by intense carbonate and silica alteration and replacement of serpentinized ultramafic rock. Gold occurs in faulted and sheared lenses in association with listvenite. The fault zone acts as a pathway for CO_2-rich fluids that react with ultramafic rocks and result in precipitation of metals. López-Kramer et al. (1998) pointed out an association of mercury with gold in Cuban listvenites.

The Descanso and Melonera deposits are located in the Villa Clara district (Fig. 2B). These are small deposits in which narrow alteration envelopes (3 to 4 meters across) host high-grade gold mineralization with associated arsenopyrite (López-Kramer, 1988). Another cluster of listvenite gold deposits (Nuevo Potosí, Agrupada, and Reina Victoria) occurs in a faulted ophiolite in the Holguín region (Fig. 2C) of eastern Cuba (Lavandero et al., 1988; López-Kramer et al., 1998). Nuevo Potosí is the largest of the deposits in the Aguas Claras district with over 100,000 ounces in past production. Listvenite gold deposits are assigned to the orogenic gold group based on their mineralogy and host rock.

Tungsten deposits

Tungsten was mined from the Lela Mine on the Isla de la Juventud (Fig. 1). Mineralization occurs in veins that are associated with porphyritic dikes that intrude the metamorphic host rocks (Page and McAllister, 1944; Lavandero et al., 1988; Pardo, 1990; Kesler et al., 1990). Ferberite and small amounts of scheelite occur in quartz-tourmaline veins, tourmaline-bearing silicified rocks, and tourmaline-bearing schists and quartzites (Page and McAllister, 1944; López-Kramer et al., 2008a). Sulfide minerals include arsenopyrite, pyrite, chalcopyrite, pyrrhotite, bismuthinite and sphalerite.

ORTHOMAGMATIC (PODIFORM CHROMITE) DEPOSITS

Most ophiolites of the Greater Antilles consist of supra-subduction zone lithosphere (Proenza et al., 1999; García-Casco et al., 2006; Marchesi et al., 2006; Lewis et al., 2006). The supra-subduction zone is defined as lithosphere that forms directly above a subducted oceanic plate (Pearce et al., 1984; Dilek and Furnes, 2009). Mantle sequences of supra-subduction zone ophiolites in the Greater Antilles host numerous podiform chromite deposits and occurrences, especially in the Mayarí, Moa-Baracoa and Camagüey ophiolites of Cuba (Fig. 2C). Mercedita, an intermittently active chromite mine, contains over 5Mt of ore and is one of the largest chromite resources in the Americas. The Camagüey ophiolitic massif of central Cuba is host to over 340 known refractory chromite occurrences (Thayer, 1942; Flint et al., 1948; González-Pontón, 1998; Henares et al., 2010). Chromite deposits are plotted on Fig. 2C; production and resource figures are provided in Table 7.

Chromite deposit clusters of the Mayarí-Baracoa belt, eastern Cuba (Fig. 2C) define three districts (Proenza et al., 1998a, 1999). The Mayarí district contains Cr-rich chromite, the Sagua de Tánamo district contains both Al- and Cr-rich chromite, and the Moa-Baracoa district contains Al-rich chromite (Proenza et al., 1999; Gervilla et al., 2005). Chromite deposits of the Mayarí district, with chromium numbers [Cr#=Cr/(Cr+Al)] of 0.69 to 0.83, are medium to small in size and occur in the deeper portions of the ophiolitic sequence, hosted by harzburgites and dunites. Chromite deposits of the Sagua de Tánamo district are enclosed in serpentinized dunites and harzburgites that show mantle tectonite textures. Sagua de Tánamo chromites exhibit large and continuous chemical variation from typical Al-rich (Cr#~0.45) to Cr-rich (Cr#~0.78) compositions (González-Jiménez et al., 2011). The Al-rich Moa-Baracoa chromite deposits (Cr#=0.40-0.55) occur at the mantle-crust transition, immediately beneath the exhumed Mohorovičić discontinuity, where they are associated with harzburgites, dunites, plagioclase-bearing peridotites, gabbro sills and gabbro dikes. Proenza et al. (1998a) provided a detailed description, with maps and stratigraphic columns, of the Mayarí-Baracoa ophiolite.

According to Proenza et al. (1999), the melts in equilibrium with Al-rich chromites are close to the composition of back-arc basin basalts whereas melts in equilibrium with the Cr-rich chromites are of magnesian andesitic or boninitic affinity, characteristic of fore-arc regions (Fig. 5).

BAUXITE AND LATERITIC NICKEL-COBALT DEPOSITS

Bauxite and lateritic nickel deposits formed after the Late Cretaceous to Paleocene collision of the Greater Antilles with North America. Strike-slip motion that began in Eocene time resulted in the uplift and exposure of ophiolites across the northern margin of the Caribbean plate and of platform carbonates in Jamaica. Although the last to form chronologically, bauxite and lateritic nickel-cobalt deposits, are by far the most important deposits in the Greater Antilles from an economic perspective. The Greater Antilles host roughly 10% of the world's nickel laterite resources (Dalvi et al., 2004; Lewis et al., 2006). Cuban laterite deposits contain some of the largest reserves of cobalt in the world (http://minerals.usgs.gov/minerals/pubs/commodity/cobalt/). Jamaica currently produces about 8% of the world's aluminium, down from a high of 18% during the 1970's (Jamaica Bauxite Institute).

Bauxite deposits

Bauxite is a weathering product containing a high proportion of hydrated aluminium oxides (gibbsite and boehmite). In Jamaica, the protolith is volcanic ash (Comer, 1971) which weathers to form a ferruginous soil rich in alumina and typically containing less than 5% silica. Ores typically run between 40% and 50% alumina and are mined from open pits. Processing employs the Bayer process which involves dissolution of alumina with sodium hydroxide followed by precipitation of dissolved silica, separation of solid waste, precipitation of pure gibbsite, and heating (calcination) to drive off water. The processing plant at Kirkvine went into production in 1952 followed by Ewarton, Nain (1969), Maggotty (1971), and Halse Hall (1973). These plants produce alumina for export to Europe and North America where it undergoes the energy-intensive conversion to aluminium metal.

The largest bauxite deposits in the Greater Antilles are located in the central highlands of Jamaica. The deposits occur as clusters of irregularly shaped pockets, pipes, fissures, and blankets that fill solution cavities within the Middle Eocene to Middle Miocene White Limestone Group (Fenton, 1981), a well-developed (up to 3000 meters in thickness) sequence of platform carbonates that extended across the Nicaraguan Rise (Mitchell, 2006). There is no cover other than a thin layer of soil and the contact between bauxite ore and the surrounding limestone, although typically sharp, is quite irregular. Individual pockets can contain as much as 5 million tonnes of ore although most are much smaller. Bauxite ore is locally as much as 30 meters in thickness and can extend along fractures for five or ten meters into the underlying limestone. The best ore occurs at an elevation of over 300 meters where there is a greater separation between bauxite and the water table (Hill, 1955; Fenton, 1981).

Jamaica produced its first bauxite in 1952 followed by Haiti in 1957 and the Dominican Republic in 1959. The industry thrived and, by 1957, Jamaica was the world's leading producer of aluminum. Production from Jamaica has continued to increase over the years to current levels of around 15 million metric tonnes (Mt) per year of bauxite and 4Mt of alumina, accounting for roughly 10% of Jamaica's gross domestic product (GDP). The Jamaica Bauxite Institute estimated total bauxite resources for the island at 2.5 billion tonnes in 2010. Bauxite mines in Haiti and the Dominican Republic closed in 1982 and 1991

TABLE 7 | **Orthomagmatic (Podiform Chromite) Deposits**

Deposit	Past production	Current resource	Observations	References
Moa-Baracoa district		> 6 Mt	Al-rich	Proenza et al. (1998a, 1998b, 1999), Rabchevsky (1994), Torres (1999), Bermudez-Lugo (2004, 2008), Gervilla et al. (2005)
Mercedita	695,487 tons (1990 – 2008)	> 5 Mt at 36% Cr_2O_3, 24.6% Cr	Intermittently active mine	
Amores		>100,000 tons		
Loro		>100,000 tons		
Yarey		>100,000 tons		
Piloto		>100,000 tons		
Cayo Guam	300,000 tons			
Potosí	300,000 tons			
Sagua de Tánamo district	1930-1940	42% Cr_2O_3 ave., or 28.7% Cr	35 small deposits; 10 Cr-rich and 25 Al-rich	Proenza et al. (1998a, 2003), Gervilla et al. (2005)
Mayarí district	500,000 tons	> 500,000 tons at 54% Cr_2O_3 ave., 36.9% Cr	Cr-rich	Lavaut et al. (1994), Proenza et al. (1998a, 2004), Gervilla et al. (2005)
Caledonia		200,000 tons		
Casimba		200,000 tons		
Estrella de Mayarí		200,000 tons		
Juanita		<100,000 tons		
Victoria		<100,000 tons		
Camagüey district		> 1 Mt	Al-rich	González-Pontón (1998), Henares et al. (2010)
Camagüey II		705,375 tons		
Victoria I		149,770 tons		
Mamina		97,450 tons		
Lolita		86,675 tons		
Ofelia		55,100 tons		
Ferrolana		52,985 tons		

respectively. Deposits are shown on Figures 1 and 3B; production and resources appear in Table 8.

Lateritic Ni-Co deposits

Cuba has been an important producer of nickel and cobalt from lateritic ore since 1943 when the Nicaro processing plant went into production followed by Moa and Punta Gorda. Nickel production in the Dominican Republic dates back to 1968 and comes from the Falcondo plant near Bonao. Falcondo currently draws ore from seven nearby deposits and produces approximately 50,000 tons of nickel annually. Cuba currently produces around 80,000 tons of nickel annually from active plants at Punta Gorda, Moa and Nicaro. Production from both countries has shown overall steady growth for the past twenty years. Deposits are shown on Fig. 2C and Fig. 3A; production and resource information is provided in Table 9.

Lateritic nickel deposits form by the weathering of ultramafic rock. Nickel, derived from the dissolution of olivine, concentrates in limonitic soil and in underlying saprolite. Open pit ore bodies typically contain between 1.5% and 2.5% nickel, representing enrichment by a factor of ten over their concentration in the original ultramafic source rock.

At Falcondo, nickel is recovered in an energy-intensive pyro-metallurgical process that involves heating in a reduction furnace to melt the ore, allowing nickel and iron to separate by gravity from lighter-weight slag. The final product is ferro-nickel (38% Ni and low impurities) in the form of a cone designed for the stainless steel industry. The Moa plant in Cuba uses sulphuric acid to leach nickel and cobalt, under pressure, from lateritic ore. Neutralization of the excess acid is accomplished with carbonate leaving gypsum as a waste product. Acid leaching, which is less expensive than pyrometallurgy, is feasible for laterites with low magnesium content.

In eastern Cuba, nickel laterite deposits are classified as the oxide-type, and the typical section through the profile consists of four principal horizons, from bottom to top: serpentinized peridotite, saprolite, limonite and ferricrete (Lewis et al., 2006). The nickel and cobalt occurs mainly in the limonite zone composed of Fe hydroxides and oxides as the dominant mineralogy in the upper part of the profile.

TABLE 8 | **Bauxite Deposits**

Deposit	Past production	Current resource	Observations	References
Nain, Jamaica	49,465,619 tons Al (1969 – 2007)	66.6 Mt at 21.1 % Al		Past production for each of the bauxite deposits in Jamaica has been estimated from published yearly production figures for Jamaica (US Bureau of Mines, US Geological Survey) apportioned among individual deposits according to years of operation and plant capacity.
Mocho, Jamaica	43,646,134 tons Al (1963 to 2007)	58.8 Mt at 21.2 % Al	Active mine	
Lydford, Jamaica	27,351,577 tons Al (1952 to 2007)	36.8 Mt at 21.2 % Al		
Water Valley, Jamaica	27,351,577 tons Al (1952 to 2007	36.8 Mt at 21.2 % Al	Active mine	Resources for each of the bauxite deposits in Jamaica has been estimated from published total resources for Jamaica apportioned according to plant capacity.
Kirkvine, Jamaica	18,913,325 tons Al (1952 to 2007)	25.4 Mt at 21.2% Al	Active mine	
Schwallenburg, Jamaica	18,913,325 tons Al (1952 to 2007)	25.4 Mt at 21.2 % Al	Active mine	
Pedernales, Dominican Republic	4,557,000 tons Al (1959-1991)			
Miragoane, Haiti	3,595,000 tons Al (1957-1982)			

Goethite particles contain up to 4.5% nickel (Proenza et al., 2007). The main cobalt ore minerals are lithiophorite, asbolane and products intermediate between lithiphorite and asbolane (Labrador et al., 2007; Roqué-Rossell et al., 2010).

In contrast, Dominican Republic deposits are classified as the hydrous silicate-type. The main Ni-bearing minerals are hydrated Mg-Ni silicates (serpentine and "garnierites") occurring in the saprolite horizon below a relatively thin cover of limonite (Lithgow, 1993; Lewis et al., 2006). The garnierites occur as veins filling fractures in the harder serpentinised peridotites in the lower part of the laterite profile. Many garnierite ores at Falcondo mine are made up of Ni-sepiolite-falcondoite or talc-like minerals consisting of fine-grained mixtures of Ni-bearing serpentine and talc (Proenza et al., 2008; Tauler et al., 2009).

Nickel-cobalt deposits in eastern Cuba formed on serpentinized harzburgite. The peneplain surface of the deposits varies from 60 to 360 meters in elevation and the weathering mantle attained a thickness of 10 to 50 meters (Linchenat and Shirakova, 1964). Weathering and lateritization of exposed serpentinite may have commenced as early as Eocene time; ultramafic rocks in the Dominican Republic were exposed to weathering during the Miocene. Lewis et al. (2006) have suggested that oxide-type laterites of Cuba were exposed to weathering for a longer time and were uplifted at a slower rate than the hydrous silicate-type laterites of the Dominican Republic.

ALLUVIAL AND BEACH PLACER DEPOSITS

Forty-nine alluvial gold deposits are reported from Cuba (Morales-Quintana and Moreira, 1998). Fluvial placers with Au and/or platinum group elements have been described from the Habana-Matanzas region (Morales-Quintana and Arzuaga, 1994) and the Sagua de Tánamo-Moa-Baracoa region (Díaz-Martínez et al., 1998; Proenza et al., 2004). Source rocks for the fluvial placer gold deposits are assumed to be nearby ophiolites and Cretaceous volcanic rocks.

Beach placers (e.g. Mejías deposit) are found on the northern coast of eastern Cuba (Díaz-Martínez et al., 1998). Mineralization consists of magnetite, titanomagnetite, chromite, ilmenite, rutile, native gold particles, mercurial gold and platinum group minerals (laurite, erlichmanite, irarsite).

In the Dominican Republic, the most important areas for alluvial gold placer deposits are Mao river basin near Monción in the Cordillera Central, Miches in the eastern part of the country, the Rio Haina near Villa Altagracia, and San Francisco de Macoris.

TABLE 9 | **Lateritic Nickel-Cobalt Deposits**

Deposit	Past production	Current resource	Observations	References
San Felipe, Cuba	none	250 Mt at 1.43 % Ni, 0.05 % Co		Brouwer and Martin (2008)
Pinares West, Cuba	100,000 tons Ni	131.3 Mt at 1.22 % Ni, 0.0116 Co	Active mine	Brouwer and Martin (2008)
Punta Gorda, Cuba	375,124 tons Ni (1986 – 2007)	106 Mt at 1.26 % Ni, 0.1 % Co	Active mine	Brouwer and Martin (2008)
Falcondo, Dominican Republic	798,702 tons Ni (1975 – 2007)	35.3 Mt at 1.73 % Ni	Active mine	Falconbridge Dominicana (1998)
Moa, Cuba	774,784 tons Ni (1959 – 2007)	62 Mt at 1.32 % Ni, 0.12 % Co	Active mine	Brouwer and Martin, 2008
Pinares de Mayarí, Cuba	400,000 tons Ni	38 Mt at 1.29 % Ni	Active mine	Brouwer and Martin (2008)
La Fangosa, Cuba	none	54 Mt at 1.38 % Ni, 0.84 % Co		Brouwer and Martin (2008)
Marti, Cuba	100,000 tons Ni	40 Mt at 1.36 % Ni, 0.1 % Co	Active mine	Brouwer and Martin (2008)
Guanajibo, Puerto Rico	none	46.8 Mt at 0.88 % Ni, 0.08% Co		Heidenreich and Reynolds (1959)
Las Iberias, Cuba	none	30.8 Mt at 1.23 % Ni		Brouwer and Martin (2008)
Las Mesas, Puerto Rico	none	25 Mt at 0.81% Ni, 0.12 % Co		Heidenreich and Reynolds (1959)
Camarioca Sur, Cuba	unknown	17.3 Mt at 1.31 % Ni	Active mine	Brouwer and Martin (2008)
Santa Teresita, Cuba	none	18.3 Mt at 1.14 % Ni, 0.11 % Co		Brouwer and Martin (2008)
Maricao East, Puerto Rico	none	5.6 Mt at 1.08% Ni, 0.11% Co		Heidenreich and Reynolds (1959)
Maricao West, Puerto Rico	none	5 Mt at 0.98% Ni, 0.1% Co		Heidenreich and Reynolds (1959)
Rosario North, Puerto Rico	none	4.8 Mt at 0.85% Ni, 0.07% Co		Heidenreich and Reynolds (1959)
Punta Guanajibo, Puerto Rico	none	2.1 Mt at 1.03 % Ni, 0.07% Co		Heidenreich and Reynolds (1959)
Rosario South, Puerto Rico	none	1.1 Mt at 0.71% Ni, 0.06 % Co		Heidenreich and Reynolds (1959)

SUMMARY AND CONCLUSIONS

Metallic mineral deposits formed throughout the tectonic evolution of the Greater Antilles. The most valuable deposits, in terms of contained metal value, are the bauxite and lateritic nickel-cobalt deposits, followed by the epithermal Pueblo Viejo Au-Ag-Cu district, and Cuban-type volcanogenic manganese.

We give below a conceptual outline of the occurrence and formation of the different types of mineral deposits as a series of events in the tectonic evolution of the Greater Antilles, based on our present knowledge. These events are matched with a series of cross sections (Fig. 5) adapted from García-Casco et al. (2009) that show the tectonic setting of each of the main deposit types with time. This gives a snapshot in time of the

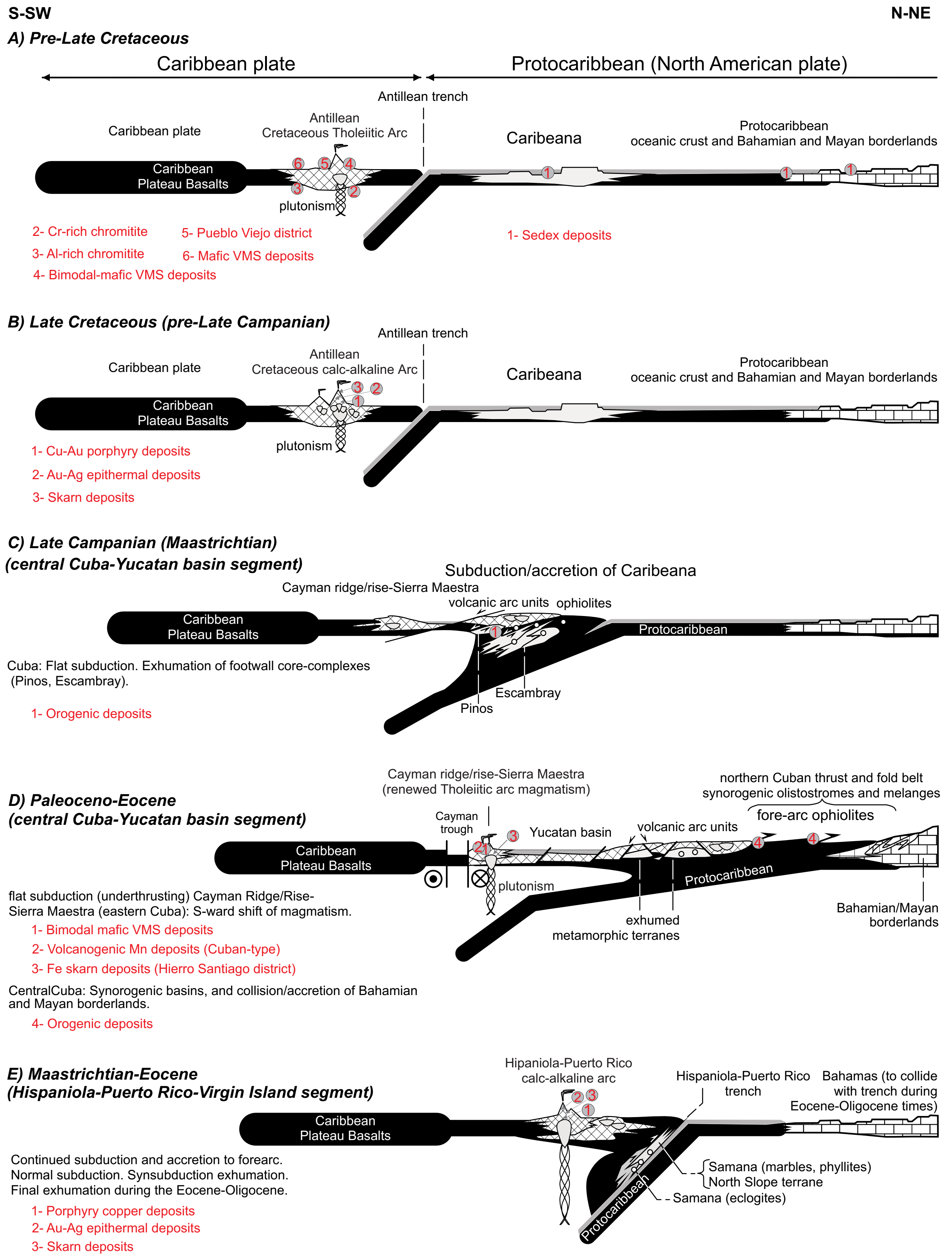

FIGURE 5 | **Tectonic setting of metallic mineral deposit types of the Greater Antilles shown on cross sections modified from Fig. 8 of García Casco et al. (2008). Deposit types discussed in this paper are shown in red.**

distribution of the deposits as the arc evolved. In fact this distribution varies across each sector along the arc.

A) The metallogenic evolution of the Greater Antilles began with the Jurassic breakup of Pangea and the formation of sedimentary exhalative deposits in rift-related terrestrial and marine sedimentary basins (Fig. 5A). The largest sedimentary exhalative deposits in the region are located in the Jurassic to Late Cretaceous San Cayetano basin of western Cuba. With the onset of subduction in Early Cretaceous time, a primitive intraoceanic island arc formed along the length of the Greater Antilles. Beneath this arc, chromite deposits formed in the mantle wedge above the subduction zone. Most Caribbean ophiolites are sections of supra-subduction zone lithosphere that were exposed much later after the collision of the Greater Antilles volcanic arc with North America. Cr-rich chromitites (Mayarí-type) formed, from boninitic magma, in the deep mantle section beneath a primitive island arc (Fig. 5A). Al-rich chromitites (Moa-Baracoa and Camagüey types) formed, from back-arc basin basalt, in the mantle-crust transition zone beneath a more evolved back-arc basin (Fig. 5A). Bimodal-mafic volcanogenic massive sulfide deposits formed in a fore-arc basin setting during the earliest stages of primitive island arc volcanism (Fig. 5A) in the Early Cretaceous. Mafic volcanogenic massive sulfide deposits formed later in mature back-arc basins (Fig. 5A). As the tholeiitic intraoceanic island arc emerged from the ocean, the Pueblo Viejo and Bayaguana high sulfidation epithermal districts formed in apical rifts or back-arc basins (Fig. 5A).

B) As Late Cretaceous island arc volcanism evolved from tholeiitic to calc-alkaline, porphyry copper, skarn and high-sulfidation and low-sulfidation epithermal Au-Ag deposits began to appear (Fig. 5B). Late Cretaceous calc-alkaline volcanic rocks in the Cordillera Central host epithermal and porphyry copper deposits in the Restauración district in the Dominican Republic, the Massif du Nord district in Haiti and the Camagüey district in Cuba.

C) Volcanic activity along the northwest margin of the Caribbean Plate was interrupted during the Late Cretaceous by the subduction of Caribeana (García-Casco et al., 2008). According to these authors, subduction-accretion of Caribeana may have blocked subduction and triggered the emplacement of metamorphic core complexes. Collision/accretion processes led to closure of the proto-Caribbean ocean basin and tectonic emplacement of ophiolites during latest Cretaceous and Paleocene times. Small orogenic gold and tungsten deposits, formed during collision and metamorphism (Fig. 5C), were exposed by later uplift and erosion.

D) During the Paleocene-Eocene in eastern Cuba new intraoceanic island arc-related volcanic activity occurred associated with the Cayman-Ridge Sierra Maestra arc. This island arc was possibly formed as a result of low-angle intra-arc detachment (Pindell et al., 2005). Bimodal-mafic volcanogenic massive sulphide, volcanogenic (Cuban-type) manganese and volcanic-hosted skarn deposits were formed during arc rifting (Fig. 5D).

E) Renewed volcanic arc activity also occurs in Hispaniola, Puerto Rico and Virgin Islands, during the Paleocene- Early Oligocene. In this case, the magmatism was the result of continued southwestward subduction of Proto-Caribbean crust. Small porphyry copper, skarn and epithermal gold deposits formed within and around calc-alkaline stocks (Fig. 5E). The largest of these porphyry copper deposits formed during Eocene to Early Oligocene rifting and intrusion of low-K plutons in Puerto Rico.

Finally, regional uplift exposed the peridotite massifs as a land surface to effective laterization in the beginning of the Miocene. Weathering and secondary enrichment produced economically important deposits of bauxite and lateritic nickel-cobalt in Cuba, Jamaica, Haiti, the Dominican Republic and Puerto Rico.

A connection between rifting and mineralization is the common thread that unites diverse metallic mineral deposit types throughout the tectonic evolution of the Greater Antilles. Jurassic rifting as North and South America drifted apart triggered the accumulation of sediment-hosted base metal deposits. As an intraoceanic tholeiitic island arc (IAT) began to develop in the Early Cretaceous, extension in the fore-arc basin led to the accumulation of bimodal-mafic volcanogenic massive sulfide deposits. Mafic VMS deposits formed in back-arc basins. At 108-112Ma (Pueblo Viejo district) and 116 Ma (Bayaguana district) epithermal Au-Ag-Cu deposits formed in an apical rift or back-arc setting. Eocene rifting at the eastern end of the arc (Puerto Rico) triggered emplacement of the region's largest porphyry copper deposits.

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