



Geologic setting of the Pueblo Viejo Au–Ag–Cu–(Zn) mining district, Dominican Republic - Links to volcanic domes and volcanogenic massive sulfide mineralization

Carl E. Nelson^{a,*}, Hugo Dominguez^b, Rene Leonardo A.^b, Jose Polanco^b, Carlos Carrasco C.^c

^a Recursos Del Caribe, S.A. 2360 23rd Street, Boulder, CO, 80304, USA

^b SI Geomaticas EIRL, Mario García 83. Ens. Quisqueya, Santo Domingo, 10145, Dominican Republic

^c Consulting Geologist, La Chorrera, Panama

ARTICLE INFO

Keywords:

Pueblo Viejo mine
Volcanic domes
Lithocaps
VMS deposits
Epithermal deposits
Porphyry deposits
Los Ranchos formation
Maimón formation

ABSTRACT

Geologic mapping at the Pueblo Viejo Au–Ag–Cu–(Zn) mine, Dominican Republic, and across the surrounding Pueblo Viejo district, reveals the geologic setting at the time of mineralization. Ore deposits consisting of disseminated sulfide, bedded massive sulfide, and high-grade massive sulfide veins formed (~112 Ma) in a volcanic dome field during a period of extension across an emergent, intraoceanic island arc. Geologic maps reveal the links between volcanic domes and structure, hydrothermal alteration and mineralization, and ore deposits and gossans. Whole-rock geochemical data establish a tholeiitic signature for Early Cretaceous magmatism including the volcanic dome field. Northerly-striking, high-angle faults controlled the emplacement of volcanic domes and served as feeders for hydrothermal solutions. The largest ore deposits formed in a subsiding, marginal marine, volcano-sedimentary basin. Stacked intervals of bedded massive sulfide mineralization indicate that the basin was subsiding while mineralization was underway. Calc-alkaline dikes and plutons in the Pueblo Viejo district intruded at ~88 Ma, well after mineralization had ended. Low-angle reverse faulting, greenschist facies metamorphism, and milky quartz veining and replacement were also Late Cretaceous (post-mineral) events. Ore deposits in the Pueblo Viejo district are best described as hybrid epithermal – VMS deposits, formed during a period of Early Cretaceous extension, tholeiitic volcanism, and volcanic dome emplacement in a shallow, marginal marine environment. Exploration for Au–Ag–Cu–(Zn) deposits like Pueblo Viejo should focus on intraoceanic island arcs, tholeiitic volcanic dome fields, extensional volcano-sedimentary basins, and VMS mineral occurrences.

1. Introduction

The Pueblo Viejo Au–Ag–Cu–(Zn) mine, Dominican Republic, is one of the largest gold deposits in the world with yearly production that sometimes exceeds one million troy ounces (Moz). Past production plus known resources reported by Cardenas et al. (2018) total 41 Moz Au, 210 Moz Ag, and 343,000 tons Cu. Zinc, although averaging close to 1% in higher grade ore, is not recovered. Open-pit mining of a blanket of weathered and oxidized ore began in 1972. The underlying sulfide resource was not amenable to the carbon-in-leach process used to treat oxide ore and, by 1999, the mine had closed. Production from sulfide ore commenced in 2013 as a joint venture of Barrick Gold Corporation and GoldCorp (now Newmont Corporation).

Because of their size and economic impact, the geologic setting of the Pueblo Viejo ore deposits has been studied by many geologists over many decades. Published genetic models (e.g., Kesler et al., 1981; Russell and Kesler, 1991; Sillitoe et al., 1996; Nelson, 2000a; Sillitoe et al., 2006; Torró et al., 2017a) disagree sharply over the age of mineralization (Early Cretaceous versus Laramide), the geologic setting (maar-diatreme, volcanic dome field, lithocap), and the genetic model (epithermal, volcanogenic massive sulfide, porphyry). This paper describes the geologic setting at the time of mineralization as revealed by regional geologic mapping and supplemented by new geochemical and geochronological data.

New geologic maps show the district-scale distribution of: 1) volcanic domes and shallow intrusions, 2) hydrothermal alteration and high-

* Corresponding author.

E-mail address: carlericnelson@gmail.com (C.E. Nelson).

<https://doi.org/10.1016/j.jsames.2022.104158>

Received 9 August 2022; Received in revised form 7 December 2022; Accepted 11 December 2022

Available online 27 December 2022

0895-9811/© 2022 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

angle feeder structures, 3) Au–Ag–Cu–(Zn) deposits, and 4) gossans. The maps distinguish Early Cretaceous rock units and hydrothermal alteration from Late Cretaceous, post-mineral events including: 1) low-angle, reverse faulting, 2) incipient to greenschist facies metamorphism, and 3) milky quartz veining and replacement. Field observations, radiometric dates, and geochemical analyses are marshalled in support of a proposed genetic link between tholeiitic volcanism, volcanic dome emplacement, and Au–Ag–Cu–(Zn) mineralization.

2. Geologic background

The Pueblo Viejo district is part of a dominantly-tholeiitic, intra-oceanic island arc that stretches for 2000 km across the northern margin of the Caribbean plate (Fig. 1A). According to (most) tectonic models (e. g., Mann et al., 2007; Pindell et al., 2011) the arc emerged in the Early Cretaceous off the western coast of the Americas and was swept into the opening proto-Caribbean basin as westward-marching North and South America drifted apart. Late Cretaceous to Paleogene oblique collision of the volcanic arc with the southern margin of North America put an end

to volcanism (e.g., García-Casco et al., 2006 and references therein).

The Pueblo Viejo district was mapped by Bowin (1966) who described the Los Ranchos and Maimón Fms. and the Hatillo Limestone (Fig. 1B). He established a Cretaceous age for these rock units and published a regional map covering an area of 5000 km².

Kesler and Galbraith (1973) divided the Los Ranchos Fm. into four members based on 1:20,000-scale geologic mapping of 75 km² in the Pueblo Viejo district. Kesler et al. (1981) described the ore deposits and pointed out that “the size and shape of the mineralized system at Pueblo Viejo resemble active hot spring systems.” Russell and Kesler (1991) modified the stratigraphic column, to six rather than four members, and proposed a maar-diatreme origin for the volcano-sedimentary basin that hosts the ore deposits.

Sillitoe et al. (1996) described Pueblo Viejo as representative of the transition between “high sulfidation systems of volcanogenic massive sulfide and subaerial epithermal affiliations.” Their description of the geologic setting at the time of mineralization “invokes an emergent volcanic edifice with a subaerial maar lake above a diatreme complex.”

Nelson (2000a, 2000b) described the geologic setting at Pueblo Viejo

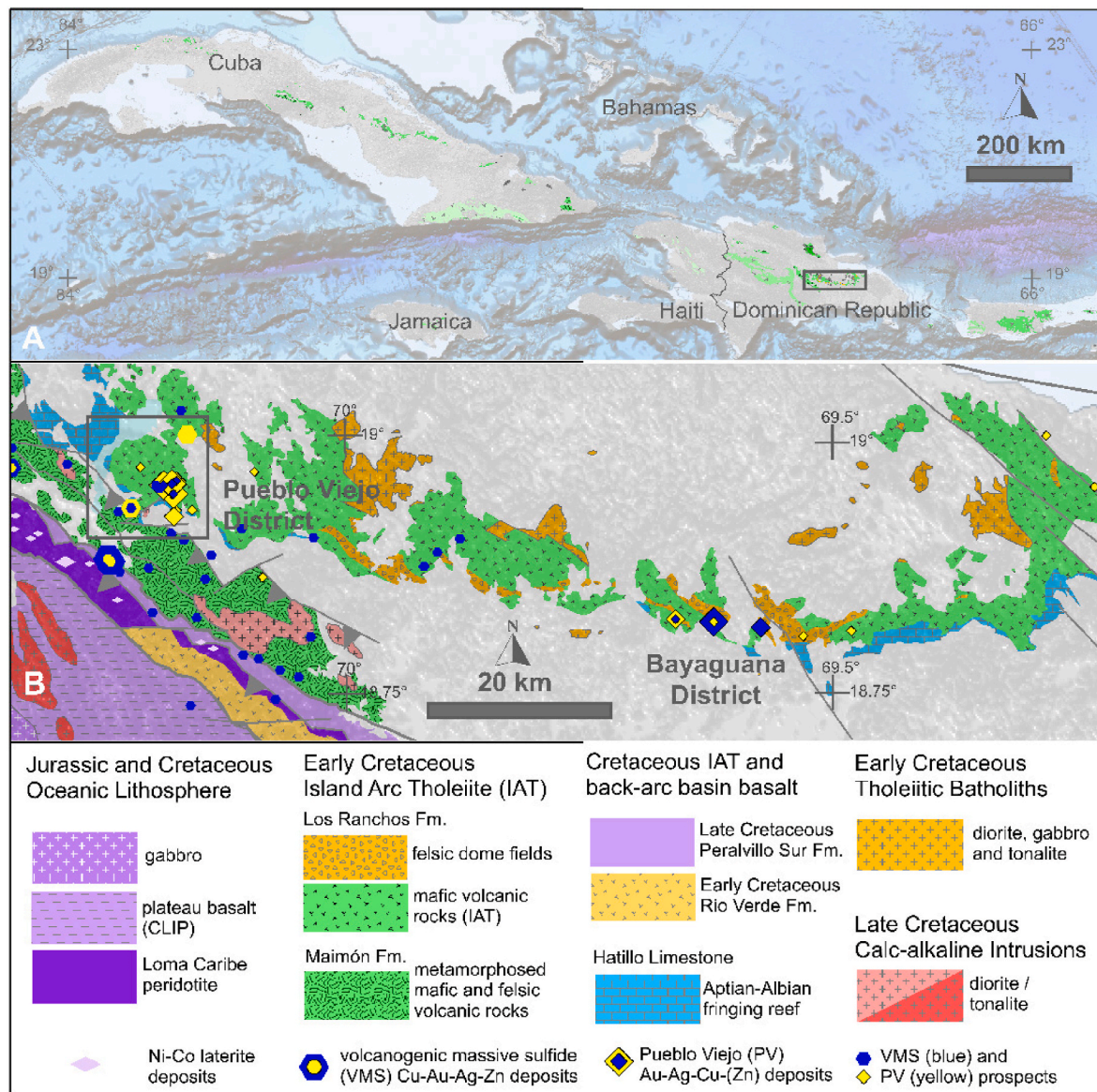


Fig. 1. Pueblo Viejo district location maps. (A) Distribution of tholeiitic island arc volcanic rocks across the Greater Antilles. The grey box shows the location of Fig. 1B. (B) Regional geologic map of the Los Ranchos Formation, modified from Escuder-Viruete et al. (2007a) and Nelson et al. (2015). Grey box indicates the location of the Pueblo Viejo district (Fig. 2).

as a volcanic dome field. His observations in the pits indicated that “volcanic dome emplacement, epiclastic sediment accumulation, hydrothermal alteration, and gold mineralization were coeval events.”

Some models favor a link to porphyry deposits. Sillitoe et al. (2006) described high-sulfidation epithermal ore deposits at Pueblo Viejo as belonging to a lithocap related to Laramide calc-alkaline intrusions. They stated that “there is no genetic relationship between the gold-silver ore bodies and either a maar-diatreme system or a volcanic dome complex.” Torró et al. (2017a) described the Pueblo Viejo ore deposits as

Early Cretaceous “porphyry Cu(-Mo)-high sulfidation epithermal mineralization.”

3. Methods

Fieldwork by the senior author began with 1:2000-scale mapping of the pits and 1:5000-scale mapping of the mine area, and, in conjunction with the co-authors, continued with 1:15,000-scale mapping across the entire Pueblo Viejo district, an area of over 100 km². The maps in this

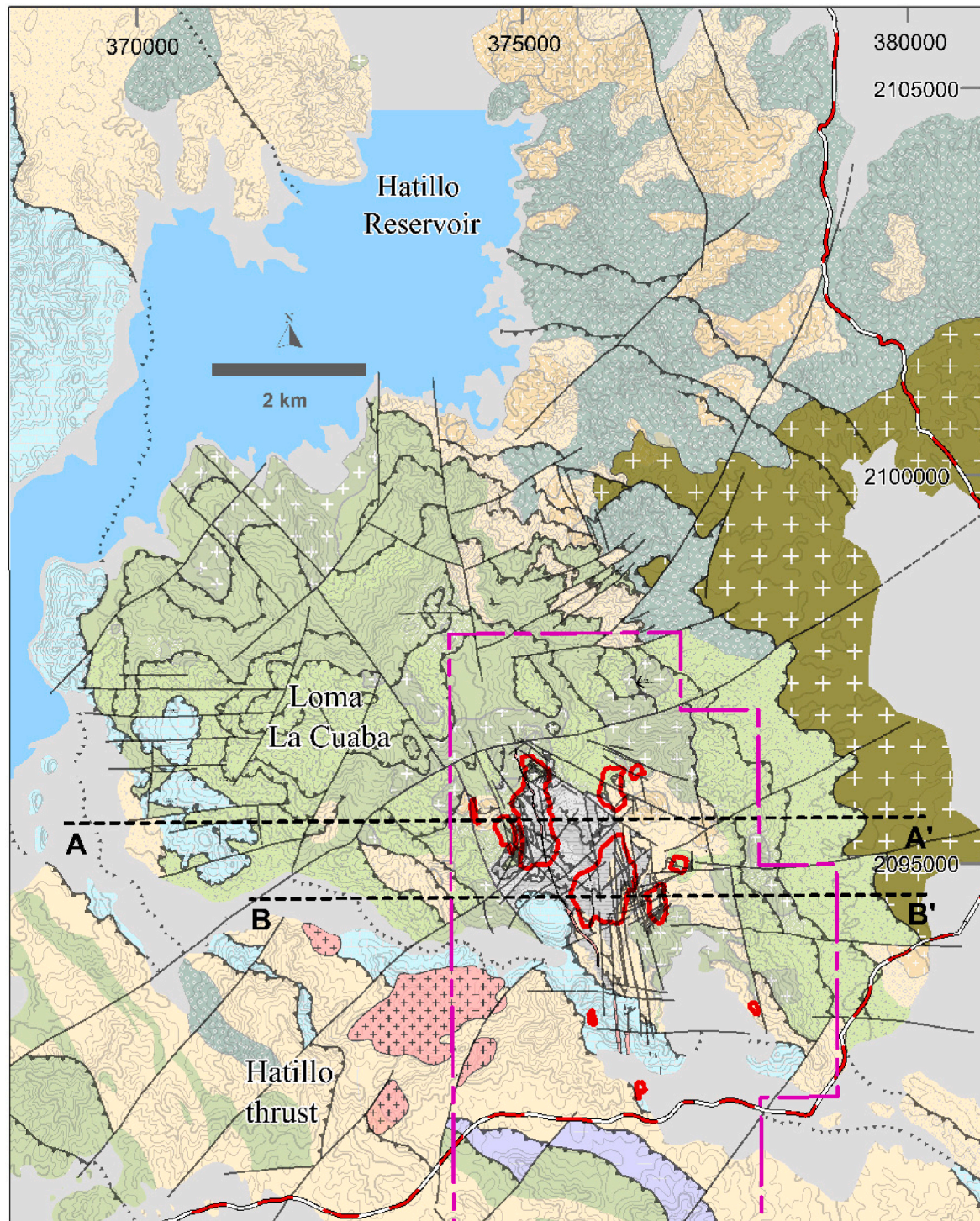


Fig. 2. Pueblo Viejo district geologic map showing rock units and structure. A stratigraphic section and map legend follow (Fig. 3). The Los Ranchos and Maimón Fms. are shown as a single unit based on similar lithologies and similar lithogeochemistry. A-A' and B-B' show the location of cross sections (Fig. 6).

paper represent a compilation of fieldwork carried out over a period of four decades. Locations cited in the text and displayed on the maps (figures) are shown in UTM coordinates (NAD 27, zone 19).

4. Rock units

Several distinct rock packages belonging to the Early Cretaceous Los Ranchos Fm. are well exposed across the Pueblo Viejo district (Fig. 2). Amygdaloidal and locally pillowed basalt flows underlie the northern portion of the district. The basalt package is overlain by a gossan-bearing, volcano-sedimentary unit that is, in turn, overlain by interfingering volcanic andesite and basaltic andesite (andesite), quartz-plagioclase-pyroxene phyrlic dacite with distinctive embayed quartz phenocrysts (dacite porphyry), and carbonaceous volcano-sedimentary rocks (Fig. 3). Detailed descriptions for rock units of the Los Ranchos Fm. can be found in Bowin (1966), Kesler et al. (1981), Kesler et al. (1991a), Russell and Kesler (1991), Nelson (2000a), Vaughan et al. (2020), and Nelson et al. (2020). A series of papers by Torró et al. (2016,

2017a, b, c, 2018) provide a comprehensive description of the Early Cretaceous volcanic rock section in the Pueblo Viejo district and its lithogeochemical evolution. The rock unit descriptions in this paper supplement the previous work with additional observations based on geologic mapping in the pits and across the surrounding Pueblo Viejo district.

Recognition of overlapping and interfingering volcanic and volcanoclastic facies results in a stratigraphic section (Fig. 3) that is largely horizontal (“flat”). It differs, in this respect, from previously published sections that display the volcanic stratigraphy as a vertically-stacked “layer-cake” of progressively younger units. A marked change in volcanic lithologies occurs at an erosional unconformity and volcano-sedimentary interval separating amygdaloidal basalt flows below from volcanic flows, domes and pyroclastic units above (Fig. 3). Detailed sections for the Moore and Monte Negro ore deposits (Borst et al., 2012; Cardenas et al., 2018) display interbedded andesite, dacite porphyry, and volcano-sedimentary rocks, consistent with the “flat” stratigraphic section presented here.

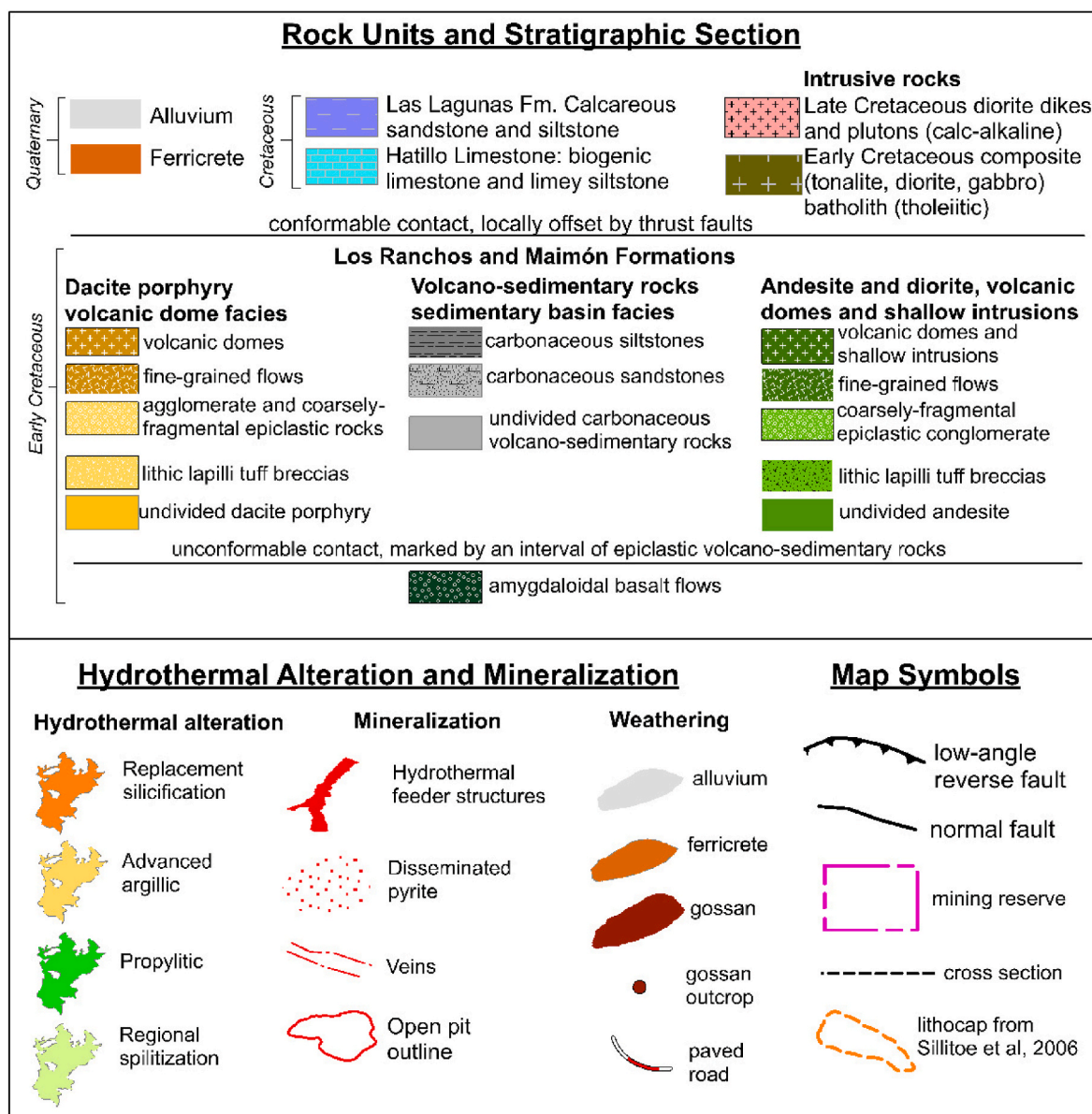


Fig. 3. Legends for Pueblo Viejo district rock units, hydrothermal alteration and mineralization, and map symbols. The stratigraphic section consists of interbedded and interfingering rock units including: andesite and basaltic andesite (andesite), quartz-plagioclase-pyroxene phyrlic dacite (dacite porphyry), and carbonaceous volcano-sedimentary rocks.

Another important difference, reflected in the stratigraphic section (Fig. 3), is the absence of the distinction proposed by Bowin (1966) between the Los Ranchos and the Maimón Fms. These Early Cretaceous formations both consist of basalt, andesite, dacite porphyry, and volcano-sedimentary rock units (Escuder-Viruet et al., 2007b). Their lithogeochemical signatures and hydrothermal alteration assemblages, addressed later in the text, are also similar. Although the Los Ranchos Fm. has been reliably dated as Early Cretaceous, there is very little radiometric dating available for the Maimón Fm. Differentiation of the two units has traditionally been based on the presence or absence of a metamorphic overprint.

4.1. Dacite porphyry volcanic domes

A well-exposed contact between massive, quartz-plagioclase-pyroxene phryic dacite (dacite porphyry) and volcano-sedimentary host rocks was accessible during the 1990's along the eastern margin of the Moore pit. There, a sub-horizontal package of carbonaceous siltstone with occasional carbonate beds is tilted to as much as 80° adjacent to a contact with massive dacite porphyry (Fig. 4A). The contact cuts across bedding (Fig. 4B) and is bordered by an irregularly-shaped "bleached" zone (Fig. 4A and B) that extends for up to 20 m into the volcano-sedimentary section. Four samples of the volcano-sedimentary rock package were collected at distances of up to 40 m from the contact. All four of the carbonaceous siltstone samples are hydrothermally altered (pyrophyllite + pyrite). But, near the cross-cutting contact with dacite porphyry, the finely-laminated siltstone texture (Fig. 5A and B) is lost and a mosaic texture develops (Fig. 5C and D). Organic carbon is driven off (Fig. 5D, H) and diopside, magnetite, and andalusite are added to the mineral assemblage (Fig. 5F, H). These textural and mineralogical changes are evidence for contact metamorphic recrystallization of the carbonaceous volcano-sedimentary host rock in response to dacite porphyry intrusion.

Drilling beneath the massive dacite porphyry in the Moore pit (Fig. 4A and B) confirms the presence of an intrusive root (Fig. 4C). Intrusive roots for the Moore dacite porphyry also appear on other published cross sections (e.g., Figs. 3 and 4 in Nelson, 2000a, Fig. 7.3 in Lomas, 2005, Fig. 14.1 in Smith et al., 2008). Cross sections presented here (Fig. 6) show the shape of massive dacite porphyry bodies, their intrusive roots, and their close spatial relationship to the Moore and Monte Negro ore deposits. Cross sections for hydrothermal alteration, discussed later in the text, are provided (Fig. 6) to facilitate comparison with rock units and structure.

The volcano-sedimentary section along the eastern margin of the Moore pit contains dacite porphyry clasts, quartz phenocrysts as clasts, and interbedded lenses of epiclastic dacite porphyry (Fig. 4E), evidence that massive dacite porphyry underwent erosion as the volcano-sedimentary section accumulated. An apparent contradiction is presented by massive dacite porphyry that both intrudes and is eroded into the volcano-sedimentary host rock section. The contradiction is reconciled by recognizing the massive dacite porphyry intruded, breached the paleosurface, was locally eroded into and, later, was buried by younger volcano-sedimentary rocks as the basin continued to subside.

By 2018, mining at the south end of the Moore pit had exposed a locally flow banded, massive dacite porphyry (UTM coordinates: 375840E, 2094338N). Although this massive dacite porphyry body is intrusive at depth (Smith et al., 2008, Fig. 6.2), its mushroom-shaped top is mantled by and in sedimentary contact with a poorly-sorted, coarsely-fragmental, wedge-shaped deposit of epiclastic dacite porphyry (Fig. 7A and B). Both the massive dacite porphyry and its coarsely-fragmental "apron" are conformably overlain by bedded volcano-sedimentary rocks (Fig. 7A). The presence of a coarsely-fragmental apron and the recognition of sedimentary upper contacts with overlying volcano-sedimentary rocks provide evidence that, like the massive dacite porphyry described previously (Figs. 4 and 5), this massive dacite porphyry intrusion also breached the

paleosurface and was partially eroded to form a coarsely-fragmental, epiclastic apron. After emplacement, continued basin subsidence and continued accumulation of volcano-sedimentary rocks resulted in burial, incorporating the massive dacite porphyry as part of the basin stratigraphy (Fig. 6).

Sedimentary upper contacts of massive dacite porphyry (and massive andesite) are described here as "conformable" recognizing, however, that, since an igneous rock unit is involved, some might prefer the term "concordant." The term "conformable" is preferred since there is no break in the volcano-sedimentary section (no unconformity) and to emphasize that volcanic domes, once buried, become part of an uninterrupted volcano-sedimentary section.

A cross-cutting, matrix-supported, dacite porphyry breccia (Fig. 4D) contains hydrothermally-altered, angular lithic fragments in a finely-communited, fragmental dacite porphyry matrix. These breccias fill northerly-striking, high-angle structures and contain quartz phenocrysts with partially resorbed borders. Given this evidence for direct magmatic input, they are interpreted as phreato-magmatic breccias. They fill vents that are much smaller in diameter (~100 m) than the maar-diatreme (~2000 m) proposed by Russell and Kesler (1991).

4.2. Andesite volcanic domes and diorite intrusions

Massive andesite in the Monte Negro pit is homogenous and without stratification (Fig. 8A, B) over vertical distances of several tens of meters. The roots of these mushroom-shaped bodies (Fig. 6) clearly cut (intrude) the sub-horizontal, volcano-stratigraphic section (Nelson, 2000a; Smith et al., 2008; Vaughan et al., 2020). However, the upper contacts of massive andesite bodies with overlying volcano-sedimentary beds are sedimentary rather than intrusive. Sedimentary upper contacts (Fig. 7C, D, E, F) are clearly visible in spite of strong hydrothermal alteration and minor offset along faults. There is no recrystallization of volcano-sedimentary rocks at the upper contacts nor other evidence of intrusion. As with the sedimentary upper contacts of massive dacite porphyry, the sedimentary upper contacts of massive andesite bodies are described as conformable rather than concordant.

Monomictic, clast-supported breccias composed of angular andesite fragments are locally well developed within but near the upper margin of mushroom-shaped massive andesite bodies; they are interpreted as carapace breccias and, in the pits, are typically strongly silicified. Good exposures can be observed at the north end of the Monte Negro pit (near UTM coordinates 375110, 2096370). Peperites have also been observed, locally, along the sub-horizontal, basal contacts of massive andesite with underlying volcano-sedimentary rocks indicating extrusion onto a paleosurface.

A mushroom-shaped body of massive andesite at the north end of the Monte Negro pit (Fig. 8A and B) is mantled by a coarsely-fragmental, poorly-sorted apron of andesite clasts (Fig. 8C) referred to as "spilite conglomerate" by Kesler et al. (1981). This wedge-shaped, epiclastic unit is thickest adjacent to its contact with massive andesite. Moving away from the conformable contact with massive andesite, towards the distal edge of the wedge, the apron is less coarsely fragmental and interfingers with the volcano-sedimentary section (Fig. 8D). Massive andesite, its coarsely-fragmental epiclastic apron, and its gradational, interfingering contact with volcano-sedimentary rocks are well exposed along the upper benches at the north end of the Monte Negro pit.

4.3. Volcano-sedimentary rocks

The volcano-sedimentary basin at the Pueblo Viejo mine measures close to 2 km in width and over 400 m in thickness. The term "volcano-sedimentary" is used to describe sedimentary rocks that were, for the most part, eroded from volcanic and volcanoclastic rocks. They include thinly-bedded, carbonaceous, volcanoclastic siltstone, sandstone and limey siltstone. Terrestrial plant fossils were reported by Russell and Kesler (1991) and by Smiley (2002). Wavy layers suggest an algal origin

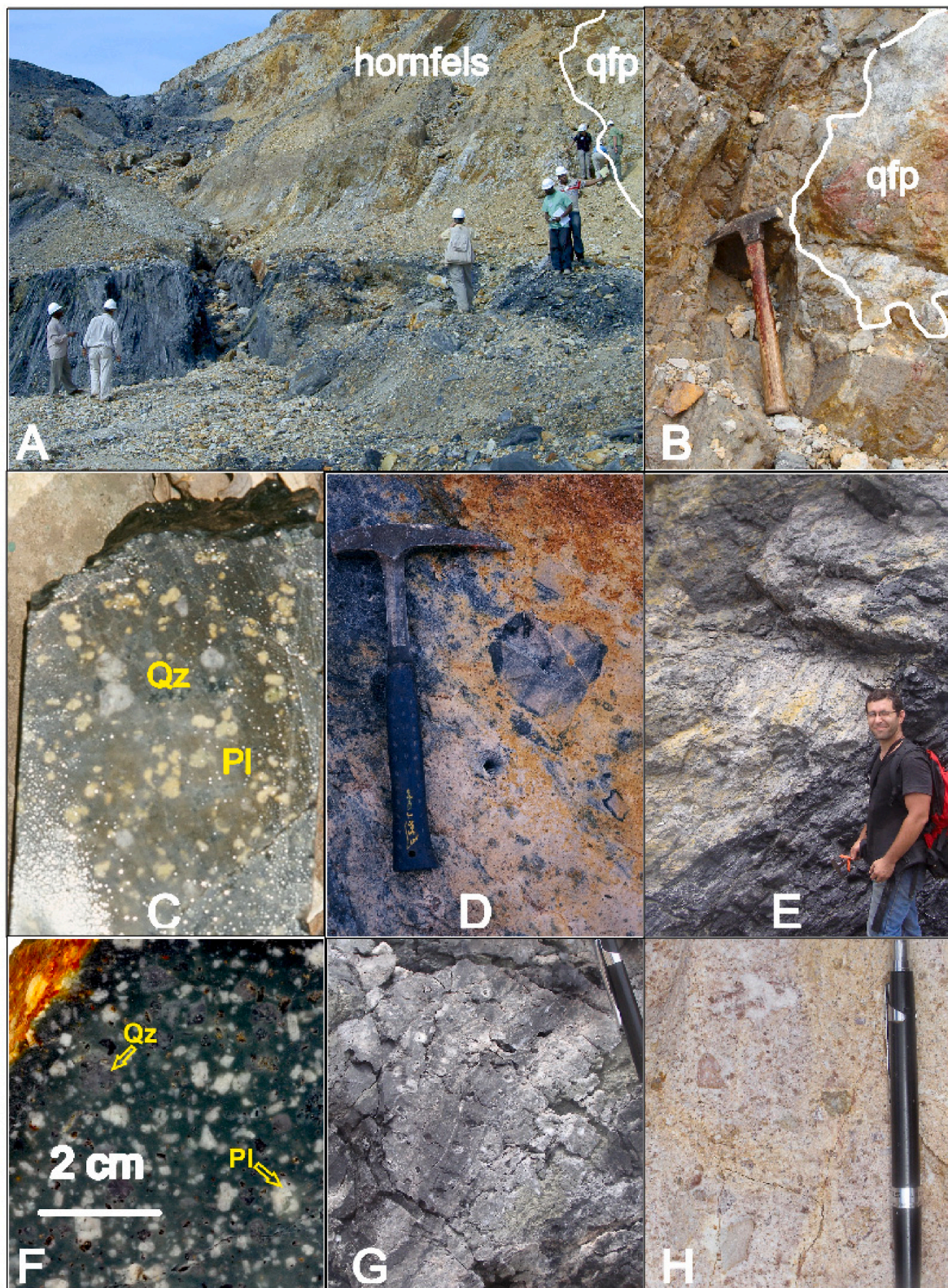


Fig. 4. Dacite porphyry volcanic dome facies. (A) Overview of the contact (white line) between intrusive dacite porphyry (qfp) and volcano-sedimentary rocks showing tilted beds of carbonaceous siltstone (left) and hornfels with bedding still visible (center). This photo was taken during the 1990's along the Moore pit haul road at UTM coordinates: 376218E, 2094432N. (B) Close-up of the intrusive contact (white line) showing cross-cutting dacite porphyry (qfp) on the right and recrystallized carbonaceous volcano-sedimentary rocks (hornfels) on the left. (C) Massive, dacite porphyry volcanic dome from the Moore pit with large, white quartz (Qz), tan plagioclase (Pl), and small, black pyroxene phenocrysts; field of view is 48 mm. (D) Fragmental, dacite porphyry vent breccia from the Moore pit. (E) Lens of dacite porphyry slump breccia interbedded with carbonaceous volcano-sedimentary rocks from the Moore pit. (F) Plagioclase rhyolite from Torr  et al., 2017a, Fig. 4D, UTM coordinates: 377101, 2105768 with the same texture and phenocryst assemblage as massive dacite porphyry (Fig. 4C). (G) Flow-banded dacite porphyry volcanic dome from the Moore pit. (H) Fragmental, dacite porphyry vent breccia from the Arroyo Hondo II pit.

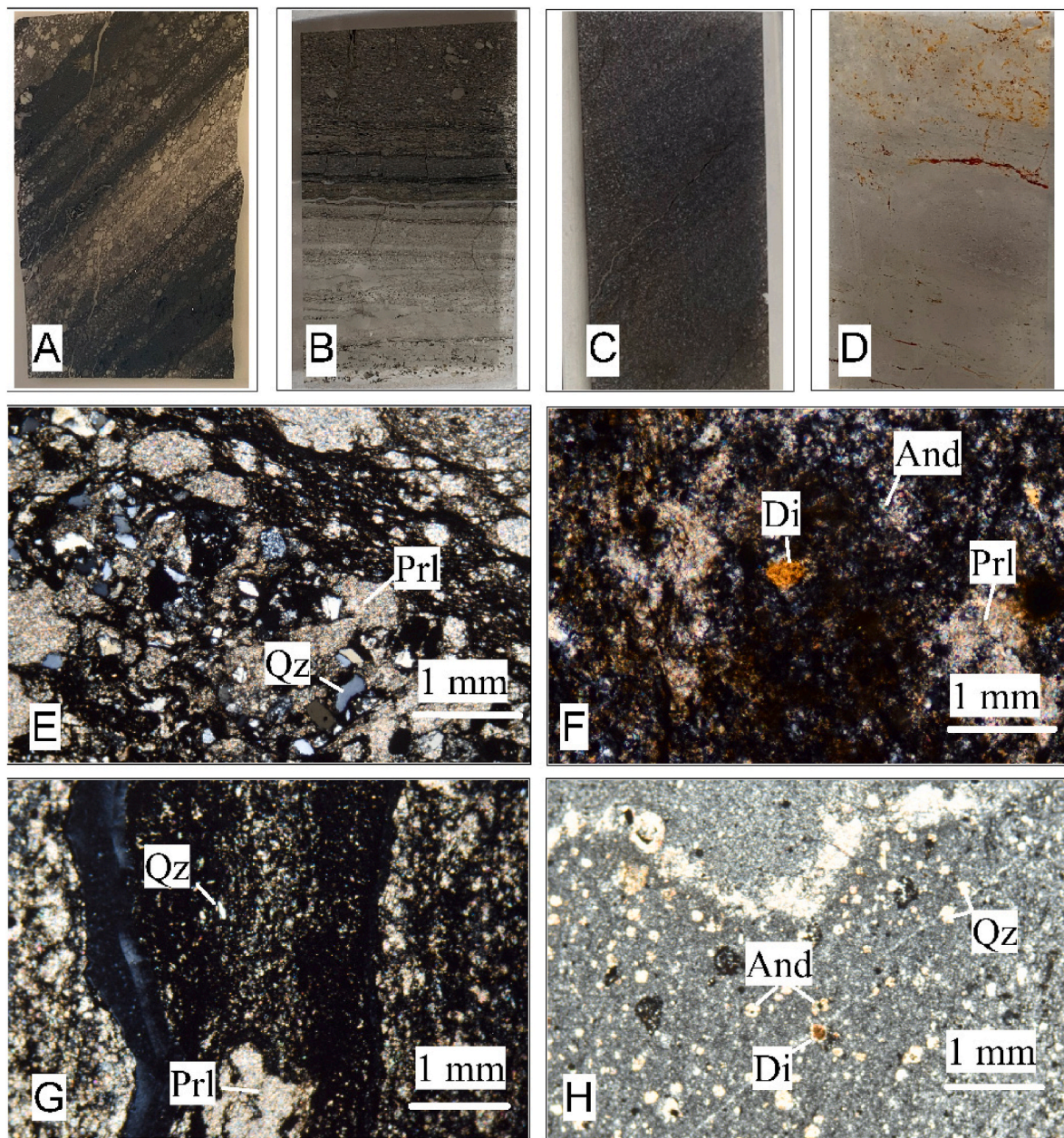


Fig. 5. Thin sections (A, B, C, D) and cross-polarized, transmitted-light photomicrographs (E, F, G, H) of carbonaceous volcano-sedimentary rocks collected from near an intrusive contact of dacite porphyry in the Moore pit (Fig. 4A and B). (A) sample SED-1 collected at a distance of 40 m from the intrusive contact - a hydrothermally altered (pyrophyllite, pyrite), finely-laminated mudstone with beds of carbonate; lighter-colored layers contain more abundant volcanic clasts; darker layers are more carbonaceous. (B) sample SED-2 collected at a distance of 10 m from the intrusive contact - a hydrothermally altered (pyrophyllite, pyrite) finely-laminated mudstone with beds of carbonate, similar to SED-1 (C) sample Hornfels-1 collected at a distance of 3 m from the intrusive contact. Contact metamorphic recrystallization has destroyed the original, finely-laminated, carbonaceous mudstone texture. (D) sample Hornfels-2 collected immediately adjacent to the intrusive contact. Contact metamorphic crystallization has destroyed the finely-laminated texture and driven off organic carbon from this originally carbonaceous mudstone. (E) Photomicrograph of SED-1 showing volcanic clasts replaced by pyrophyllite along with eroded quartz phenocrysts. (F) Photomicrograph of Hornfels-1 showing contact metamorphic diopside and andalusite. (G) Photomicrograph of SED-2 showing thin carbonaceous laminae and volcanic clasts replaced by pyrophyllite. (H) Photomicrograph of Hornfels-2 with contact metamorphic diopside and abundant andalusite. Finely-laminated bedding has been recrystallized forming a mosaic texture. Organic carbon has been driven off. Abbreviations for photomicrographs: prl: pyrophyllite, and: andalusite, qz: quartz. Thin sections (A, B, C, D) measure 2 cm horizontally.

for much of the carbonaceous matter. The section in the Monte Negro pit is composed primarily of eroded andesite whereas, in the Moore pit, the volcano-sedimentary section includes dacite porphyry clasts and eroded quartz phenocrysts. Within the basin, volcano-sedimentary rocks underlie, overlie, and interfinger with volcanic rocks (including volcanic domes) of andesite and dacite porphyry.

The contact between the volcano-sedimentary section and the

overlying Hatillo Limestone was described as conformable by [Bowin \(1966\)](#), by [Bonilla-Rodríguez et al. \(2014\)](#), and by [Nelson et al. \(2020\)](#). Interbedded carbonaceous sandstones, siltstones and minor calcareous volcano-sedimentary rocks of the Los Ranchos Fm. are overlain by near-shore to shallow-water marine sedimentary rocks of the Hatillo Limestone. The contact marks the Aptian-Albian transition (at ~112Ma) from an emergent, intraoceanic island arc and marginal-marine

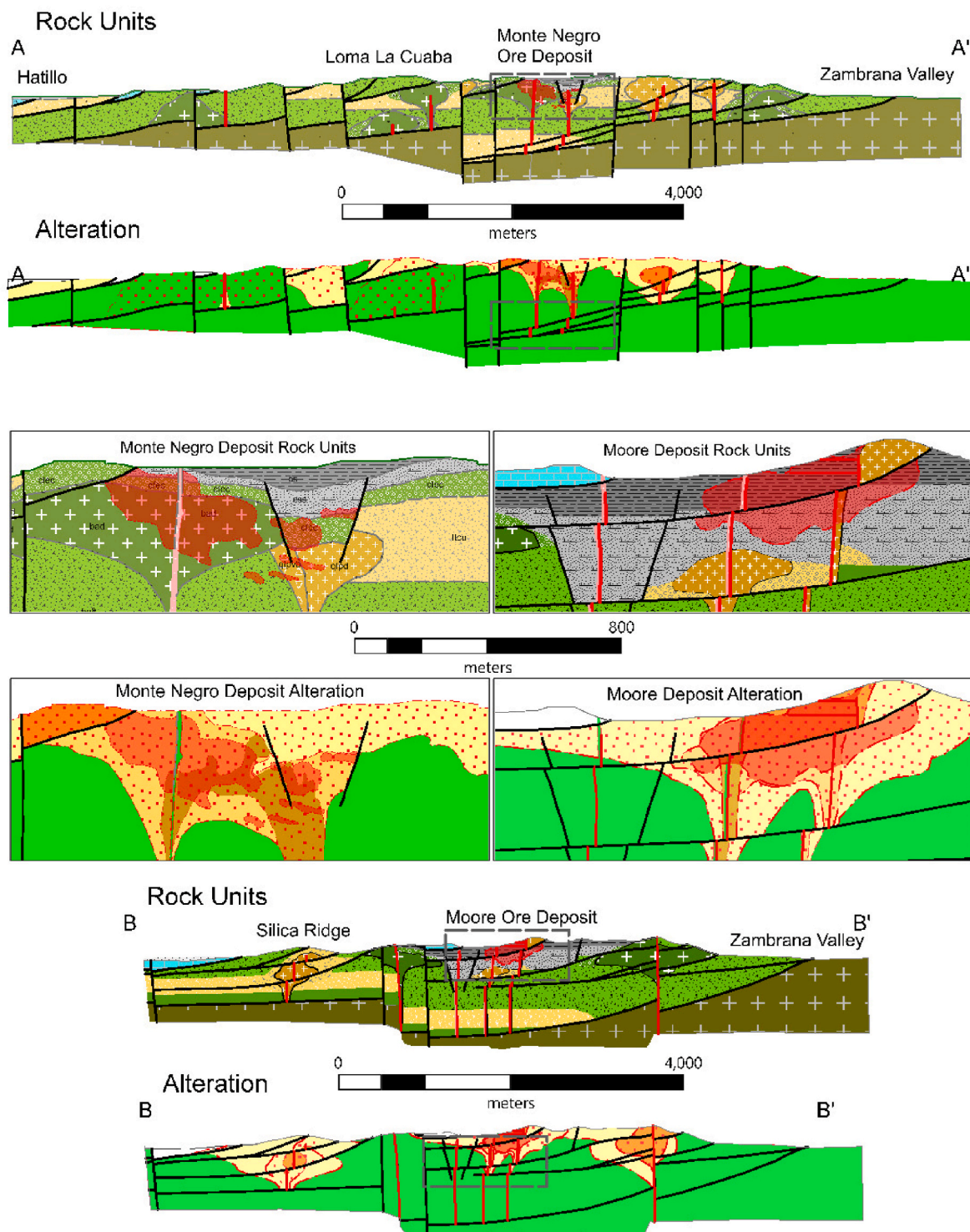


Fig. 6. East-West cross sections for the Pueblo Viejo district. Section A-A' is drawn at UTM 2095600N through the Monte Negro deposit (Fig. 2). Section B-B' is drawn at UTM 2094600N through the Moore deposit (Fig. 2). Legends for the cross sections are the same for the maps (Fig. 3). The Moore and Monte Negro ore deposits, shown as translucent red polygons, are superimposed on the cross sections. The Zambrana composite batholith (undivided gabbro, diorite, and tonalite) underlies the entire district and is the presumed source for overlying intrusive and extrusive rock units of the Los Ranchos Fm. Grey, dashed-line rectangles on cross sections A-A' and B-B' show the location of cross section enlargements for the Monte Negro and Moore deposits (third and fourth rows). The enlargements for rock units show volcanic and volcano-sedimentary facies, volcanic domes, and growth faults (faults that exhibit increasing displacement with depth). The enlargements for hydrothermal alteration show a zoned pattern of advanced argillic alteration including quartz-alunite-dickite (brown), quartz-pyrophyllite-dickite (orange) and quartz-illite-kaolinite $\pm$ pyrophyllite (yellow). Zones of strong replacement silicification (dark orange) and disseminated pyrite (red dots) are also displayed. High-angle faults (black) controlled the location vents for phreato-magmatic eruptions and acted as conduits for volcanic domes of andesite and of dacite porphyry. These same high-angle faults served as feeders (highlighted in red) for hydrothermal alteration and mineralization. These cross sections are based on geologic mapping (Fig. 2), logging of drill core, and previously-published cross sections by Nelson (2000), Smith et al. (2008), Cardenas et al. (2018), and Vaughan et al. (2020).

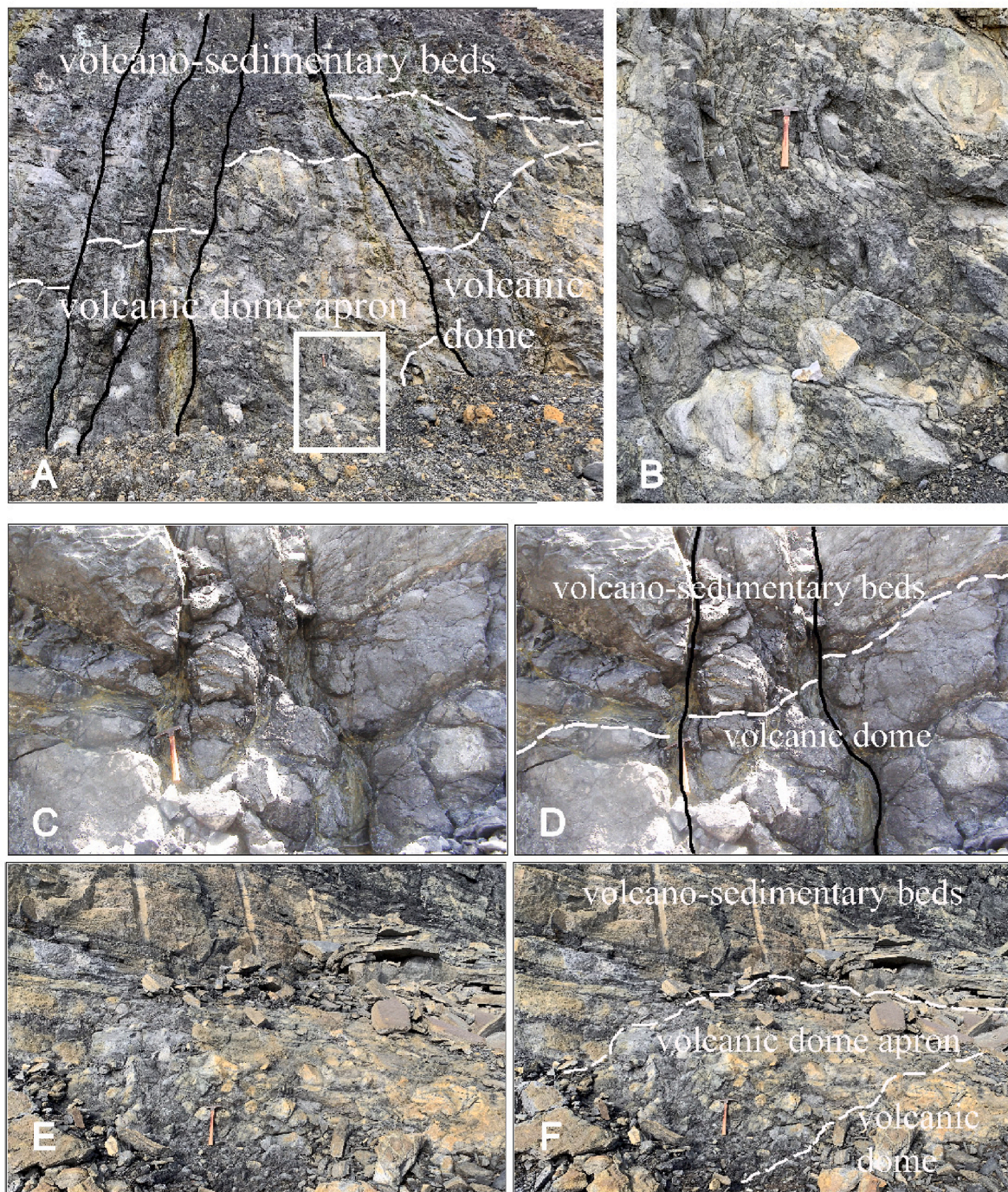


Fig. 7. Sedimentary (conformable) contacts (shown as dashed white lines) between exogenous volcanic domes; marginal, coarsely-fragmental, epiclastic volcanic dome aprons; and overlying, bedded, carbonaceous, volcano-sedimentary rocks. Faults, showing minor displacement, are shown as solid black lines. (A) Volcano-sedimentary beds of carbonaceous siltstone overlie a dacite porphyry volcanic dome and coarsely-fragmental volcanic dome apron, southern Moore pit; the white box shows the location of a close-up photo (B) of the coarsely-fragmental dome apron. (C) Volcano-sedimentary beds of carbonaceous sandstone overlie an andesite volcanic dome, northern Monte Negro pit; the volcanic dome contact with conformably overlying carbonaceous sandstone is highlighted in (D). (E) Volcano-sedimentary beds of carbonaceous sandstone and siltstone overlie an andesite volcanic dome and coarsely-fragmental dome apron, southern Monte Negro pit; the volcanic dome contact with the marginal volcanic dome apron and overlying carbonaceous sandstone and siltstone is highlighted in (F).

volcano-sedimentary basin (Los Ranchos Fm.) to near-shore marine sediments that were subsequently overlain by deeper-water limey mudstones (Hatillo Limestone). Calcareenites, calcareous sandstone, and marly limestone of the basal Hatillo Limestone and an associated fossil assemblage of corals, rudist bivalves, and echinoids are described in more detail by [Bonilla-Rodríguez et al. \(2014\)](#).

High-angle normal faults occur within and along the margins of the

volcano-sedimentary basin. Those that exhibit evidence for displacement during basin sedimentation are referred to here as growth faults. Growth faults are recognized by 1) increasing displacement with increasing depth and, 2) volcano-sedimentary units that are thicker on the footwall side than on the hanging wall side ([Fig. 6](#)). These features are evidence that the faults were active ("growing") while volcano-sedimentary rocks were being deposited.

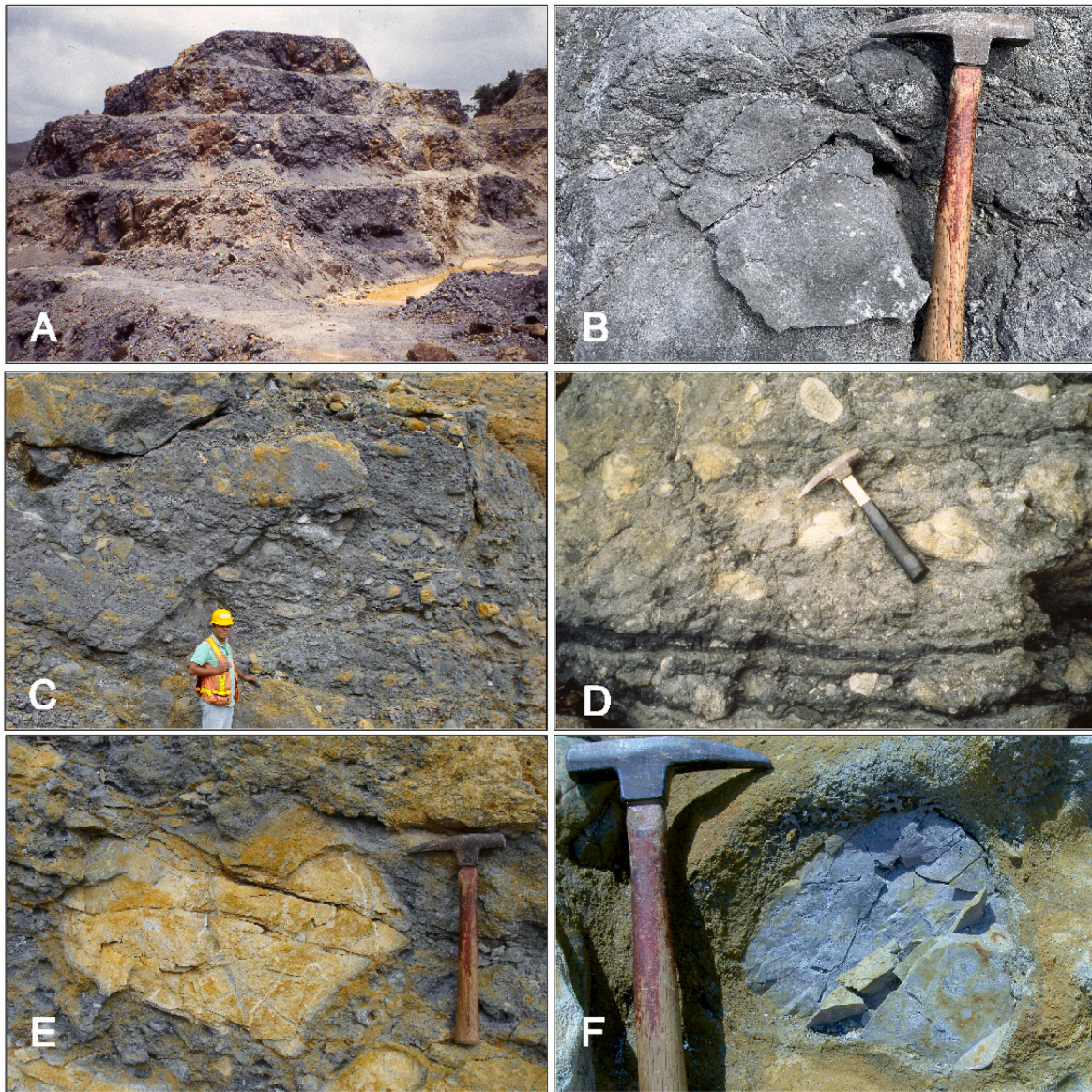


Fig. 8. Andesite volcanic dome facies from the north end of the Monte Negro pit. (A) Massive andesite with no stratification (UTM coordinates 375080E, 2096250N). Benches are 10 m in height. Surrounding fragmental rock units have been mined away. (B) Close-up photo of massive andesite. (C) Coarsely-fragmental andesite mantles the volcanic dome shown in Fig. 7A. This volcanic dome “apron” forms a wedge that thins away from a conformable depositional contact with massive andesite into the adjacent volcano-sedimentary basin. The photo was taken at UTM coordinates 375161E, 2096297N. (D) Coarsely-fragmental, epiclastic andesite interbedded with carbonaceous volcano-sedimentary rocks. The photo taken from 50 m basin-ward (east) of Fig. 7C, at the distal edge of the wedge-shaped volcanic dome apron. (E) Andesite fragment (with quartz veins) from the volcanic dome apron. (F) Silicified andesite fragment from the volcanic dome apron.

4.4. Zambrana batholith

Early Cretaceous tholeiitic batholiths are well exposed along the length of the Los Ranchos Fm. (Fig. 1B). Escuder-Viruet et al. (2006, 2007a) described these composite batholiths as consisting largely of tonalite with lesser diorite and gabbro. In the Pueblo Viejo district, the Zambrana composite batholith is a medium-to coarse-grained, largely tonalitic, equigranular intrusion. Torró et al. (2017a) recognized gabbro at the western margin of the Zambrana batholith (near UTM coordinates: 377310E, 2098550N). Diorite is well exposed along the eastern margin of the Hatillo Reservoir (near UTM coordinates: 370200E, 2100000N) and underlies much of Loma la Cuaba (Figs. 2 and 6).

4.5. Pyroxene diorite intrusions

A pyroxene diorite stock intrudes the Early Cretaceous volcanic section and the Aptian-Albian Hatillo Limestone immediately south of the Pueblo Viejo mine (Figs. 9 and 10). Primary minerals include plagioclase, clinopyroxene, apatite, and zircon. Similar stocks (Fig. 9) are exposed at Mogote (MO-diorite) and El Llagal (LL-diorite).

Pyroxene diorite dikes intrude the Early Cretaceous volcanic section, the overlying Aptian-Albian Hatillo Limestone, and the Moore and Monte Negro ore deposits along northerly-striking high-angle faults (Figs. 10 and 11A, B). The dikes have a similar fine-grained, homogeneous texture and similar pyroxene plus plagioclase mineralogy (Fig. 11C, D, E, F, G, H). These same high-angle faults are a focus of hydrothermal alteration and mineralization in the ore deposits but the dikes themselves are not mineralized. They exhibit weak propylitic alteration (chlorite-calcite-local illite-minor pyrite), are cut by calcite

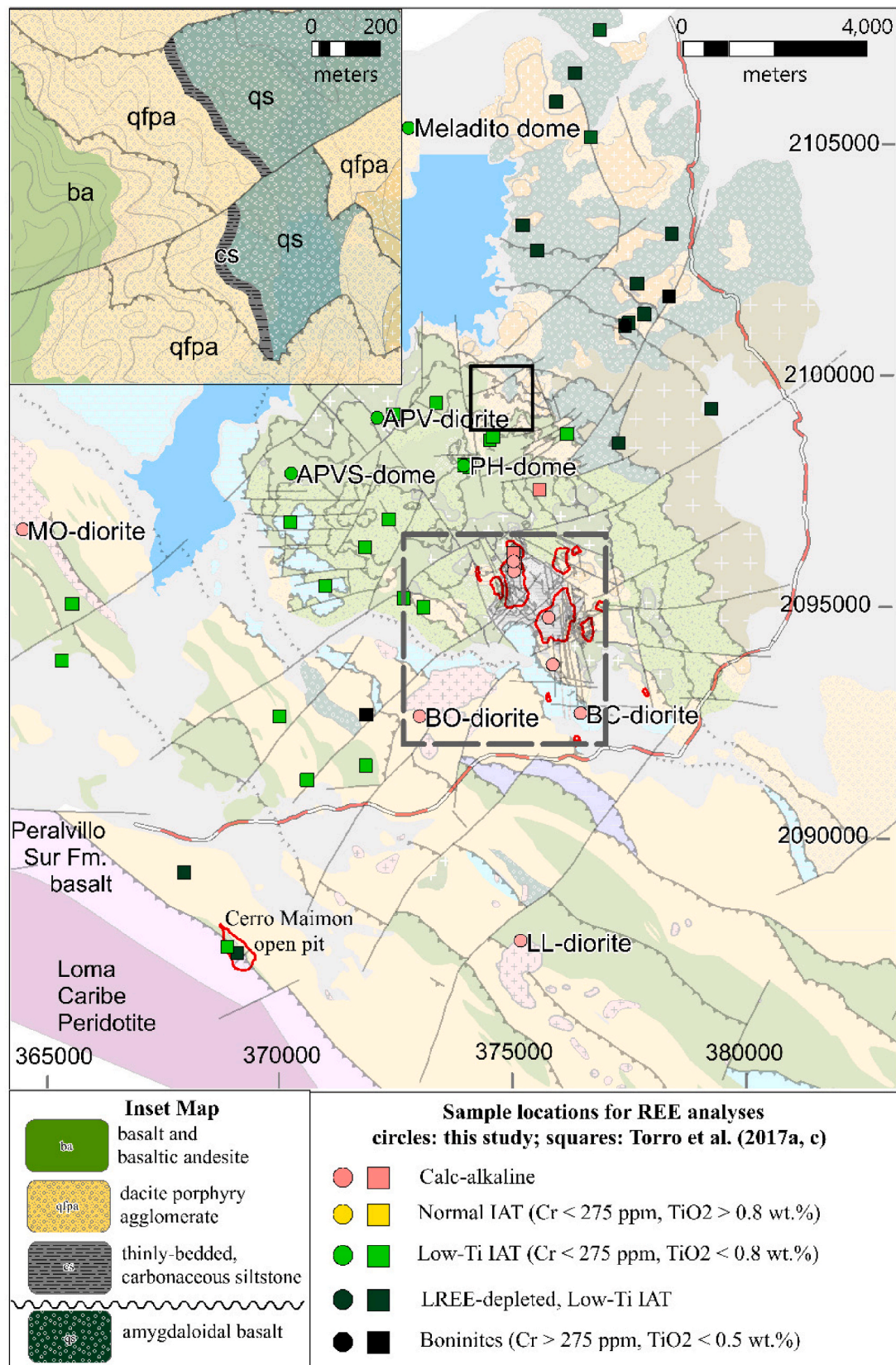


Fig. 9. Geologic map showing the location of mafic rock samples (basalt, basaltic andesite, andesite, and diorite) analyzed for major and minor elements in the Pueblo Viejo district (see Fig. 3 for a rock unit legend and stratigraphic section). Amygdaloidal basalt exposed at the north end of the map area consists of boninite and LREE-depleted, low-Ti, island arc tholeiite (IAT). Overlying andesite and basaltic andesite are low-Ti IAT. The change from older, more primitive IAT to younger, more evolved IAT occurs at an erosional unconformity marked by a volcano-sedimentary interval of carbonaceous sandstone and siltstone (Fig. 9, inset map). A small, black square marks the location of the inset map; a larger, grey square marks the location of Fig. 10.

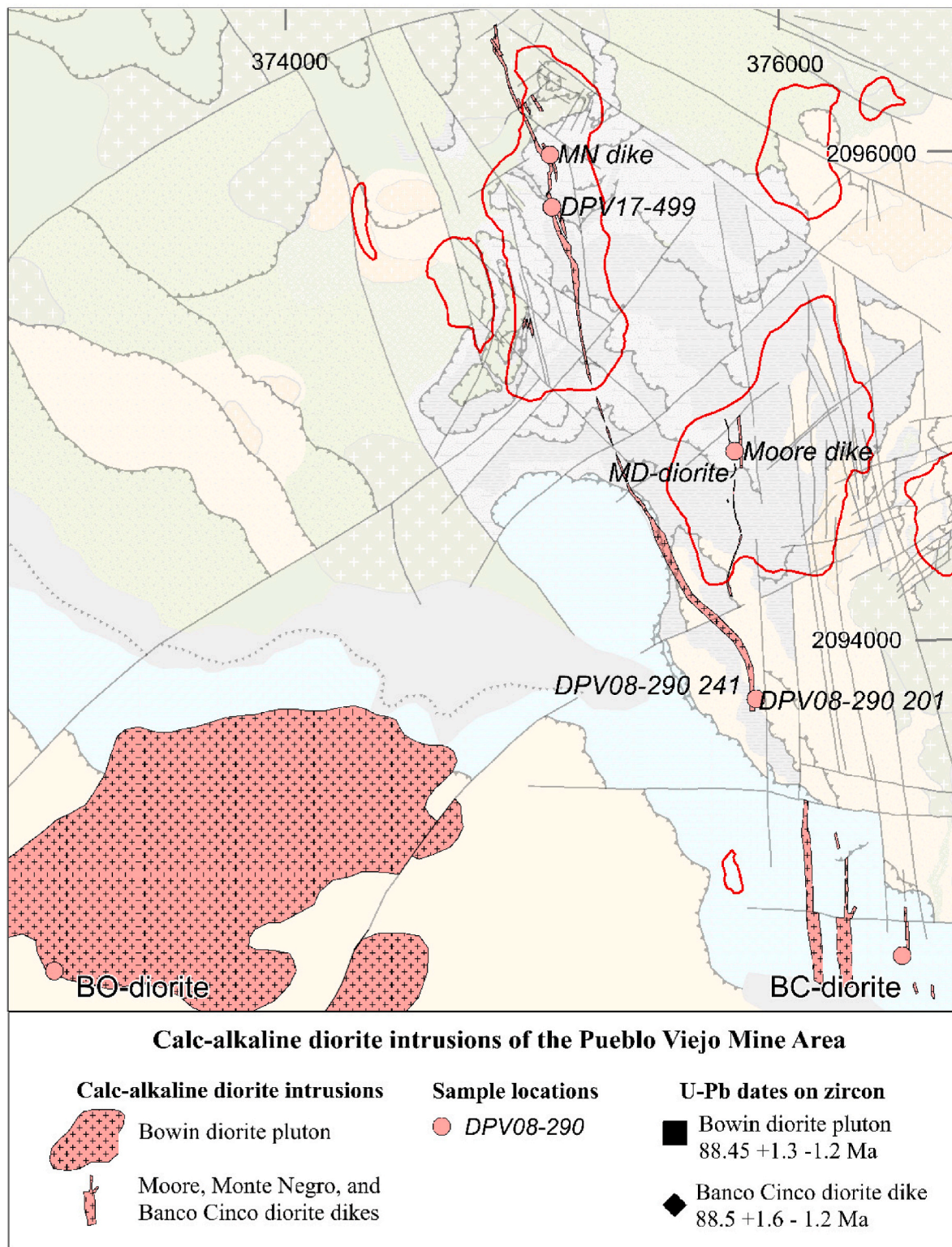


Fig. 10. Calc-alkaline pyroxene diorite intrusions of the Pueblo Viejo mine area showing the location of stock and dike samples collected for major and minor element geochemical analysis and U-Pb dating of zircon. The Bowin diorite stock (BO-diorite) and the Banco Cinco diorite dike (BC-diorite) are similar in terms of texture and mineralogy (Fig. 11), major and minor element geochemistry (Fig. 12), and age (~88.5 Ma). Pyroxene diorite dikes in the Banco Cinco area occupy the same northerly striking structures as the Moore and Monte Negro dikes. The Monte Negro dike intrudes the Hatillo Limestone (pale blue) at UTM coordinates 375400, 2094605. See Fig. 3 for a rock unit legend. Open pits are outlined in red.

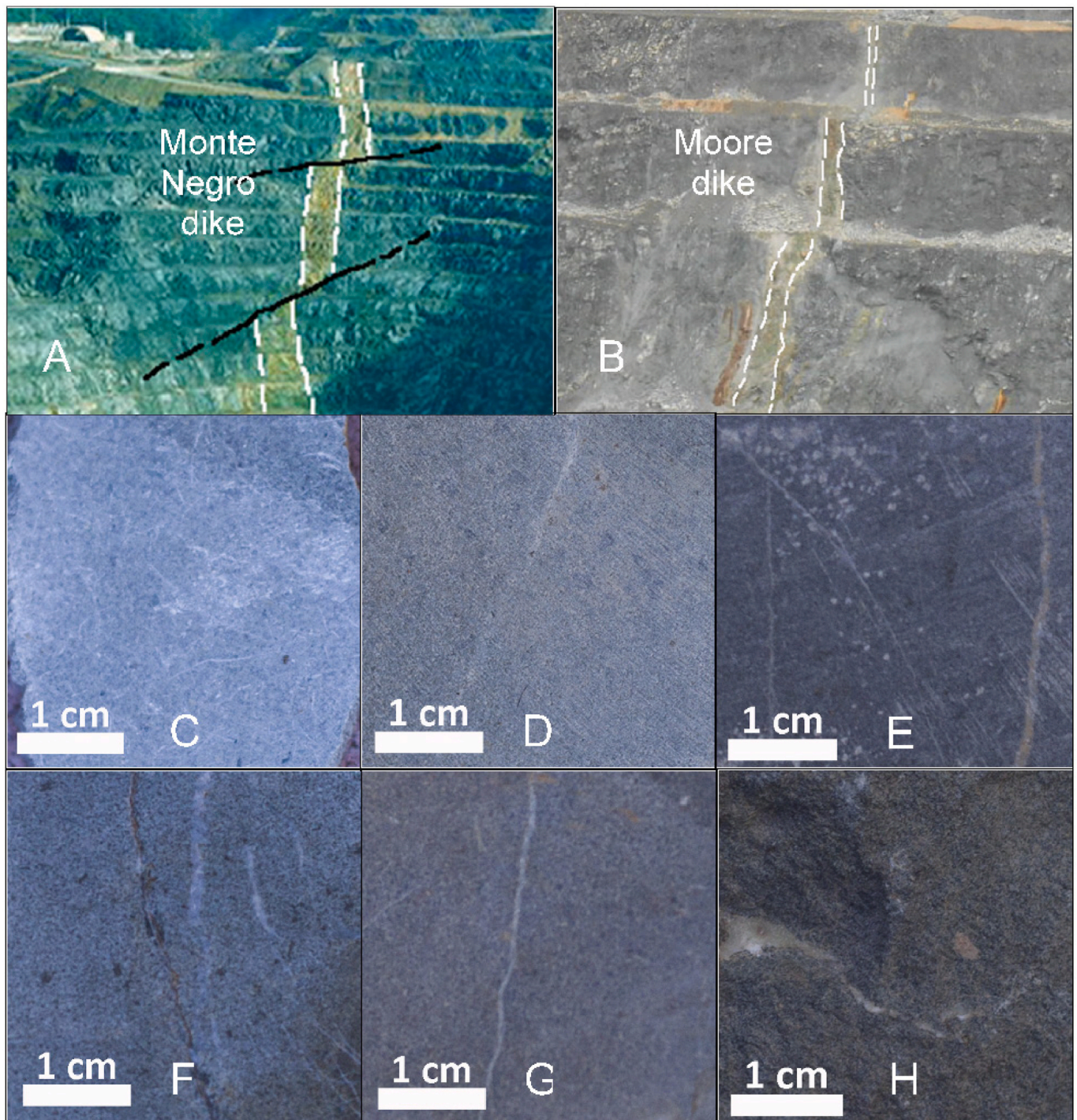


Fig. 11. Pyroxene diorite dikes. A, B) overview, looking north, of the Moore and Monte Negro pits showing high-angle pyroxene diorite dikes. Dike contacts are highlighted with dashed white lines; low-angle reverse faults are shown as black lines. Samples of pyroxene diorite from the Moore (C, D), Monte Negro (E), and Banco Cinco dikes (F, G, H). All of the samples exhibit weak propylitic alteration (chlorite, calcite, minor pyrite); veinlets are calcite.

veinlets, and are unaffected by ore-related sulfidic silicification and advanced argillic alteration. The dikes, locally, show minor offset (less than 30 m) by post-mineral, low-angle reverse faults.

The Monte Negro dike (5–10 m wide) intrudes the Monte Negro ore deposit (Fig. 11A) and intrudes the Hatillo Limestone (at UTM coordinates 375400, 2094605). The Moore dike (up to 3 m wide) intrudes the Moore ore deposit (Fig. 11B) but is less continuous than the Monte Negro dike (Fig. 10). The Moore, Monte Negro, and Banco Cinco dikes all occupy the same northerly-striking, high-angle faults (Fig. 10).

Six samples were collected from the Moore and Monte Negro dikes

along with three samples of the Banco Cinco dike. All of the dike samples exhibit a fine-grained, homogeneous texture (Fig. 11); contain primary plagioclase and pyroxene; and exhibit weak propylitic (chlorite-calcite, local illite-minor pyrite) alteration. The Moore, Monte Negro, and Banco Cinco pyroxene diorite dikes, indistinguishable in the field, are treated as a single unit. Small magnetite replacement deposits occur in the Hatillo Limestone near intrusive contacts with pyroxene diorite dikes in the Banco Cinco area (Fig. 10) and adjacent to the pyroxene diorite stock at Mogote (Fig. 9).

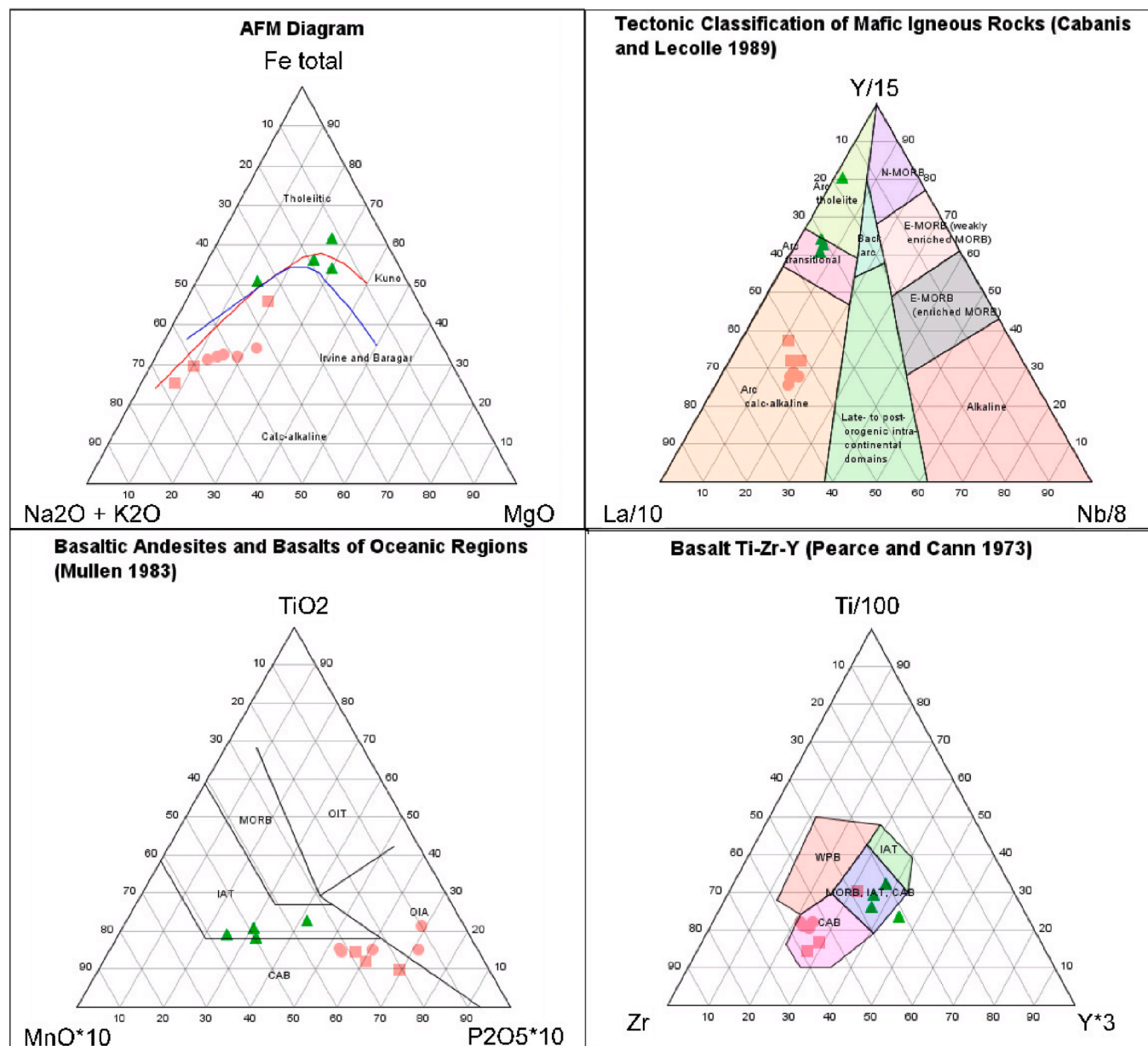


Fig. 12. Rock classification diagrams for mafic (basalt, basaltic andesite, andesite) volcanic domes, dikes, and stocks of the Pueblo Viejo district. Early Cretaceous volcanic domes and shallow intrusions are shown as green triangles; Pyroxene diorite dikes are shown as pink circles; pyroxene diorite stocks are shown as pink squares. A) AFM diagram B) Tectonic classification of mafic igneous rocks of Cabanis and Lecolle (1989) C) Basaltic andesites and basalts of oceanic regions of Mullen (1983) D) Basalt Ti – Zr – Y diagram of Pearce and Cann (1973). Two strongly altered, pyrite-bearing, pyroxene diorite samples with high loss on ignition values of 6.1% and 10.8% (Appendix 1) were excluded from the plots.

5. Lithogeochemistry

Fourteen samples of mafic volcanic domes, dikes, and stocks were collected for multielement geochemical analysis. Major and minor element analytical data used in the preparation of rock classification diagrams (Fig. 12) are tabulated in Appendix I. Chondrite-normalized REE and N-MORB-normalized multielement values used in the preparation of REE spider diagrams (Fig. 13) are recorded in Appendix II. Sample locations are shown on Fig. 9.

Andesite volcanic domes and diorite intrusions collected from Loma la Cuaba and the mine area contain Cr and Ti values (Appendix II) typical of low-Ti, island arc tholeiite (IAT), plot as IAT on rock classification diagrams (Fig. 12), and exhibit flat REE patterns (Fig. 13A and B). Mafic rock samples (amygdaloidal basalts) from the northern portion

of the Pueblo Viejo district (Fig. 9) are distinctly more primitive (boninites and LREE-depleted, low-Ti IAT). The change in volcanic rock composition occurs at an erosional unconformity marked by a volcano-sedimentary interval of carbonaceous sandstone and siltstone (Fig. 9, inset). REE assignments are shown for mafic rocks only; more felsic rock types, e.g., dacite porphyry, keratophyre, and plagioclase rhyolite, are omitted following the recommendation of Rollinson (1993).

The pyroxene diorite stock samples are calc-alkaline according to rock classification diagrams (Fig. 12) and all four samples exhibit similar LREE enrichment relative to C1 Chondrite and relative to N-MORB (Fig. 13A and B). The pyroxene diorite dike samples are also calc-alkaline according to rock classification diagrams and plot very close to the pyroxene diorite stocks on REE spider diagrams. Strikingly similar pyroxene diorite texture, mineralogy, rock classification, and REE

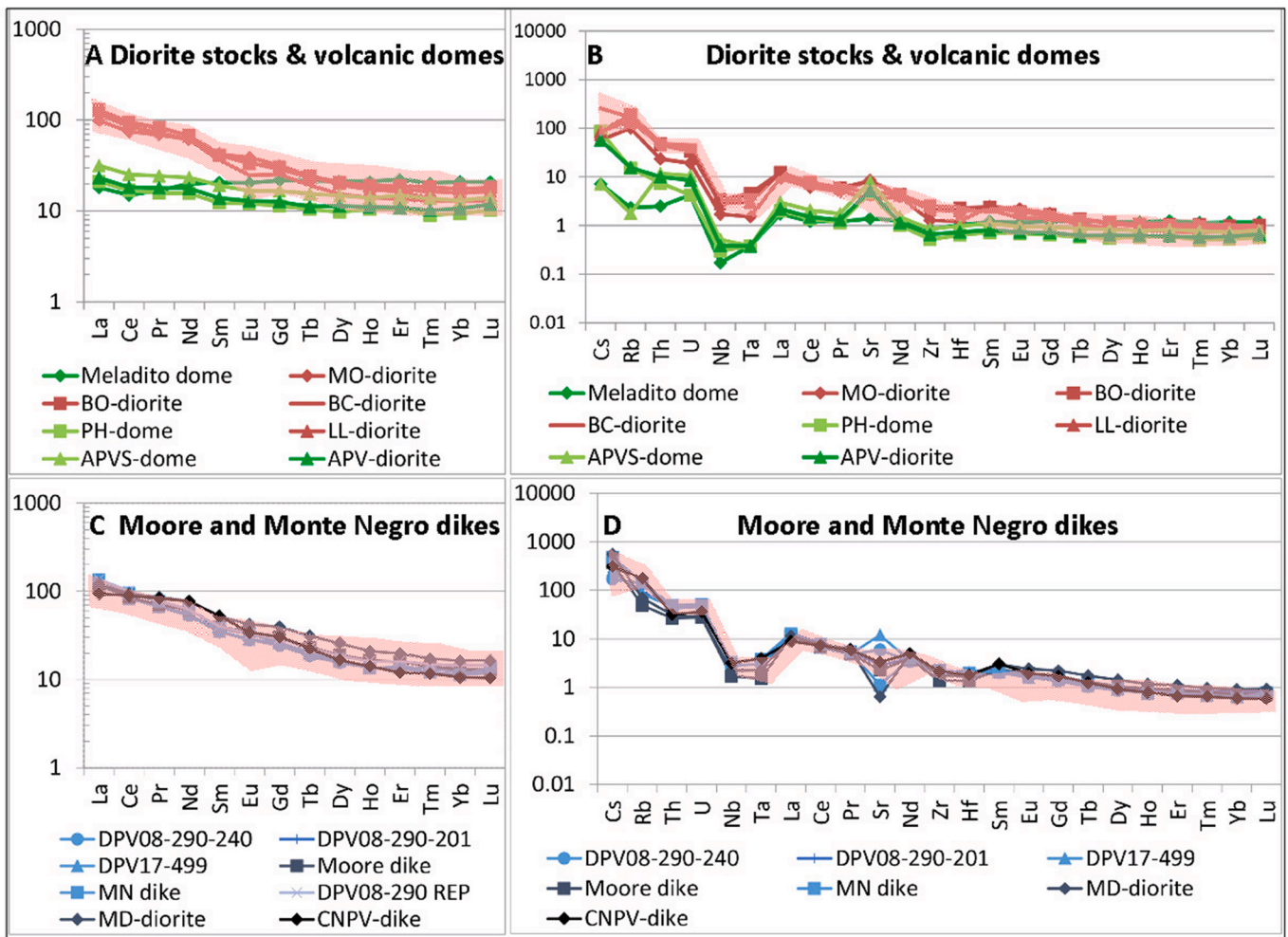


Fig. 13. Chondrite-normalized REE (A, C) and N-MORB-normalized multi-element (B, D) diagrams for andesitic volcanic domes and for diorite stocks and dikes of the Pueblo Viejo district. A, B) REE plots for volcanic domes and a diorite stock classified as tholeiitic (Fig. 12) exhibit flat REE patterns and are shown in green. REE plots for pyroxene diorite intrusions classified as calc-alkaline (Fig. 12) exhibit LREE enrichment and are shown in red. C, D) Six samples of the Moore and Monte Negro dikes classified as calc-alkaline (Fig. 12) exhibit LREE enrichment characteristic of calc-alkaline rocks and REE and multielement patterns similar to the patterns exhibited by calc-alkaline pyroxene diorite stocks (A, B) and to the field of calc-alkaline rocks ($n = 10$) from Torró et al. (2017a) shown in pink; Monte Negro dike sample CNPV-dike is from Torró et al. (2017a). Sample locations are shown on Figs. 9 and 10; Sample location coordinates are provided in Appendix I.

patterns suggest that the dikes and stocks belong to a single calc-alkaline intrusive episode.

6. Geochronology

Two pyroxene diorite samples collected for this study (BO-diorite, BC-diorite, Fig. 14A and B) were submitted for zircon separation and U–Pb dating. The samples were disaggregated using an Electro Pulse Disaggregator. Material $>350 \mu$ was processed traditionally using a Wilfley water table, Frantz paramagnetic separator, and one-step (3.32 g/cc) heavy liquid separation. Small ($\sim 30\text{--}50 \mu\text{m}$), clear to pink, anhedral to prismatic zircon grains were mounted in epoxy resin discs and polished. U–Pb ages were measured at Washington State University using an Analyte G2 193 excimer laser ablation system coupled with a Thermo-Finnigan Element 2, inductively-coupled plasma mass spectrometer. The laser parameters were $20 \mu\text{m}$ spot size diameter and 10 Hz repetition rate at a power density setting of $\sim 5.0 \text{ J/cm}^2$. Measurement of uranium and lead isotopes followed the method of Chang et al. (2006). Zircon standards and two quality control zircons were run along with the two unknowns. Common Pb correction followed the ^{207}Pb method of Williams (1998).

The pyroxene diorite samples returned weighted mean ages (Fig. 14C, D, E, F) of $88.5 \pm 1.6 \text{ Ma}$ (BC-diorite 2, $n = 24$) and $88.4 \pm$

1.3 Ma (BO-diorite 2, $n = 31$). U–Pb isotopic data is presented in Appendix III. These dates are younger than the $109 \pm 0.6 \text{ Ma}$ date reported by Mueller et al. (2008) for the Monte Negro dike (drill hole PD04-35, UTM coordinates 2095948, 375065.6, 370.7 m elevation), are older than the late Eocene age estimated by Bowin (1966) for the pyroxene diorite stock (Fig. 12), and are older than the $^{206}\text{Pb}/^{238}\text{U}$ date of $48.3 \pm 0.3 \text{ Ma}$ reported by Martin et al. (2000) for a diorite sample from the Hatillo quadrangle (unknown location).

7. Hydrothermal alteration and mineralization

Ore deposits at the Pueblo Viejo mine are sulfidic (average of 8% by weight), silicified, and surrounded by structurally-controlled envelopes of quartz-pyrite-pyrophyllite alteration that narrow with depth into quartz-pyrite-alunite alteration along high-angle, fault-controlled, hydrothermal conduits (Fig. 6). These advanced argillic envelopes are surrounded by a propylitic assemblage consisting of chlorite-illite-smectite-pyrite (Vaughan et al., 2020). Comprehensive descriptions of hydrothermal alteration and mineralization can be found in Smith et al. (2008) and Cardenas et al. (2018).

Hydrothermal alteration affects an area of over 100 km^2 and continues south beyond the limits of mapping (Fig. 15). It extends from the Moore and Monte Negro ore bodies across peripheral open pits to

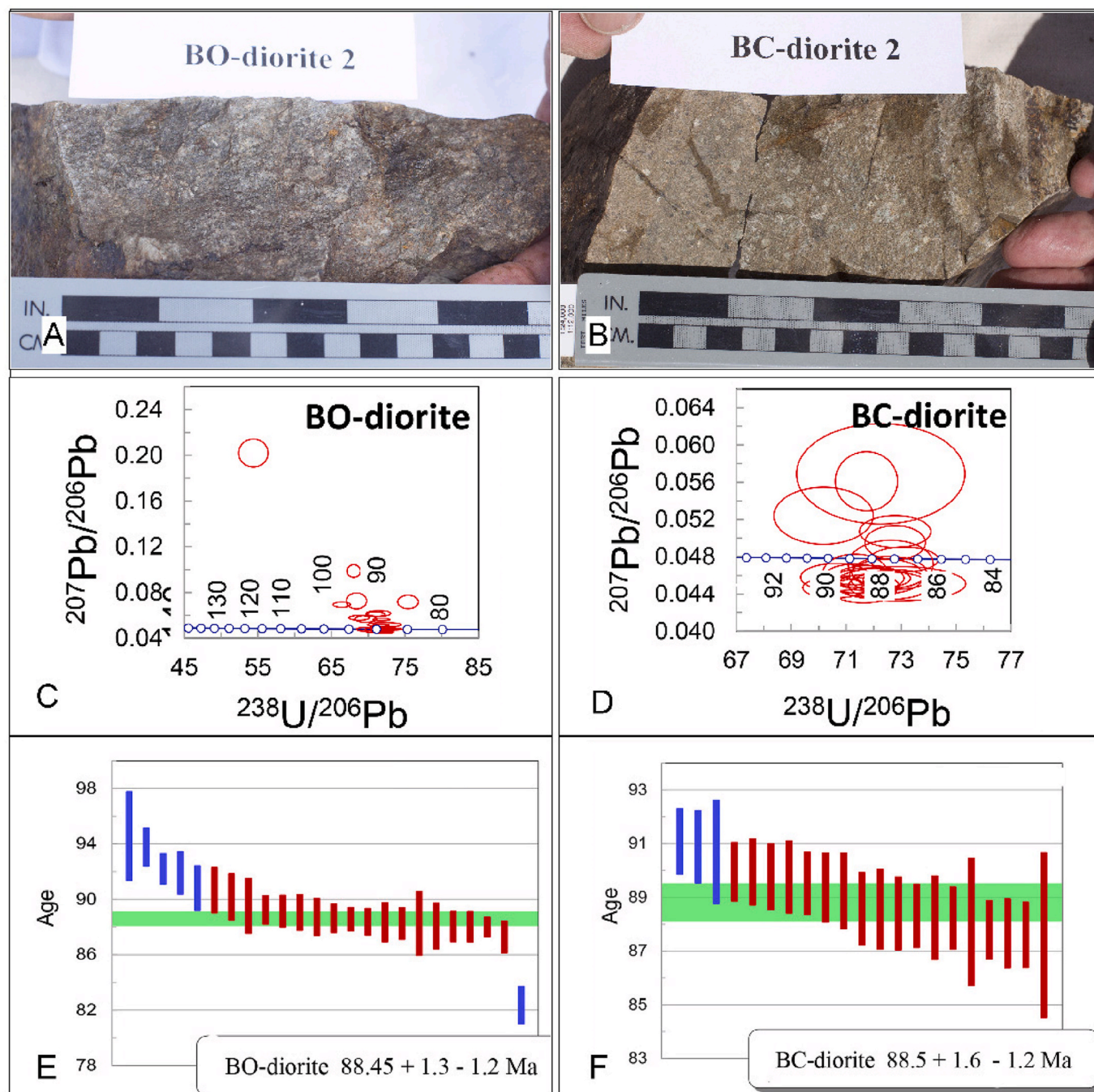


Fig. 14. Radiometric ($^{206}\text{Pb}/^{238}\text{U}$) dates for zircons collected from the Bowin diorite stock (A, C, E) and the Banco Cinco diorite dike (B, D, F). A, B) Pyroxene diorite samples BO-diorite and BC-diorite. C, D) Concordia diagrams for samples BO-diorite and BC-diorite. E, F) Eighteen zircons, shown in red, were used to calculate the age of the Bowin diorite stock (BO-diorite). Another eighteen zircons, shown in red, were used to calculate the age of Banco Cinco diorite dike (BC-diorite). Zircons that fell outside an envelope of 95% relative probability are shown in blue; bar heights represent an absolute error of 2σ . Sample locations are shown on Fig. 10.

undeveloped “satellite” deposits at La Lechoza, Loma la Mina, and Barbuito (Figs. 15 and 16). North of the Moore and Monte Negro deposits, advanced argillic alteration (quartz $\pm$ pyrophyllite $\pm$ alunite $\pm$ diasporite) grades into propylitic alteration (quartz $\pm$ chlorite $\pm$ epidote $\pm$ calcite) which grades into regional spilitization (albite-quartz-chlorite), the product of seawater-rock interaction. Volcanic domes (Fig. 16) marked by centers of strong sulfidic silicification (Fig. 15) are particularly well exposed at a quarry near the northern limit of the map area (UTM coordinates: 375045, 2107730N).

Ore deposits throughout the Pueblo Viejo district are associated with strong silicification and advanced argillic alteration. Centers of strong

alteration and mineralization coincide with the distribution of volcanic domes (compare Figs. 15 and 16). The geologic maps and cross sections presented here show that:

- 1) hydrothermal alteration, gossans, and massive sulfide deposits extend well beyond the limits of the mining reserve and well beyond the limits of a proposed lithocap (Fig. 15),
- 2) volcanic domes coincide with centers of sulfidic silicification and advanced argillic alteration (Figs. 15 and 16),

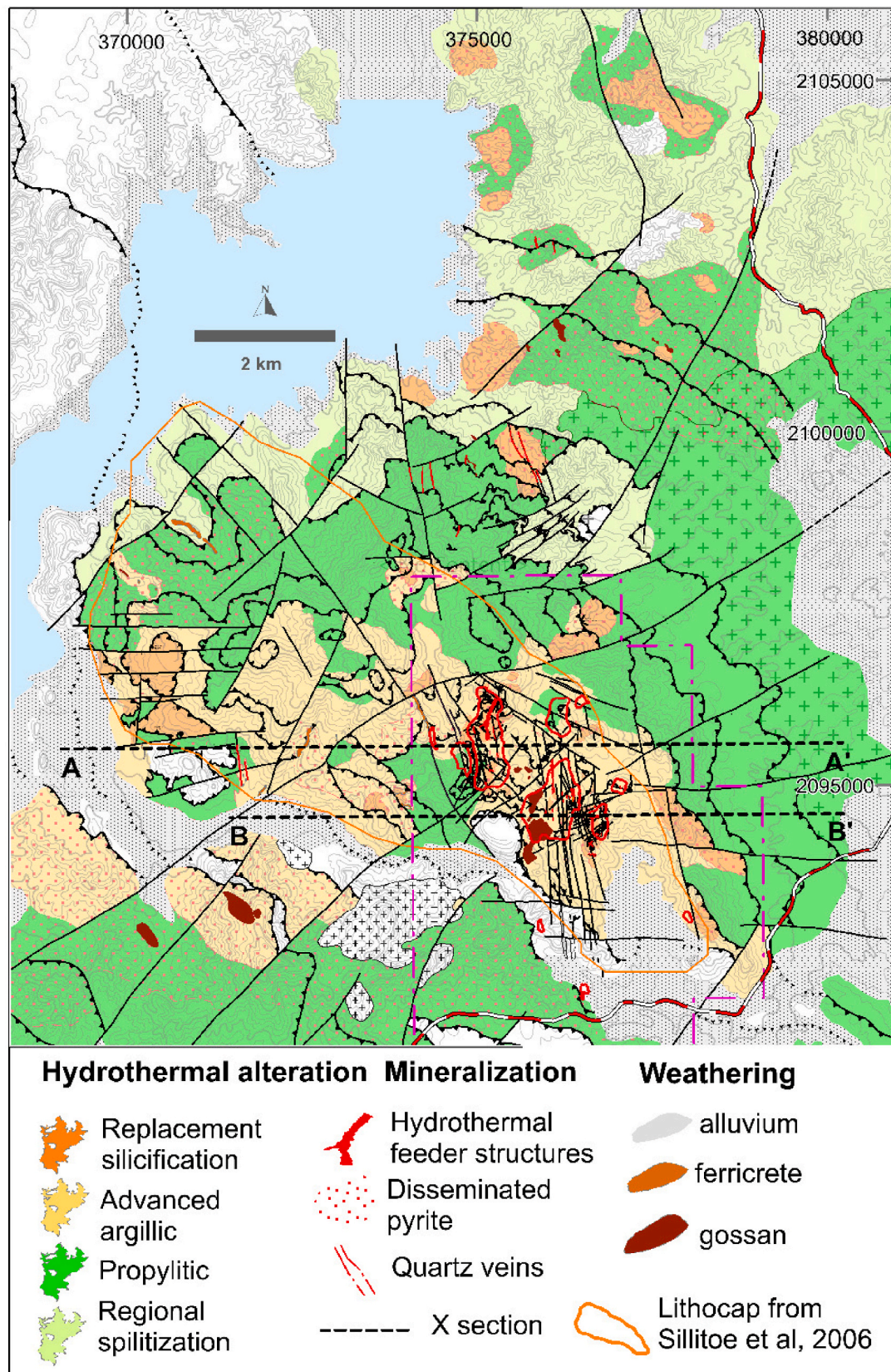


Fig. 15. Geologic map showing the distribution of hydrothermal alteration and mineralization across the Pueblo Viejo district along with the location of gossans. Advanced argillic alteration contains the mineral assemblage quartz $\pm$ pyrophyllite $\pm$ alunite $\pm$ diasporite; propylitic alteration contains the assemblage quartz $\pm$ chlorite $\pm$ epidote $\pm$ calcite; regional spilitization includes the assemblage quartz $\pm$ chlorite $\pm$ albite. Gossans refer to weathered massive sulfide mineralization. Ferricrete refers to Quaternary fluvial sediments that have been cemented by iron oxides. Replacement silicification refers to strong replacements consisting of quartz $\pm$ pyrite $\pm$ pyrophyllite. Hydrothermal feeder structures and high-grade massive sulfide veins contain the assemblage pyrite $\pm$ enargite $\pm$ sphalerite.

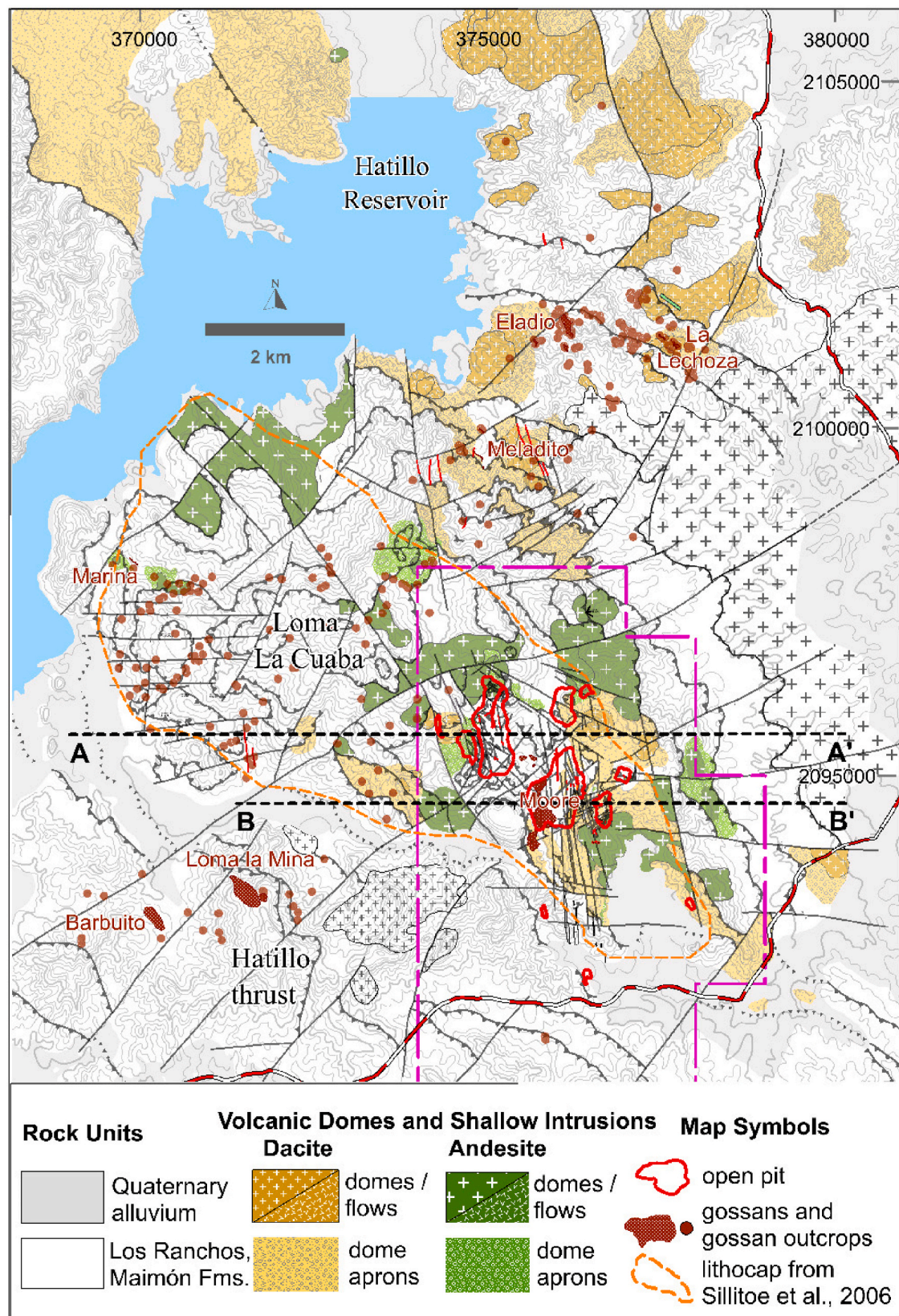


Fig. 16. Map of volcanic domes highlighting their spatial association to VMS-related gossans and Au-Ag-Cu-(Zn) ore deposits. Gossans cropped out within the mining reserve and, although now removed by open pit mining and development, were mined along the eastern margin of the Moore deposit during the 1940's. Volcanic domes and shallow intrusions have not been mapped south of the Hatillo thrust where contact relationships are obscured by post-mineral low-angle faulting, deformation, and metamorphic recrystallization. Sillitoe et al. (2006) outlined the limits of a proposed lithocap (in orange); the limits of the current mining reserve are outlined in lavender. Development and open pit mining inside the mining reserve has largely removed gossans that were present prior to the beginning of open pit mining operations in 1975. The location of the gossan shown in the Moore pit is from Zoppis de Sena (1968).

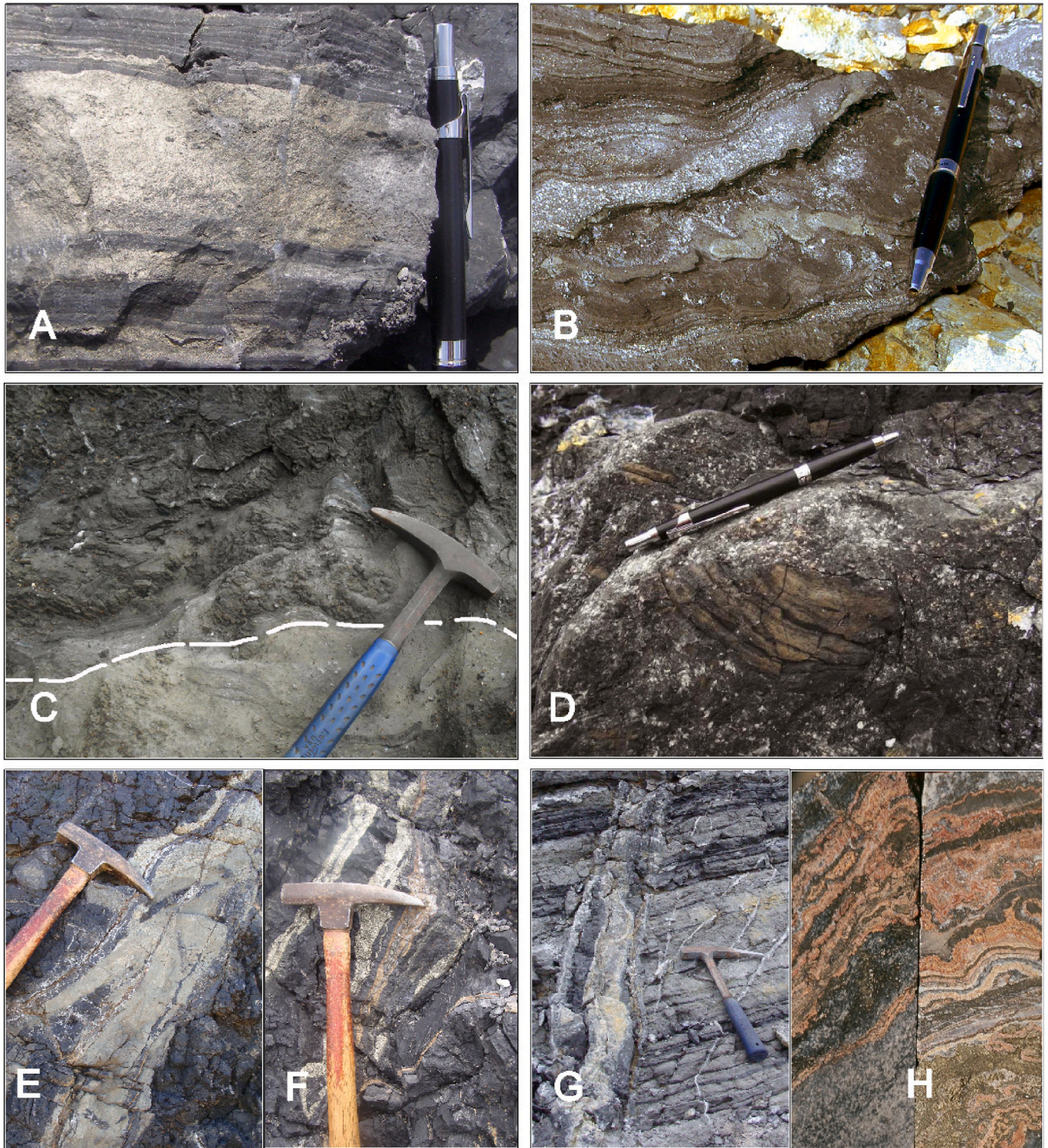


Fig. 17. Massive sulfide beds and massive sulfide veins in the Moore and Monte Negro pits. (A) Massive sulfide (VMS) bed from the Moore pit at UTM coordinates: 2094872N, 376255E (exposed in 1996). (B) Massive sulfide bed with lobate texture from near the same location. (C) Contact of massive sulfide bed, highlighted in white, with overlying carbonaceous volcano-sedimentary rocks, from the Moore pit at UTM coordinates: 2094915N, 376370E (exposed in 2018). (D) Massive sulfide fragment from the Moore pit at UTM coordinates: 2094915N, 376370E (exposed in 2018). (E, F) High-grade massive pyrite veins from the Moore pit with accompanying enargite and sphalerite. (G, H) High-grade massive sulfide (pyrite-enargite-sphalerite) veins from the Monte Negro pit; each piece of core (H) measures 27 mm across.

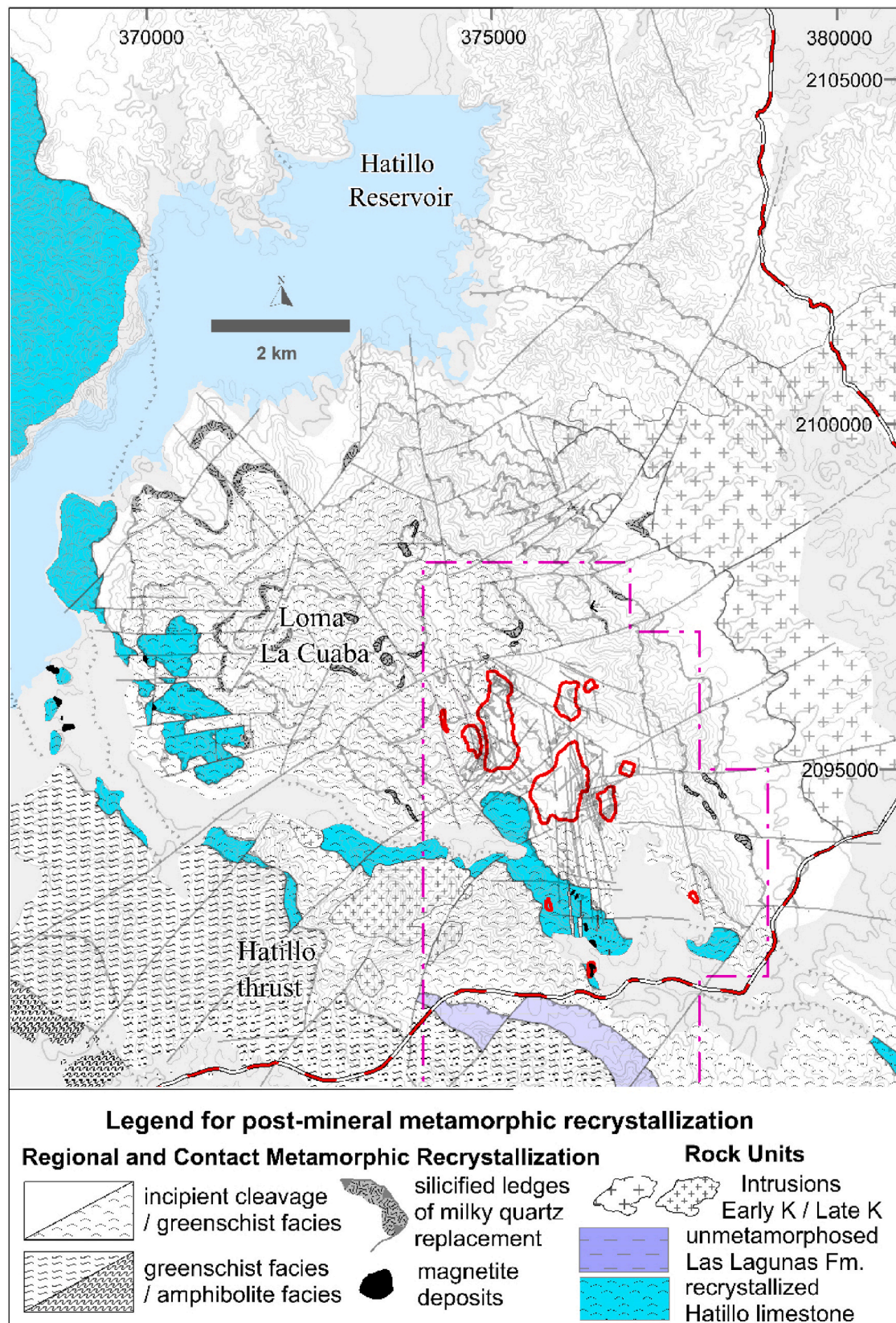


Fig. 18. Map showing the distribution of metamorphic rocks (schists) in the Pueblo Viejo district. Low-angle reverse faults form the boundaries between metamorphic rock domains and control the distribution of sugary-textured, milky quartz replacements. Greenschist facies metavolcanic rocks of the Los Ranchos Fm. (schist) are well exposed on Loma la Cuaba and east as far as a low-angle reverse fault contact with mineralized volcano-sedimentary rocks at the southern end of the Monte Negro pit (Fig. 19). Greenschist facies schists traditionally assigned to the Maimón Fm. are shown as a denser pattern than greenschist facies schists that have been traditionally assigned to the Los Ranchos Fm.

- 3) Au–Ag–Cu–(Zn) deposits are spatially associated with volcanic domes at the Pueblo Viejo mine and throughout the Pueblo Viejo district (Fig. 16), and,
- 4) volcanic domes were emplaced along the same high-angle structures that acted as feeders for hydrothermal alteration and mineralization (Fig. 6).

7.1. Bedded massive sulfide mineralization

Massive sulfide beds (Fig. 17A and B) were recognized during the 1990s during mapping of the Moore pit (at UTM coordinates: 2094872N, 376255E; 2094917N, 376314E; and, 2094902N, 376146E). These locations are close to (within 200 m of) the margin of the Moore dacite porphyry volcanic dome described in a previous section (Dacite porphyry volcanic domes). Additional massive sulfide beds (Fig. 17C and D) were exposed during mining in 2018 at UTM coordinates 2094915N, 376370E, directly below one of the Moore pit locations listed above.

Massive sulfide beds in the Moore pit contain are conformable with the volcano-sedimentary section (Fig. 17A, B, C) and, significantly,

contain eroded clasts of bedded massive sulfide mineralization (Fig. 17D). Massive sulfide beds with clasts of bedded massive sulfide provide a firm marker of the paleosurface and are clear evidence that the beds in which these clasts are found were exposed to erosion while mineralization was underway, strong evidence for an exhalative origin.

8. Post-mineral deformation and metamorphism

Low-angle reverse faults mark the boundaries of metamorphic rock packages in the Pueblo Viejo district and are well exposed in both the Los Ranchos and the Maimón Formations (Fig. 18). The faults generally strike parallel to the Hatillo thrust and dip and flatten to the southwest (Figs. 6 and 18). They consistently offset hydrothermal alteration and mineralization throughout the Pueblo Viejo district. Good exposures of low-angle reverse faults (Fig. 19A and B) and related asymmetric folds (Fig. 19C) were exposed during the 1990's at the south end of the Monte Negro pit. There, greenschist-facies schist is in low-angle, reverse fault contact with lower-plate, hydrothermally altered and incipiently metamorphosed, carbonaceous volcano-sedimentary rocks (Fig. 19D).

Sugary-textured, milky quartz replacements throughout the Pueblo Viejo district form silicified ledges (Fig. 20A, B, C) that are floored by

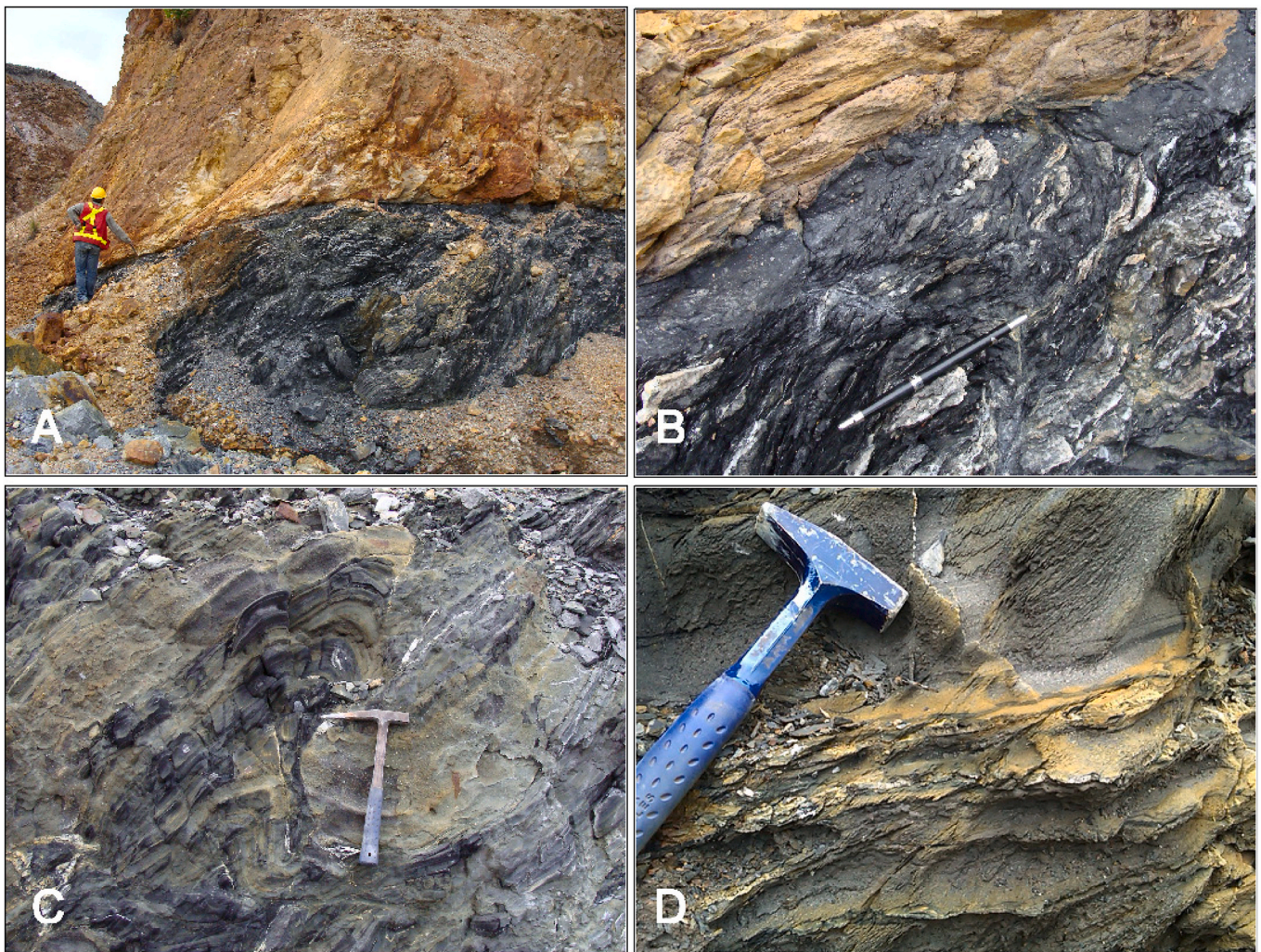


Fig. 19. Post-mineral, low-angle reverse faults and related deformation from the south end of the Monte Negro pit at UTM coordinates: 374880E, 2095050N. (A) Low-angle reverse fault with upper plate, hydrothermally altered and strongly metamorphosed, andesite schist and lower plate, hydrothermally altered and weakly metamorphosed, carbonaceous volcano-sedimentary rocks. (B) Close-up photo of the low-angle reverse fault showing fault gouge (above the pencil) and foliation-parallel milky quartz veins. (C) Asymmetric fold and reverse fault cutting carbonaceous sedimentary rocks with late milky quartz veins on fractures. (D) Incipient metamorphic foliation (cleavage) in lower-plate, carbonaceous volcano-sedimentary rocks.

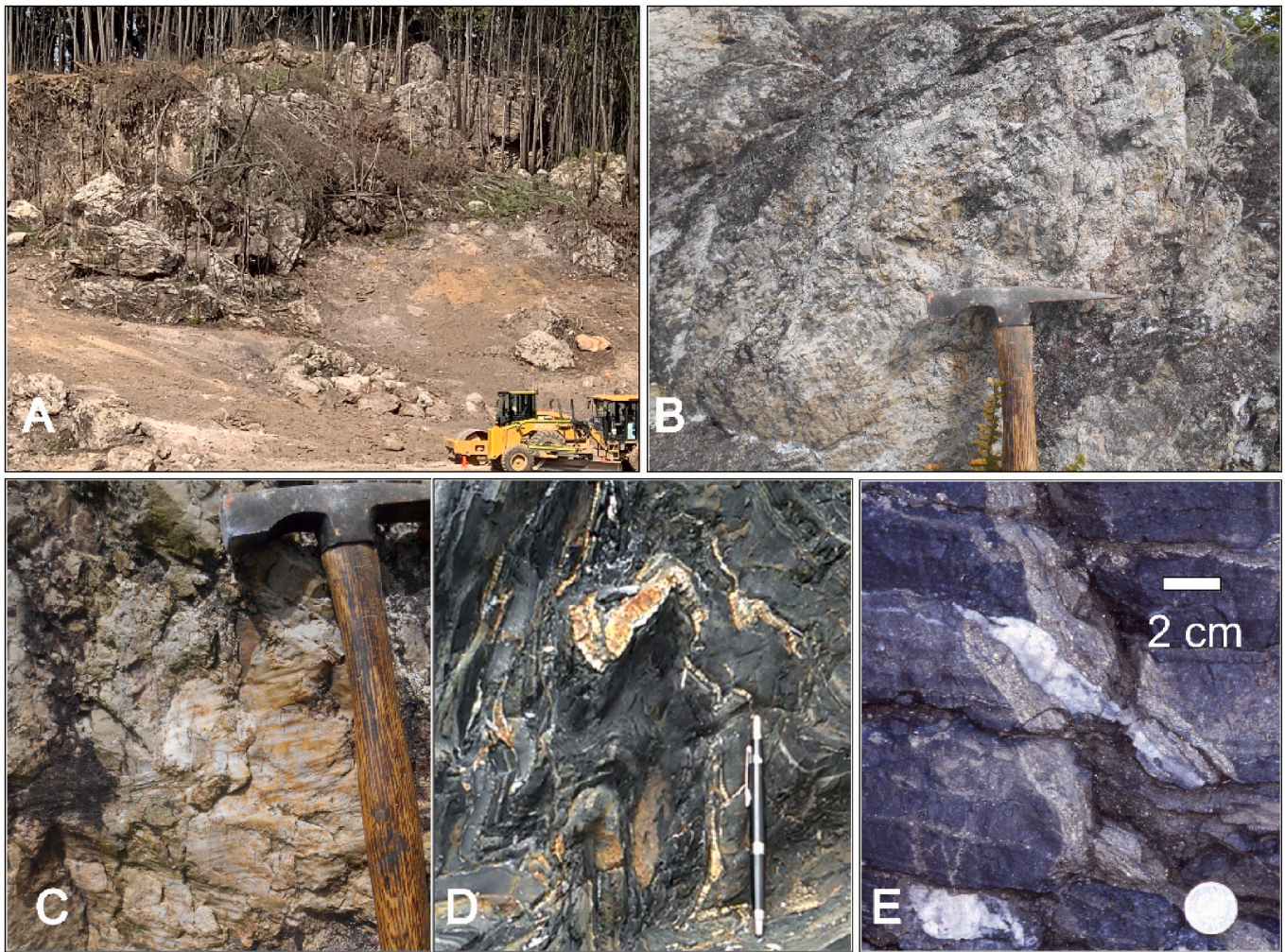


Fig. 20. Post-mineral, milky quartz veins and replacements. (A) Milky quartz replacement at UTM coordinates 375517E, 2096984N. (B) Milky quartz replacement at UTM coordinates 373676E, 2098280N. (C) Close-up view of milky quartz replacement at UTM coordinates 373676E, 2098280N. (D) Folded carbonaceous sedimentary rocks with milky quartz vein segregations from the south end of the Monte Negro pit. (E) Milky quartz vein fills a low-angle fault offsetting a massive sulfide vein, from the Moore pit.

low-angle reverse faults. Milky quartz veins (Fig. 20D and E) are also controlled by, and are most abundant within, low-angle reverse faults (Fig. 19B and C). Milky quartz veins and replacements are barren of mineralization and, since they are controlled by low-angle reverse faults, are attributed to silica mobilization during post-mineral deformation and metamorphism rather than to syn-mineral hydrothermal alteration.

Pyrophyllite, chlorite, and illite are part of the hydrothermal alteration assemblage at the Pueblo Viejo Au–Ag–Cu–(Zn) deposits (Borst et al., 2012; Vaughan et al., 2020). However, on Loma la Cuaba, these minerals typically exhibit cleavage (Nelson et al., 2020). Shallow, southwesterly dipping, structural domains on Loma la Cuaba, separated by low-angle reverse faults (Fig. 18), exhibit varying degrees of metamorphic recrystallization. Much of the pyrophyllite, chlorite and illite on Loma la Cuaba, often attributed to hydrothermal alteration is, at least in part, the product of metamorphic recrystallization, presumably of a hydrothermally altered protolith.

9. Discussion

The Greater Antilles (Fig. 1) expose the remnants of an Early Cretaceous, intra-oceanic island arc that formed as proto-Caribbean crust subducted beneath the Pacific Farallon plate (Pindell et al.,

2005, 2011; Mann et al., 2007). Composite batholiths of tholeiitic composition, emplaced during an interval of extension across the arc, fed chemically-equivalent volcanic rock packages in the Los Ranchos Fm. (Escuder-Virue et al., 2006, 2007a, 2010). Volcanic dome fields within the Los Ranchos Fm. are well exposed in the Pueblo Viejo and the Bayaguana Au–Ag–Cu–(Zn) districts (Nelson, 2000; Chénard, 2006; Nelson et al., 2011; Torró et al., 2017b).

9.1. The Maimón and Los Ranchos formations

Previous publications, following Bowin (1966), have distinguished greenschist and amphibolite facies metavolcanic rocks of the Maimón Fm. from the unmetamorphosed Los Ranchos Fm. (e.g., Kesler et al., 1981; Kesler et al., 1991b; Martin et al., 2000). These workers acknowledged, however, the “strong geochemical, isotopic and petrogenetic similarities” of the Maimón and Los Ranchos Fms (Escuder-Virue et al., 2007b).

Metavolcanic rocks (including pyrophyllite schists) are well exposed on Loma la Cuaba (Fig. 18; Nelson et al., 2020). Evidence for incipient metamorphism (cleavage) can also be observed in the pits at the Pueblo Viejo mine (Draper et al., 1996; Nelson, 2000). Evidence for metamorphism is, consequently, unreliable as a means for distinguishing the Los Ranchos from the Maimón Fm. A contact between these units should

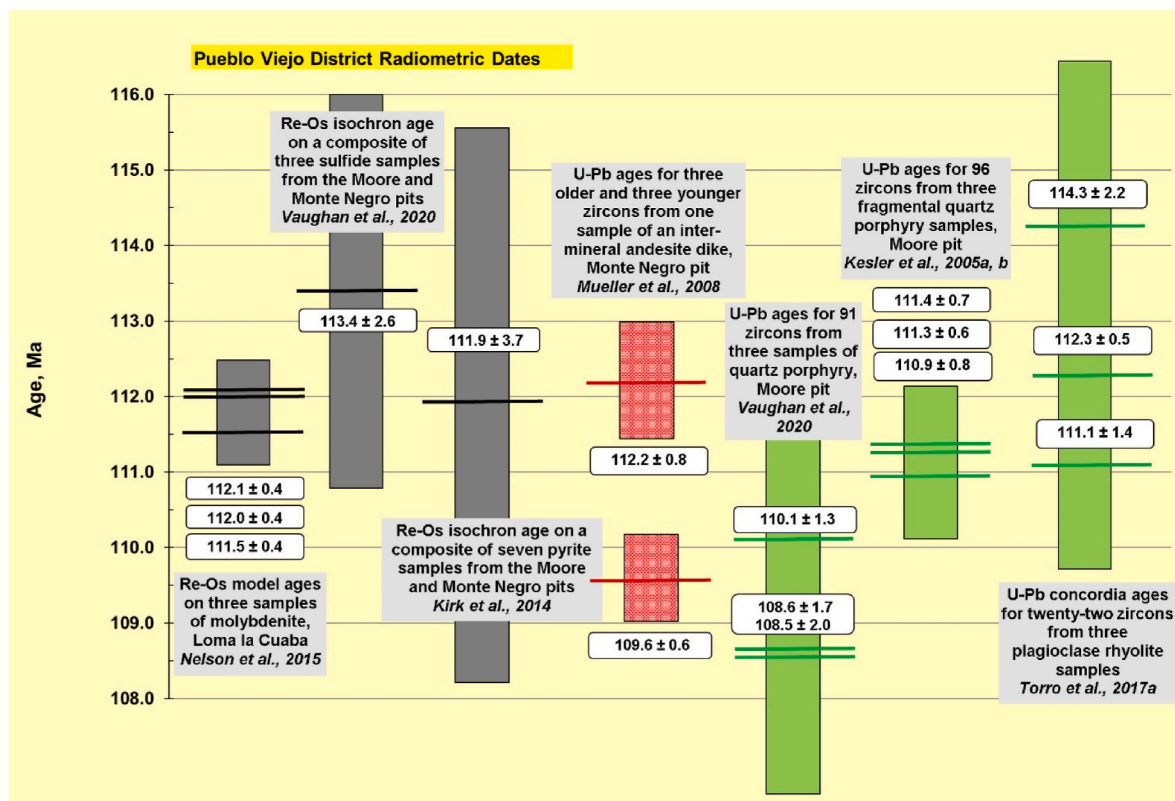


Fig. 21. Radiometric dates from the Pueblo Viejo district. Re–Os dates on mineralization are shown as horizontal black lines; uncertainties are plotted as thick grey bars. Weighted mean $^{206}\text{Pb}/^{238}\text{U}$ dates on six zircons from the calc-alkaline Monte Negro dike are shown as horizontal red lines; uncertainties are plotted as thick red bars. Weighted mean $^{206}\text{Pb}/^{238}\text{U}$ dates on zircon from tholeiitic dacite porphyry are shown as horizontal green lines; uncertainties are plotted as thick green bars. Published radiometric ages for samples of tholeiitic andesite and diorite span the entire 108 to 116 Ma interval and extend as far back as 126 Ma.

be based on lithology and age rather than on metamorphism.

A north to northwesterly-striking volcano-sedimentary interval within the Los Ranchos Fm., exposed over a strike length of ~800 m (Fig. 9, inset), separates amygdaloidal basalt flows from overlying andesites. The amygdaloidal basalts are boninites and LREE-depleted Low-Ti IAT (Torró et al., 2017a). Low-Ti IAT signatures emerge above the volcano-sedimentary interval, interpreted here as an unconformity, that separates basalt flows from the varied volcanic facies of overlying andesite and dacite porphyry. This lithogeochemical change, if it holds up regionally, could offer a more reliable contact between an older, more primitive, Maimón Fm. and a younger, more evolved, Los Ranchos Fm.

We have chosen not to distinguish between the Maimón and Los Ranchos Fms. in this paper. Nonetheless, we agree with the description by Lewis et al. (2000) of a “nascent primitive island arc” that evolved, as described by Torró et al. (2017a, c), from boninite and low-Ti IAT depleted in LREE to normal island arc tholeiite.

Contact relationships in the Los Ranchos Formation can generally be distinguished allowing for recognition and mapping of volcanic facies. Deformation and metamorphic recrystallization in rock units exposed south of the Hatillo thrust have obscured primary rock textures and contact relationships. For this reason, they are shown as undivided basalt, undivided dacite, undivided andesite, and undivided volcano-sedimentary rocks (Figs. 2 and 3).

9.2. Dacite porphyry volcanic domes

Dacite porphyry (Fig. 4C) is described as plagioclase rhyolite (Fig. 4F) by Torró et al. (2017a) and as quartz keratophyre by Kesler et al. (1981). These rock units exhibit the same porphyritic texture and mineral assemblage (phenocrysts of quartz, plagioclase, and pyroxene).

The three rock types are also similar in whole rock and minor element composition (Escuder-Viruete et al., 2007a; Torró et al., 2017a). In addition, the mapped distribution of plagioclase rhyolite (Torró et al., 2017a, Fig. 2) and quartz keratophyre (Kesler et al., 2005b, Fig. 2B) is much the same as the mapped distribution of dacite porphyry in this study (Fig. 2).

Radiometric dates ($^{206}\text{Pb}/^{238}\text{U}$) on zircons from three samples reported by Kesler et al. (2005a,b, $n = 96$) and from three samples reported by Vaughan et al. (2020, $n = 91$) indicate that zircons were crystallizing from the magma that fed dacite porphyry in the Moore pit from 106.9 ± 1.7 Ma to 115.0 ± 1.5 Ma. Radiometric dates on zircons from three plagioclase rhyolite samples reported by Torró et al. (2017a, $n = 22$) show that zircons were crystallizing from 109.7 ± 2.5 Ma to 116.2 ± 4.6 Ma. Weighted mean ages for these three groups (Kesler et al., 2005a, b; Vaughan et al., 2020; Torró et al., 2017a) also overlap (Fig. 21).

Given their similar texture, phenocryst assemblage, chemical composition, and radiometric age, district-scale geologic maps presented here (Figs. 2 and 16) display plagioclase rhyolite, quartz keratophyre, and dacite porphyry as a single rock unit. Future work may distinguish individual intrusive pulses during the 8 Ma time span (~108–116 Ma), implied by available U–Pb dates for dacite porphyry magmatism.

A longstanding controversy over an intrusive or extrusive origin for dacite porphyry along the eastern margin of the Moore pit is resolved by detailed mapping of contact relationships in the pits and the resulting recognition of both intrusive and extrusive volcanic facies. Massive dacite porphyry exhibits cross-cutting contacts (Fig. 4) accompanied by hornfels development in adjacent volcano-sedimentary rocks (Fig. 5), clear evidence for intrusion. The mushroom-shaped tops of massive dacite porphyry bodies, and their coarsely-fragmental epiclastic aprons,

are in conformable contact with overlying volcano-sedimentary rocks (Fig. 7A and B), clear evidence for erosion and sedimentation. These observations indicate that massive dacite porphyry intrusions in the Moore pit breached the paleosurface, fulfilling Williams (1932) criteria for volcanic domes.

Felsic volcanic dome fields are reported from other locations in the Los Ranchos Fm. A felsic volcanic dome field in the Bayaguana district (Fig. 1B), first described by Brouwer and Brouwer (1980), was mapped, sampled and drill tested (with limited success) during the 1990's by the Falcondo exploration team. In the Bayaguana and in the Pueblo Viejo districts mineralization is hosted by volcanic domes and by carbonaceous volcano-sedimentary rocks (Chénard, 2006; Escuder-Viruete et al., 2006; Nelson et al., 2011). Torró et al. (2017b) dated mineralization at Bayaguana at 112.6 ± 0.4 Ma, essentially identical to the age of mineralization reported by Kirk et al. (2014) for mineralization at Pueblo Viejo. Much of the volcano-sedimentary basin in the Bayaguana district, similar to Pueblo Viejo in terms of geologic setting and even larger in terms of size of the hydrothermal alteration system, is untested by drilling.

9.3. Andesite volcanic domes and diorite intrusions

Mushroom-shaped, massive andesite bodies in the Monte Negro pit have intrusive roots but display conformable upper contacts with overlying volcano-sedimentary beds indicating an origin by exogenous emplacement onto the paleosurface. Carapace breccias formed near the tops of these volcanic domes; peperites formed along their subhorizontal basal contacts. Coarsely-fragmental, epiclastic aprons form wedge-shaped units that thin rapidly away from the volcanic dome margin and, at their distal edge, are interbedded with volcano-sedimentary rocks.

Coarsely-fragmental, epiclastic aprons appear to have formed when solid crust, broken during volcanic dome growth and expansion, generated fragments that accumulated around the margin of the dome. Cross sections (Fig. 6) and pit exposures (Fig. 8) show that these epiclastic aprons mantle massive andesite (like a blanket) rather than fill channels (like a conglomerate). Although the aprons formed by erosion, they are not associated with an unconformity. The surrounding volcano-sedimentary section is uninterrupted.

Cross sections (Fig. 6) based on bench mapping and drill core show that volcanic domes of massive andesite occur at more than one level in the volcano-sedimentary section. Deep (older) volcanic domes were conformably overlain by volcano-sedimentary rocks as the basin subsided. Younger volcanic domes broke through to the new paleosurface and were extruded at a higher level in the volcano-sedimentary section. Massive andesite intrusions breached the paleosurface, generated coarsely-fragmental aprons and, as basin subsidence continued, were incorporated into the volcano-sedimentary section.

Not every massive andesite in the Pueblo Viejo district shows evidence for having breached the paleosurface. Where coarsely-fragmental, epiclastic aprons are absent and/or where conformable upper contacts are not exposed, massive andesite bodies were mapped as diorite intrusions (Fig. 2). Given the amount of vegetative cover in the Pueblo Viejo district, it is likely that volcanic domes and shallow intrusions are more abundant than they appear on the maps (Figs. 2 and 16).

Coarsely-fragmental, epiclastic volcanic dome aprons contain numerous veined and silicified clasts (Fig. 8E and F). The matrix of these volcanic dome aprons and the andesite volcanic domes themselves are also hydrothermally altered (an advanced argillic assemblage accompanied by strong silicification) and mineralized (gold-bearing, disseminated pyrite). The presence of hydrothermally altered and mineralized fragments in a hydrothermally altered and mineralized matrix indicates 1) that coarsely-fragmental volcanic dome aprons were locally derived (from within the limits of the Pueblo Viejo hydrothermal system) and, 2) that volcanic dome aprons accumulated while the hydrothermal system was active.

Torró et al. (2017a) reported lead-corrected, $^{206}\text{Pb}/^{238}\text{U}$ ages of 115.8 ± 2.4 Ma to 106.0 ± 2.6 Ma on four zircons from a diorite sample collected at UTM 373922E, 2098057N and lead-corrected $^{206}\text{Pb}/^{238}\text{U}$ ages of 117.9 ± 1.5 to 107.1 ± 1.6 Ma on ten zircons from a diorite sample collected at UTM 370998E, 2095450N. The youngest zircons from each of these samples yield essentially identical concordia ages: 108.1 ± 1.4 Ma ($n = 3$) and 108.4 ± 1.2 Ma ($n = 2$). These dates indicate that andesitic volcanic domes and shallow diorite intrusions were being emplaced during the same ~ 108 to ~ 116 Ma time interval as dacite porphyry volcanic domes.

9.4. Zambrana batholith

Escuder-Viruete et al. (2006) reported a U–Pb date of 115.5 ± 0.3 Ma on zircon from a sample of tonalite (collected at UTM coordinates: 380350E, 2100640N). The 115.5 ± 0.3 Ma date is the oldest of three dated zircon fractions from this tonalite sample. Each of the three fractions yielded concordant analyses with $^{206}\text{Pb}/^{238}\text{U}$ ages as follows: 115.5 ± 0.3 Ma, 114.9 ± 0.4 Ma, and 112.9 ± 0.3 Ma (Escuder-Viruete et al., 2006). Torró et al. (2017a) reported a date for gabbro (collected at UTM coordinates: 377337E, 2098534N) of 117.4 ± 1.0 Ma (U–Pb concordia age on seven of the youngest zircons). Torró et al. (2018) reported a date for tonalite (collected from UTM 379323E, 2098792N) of 110.2 ± 0.8 Ma. These dates fall within the range of radiometric dates (~ 108 to ~ 116 Ma) for volcanic domes and shallow intrusions of the Los Ranchos Fm. Based on its similar age and composition, and following the interpretation of Escuder-Viruete et al. (2006), the Zambrana composite batholith is the inferred source for volcanic and intrusive rocks in the Pueblo Viejo district.

9.5. Pyroxene diorite intrusions

Bowin (1966) proposed a late Eocene age for a pyroxene diorite pluton (the Bowin diorite) that intrudes metavolcanic rocks in the Pueblo Viejo district (Figs. 2 and 10). This age was based on intrusions of similar mineralogy that intrude Upper Cretaceous to Eocene sedimentary rocks, fifty km northwest of the Pueblo Viejo district. Martin et al. (2000) reported a $^{206}\text{Pb}/^{238}\text{U}$ date of 48.3 ± 0.3 Ma on a diorite intrusion from the Hatillo 1:50,000-scale quadrangle (no location provided) and mapped the Bowin diorite along with the Moore, Monte Negro, and Banco Cinco diorite dikes as Paleogene.

The weakly altered, post-mineral Moore and Monte Negro diorite dikes (Fig. 10) cut across the entire mineralized section of the Moore and Monte Negro ore deposits (Fig. 11A and B; Smith et al., 2008, Fig. 6.2; Cardenas et al., 2018, Fig. 7.3). Pyroxene diorite dikes at Banco Cinco, dated at 88.5 ± 1.3 – 1.2 Ma (this study), occupy the same northerly-striking structures as the Moore and Monte Negro dikes. The Banco Cinco, Moore, and Monte Negro dikes share the same texture and mineralogy (Fig. 11C–H) and are indistinguishable in the field.

Two samples of the Bowin diorite (BO-diorite), the Banco Cinco diorite (BC-diorite) and four samples of the Moore and Monte Negro dikes plot as calc-alkaline on rock classification diagrams (Fig. 12) and demonstrate LREE enrichment on REE plots (Fig. 13). Pyroxene diorite dikes, based on similar mineralogy and texture, similar rock classification and REE patterns, and similar structural control by northerly-striking, high-angle faults, are interpreted here as part of a single, ~ 88.5 Ma, calc-alkaline intrusive event.

9.6. Geochronology

Two samples of pyroxene diorite collected for this study generated $^{206}\text{Pb}/^{238}\text{U}$ ages that are substantially older, 88.45 ± 1.3 Ma for the Bowin diorite pluton and 88.5 ± 1.6 Ma for the Banco Cinco diorite dikes (Fig. 10) than the ages reported by Bowin (1966) and by Martin et al. (2000). The new U–Pb dates provide evidence for a Late Cretaceous, calc-alkaline intrusive event in the Pueblo Viejo district. This

event is likely part of the Late Cretaceous calc-alkaline magmatism described by Lewis et al. (1991) and Escuder-Viruete et al. (2006) from the central cordillera of the western Dominican Republic and by Rojas-Agramonte et al. (2021) from the Massif du Nord of Haiti.

Mueller et al. (2008) reported weighted average TIMS U–Pb ages of 112.2 ± 0.8 Ma for three older zircons and 109.6 ± 0.6 Ma for three younger zircons collected from the Monte Negro diorite dike. Torró et al. (2017a) interpreted their calc-alkaline suite of samples, including the Monte Negro dike, as a late phase in the evolution of the Early Cretaceous Los Ranchos Fm. The new ~ 88.5 Ma dates reported here suggest that the six zircons dated by Mueller et al. (2008) may be inherited and that the actual age of the calc-alkaline Moore and Monte Negro dikes and, by extension, of calc-alkaline magmatism in the Pueblo Viejo district, may be ~ 88.5 Ma. More work is needed to reliably date the onset of calc-alkaline volcanism in the Pueblo Viejo district.

9.7. Hydrothermal alteration and mineralization

Kirk et al. (2014) reported a Re–Os isochron age on samples of sulfide ore from Pueblo Viejo of 111.9 ± 3.7 Ma. Three molybdenite-bearing samples from Loma la Cuaba drill core dated by Nelson et al. (2015) returned model ages of 112.1 ± 0.4 Ma (2094922N, 373666E), 112.0 ± 0.4 Ma (2095696N, 373633E), and 111.5 ± 0.4 Ma (2094656N, 373432E). These dates (Fig. 21) fall on the Aptian-Albian boundary, within the ~ 108 Ma to ~ 116 Ma time interval reported here for volcanic dome emplacement.

The Los Ranchos Fm. is conformably overlain by the Aptian-Albian Hatillo Limestone (Bowin, 1966; Nelson et al., 2020). The basal portion of the Hatillo Limestone, near-shore calcarenite and interbedded calcareous sandstone and marly limestone, contains coral fragments and rudist bivalves (Bonilla-Rodríguez et al., 2014). It is also hydrothermally altered (Sillitoe et al., 2006; Nelson et al., 2020). Hydrothermal alteration and mineralization in the Pueblo Viejo district took place at ~ 112 Ma, at the Aptian-Albian boundary, in a subsiding, marginal-marine, volcano-sedimentary basin.

Hydrothermally altered fragments, common in both intrusive and extrusive facies of dacite porphyry (Fig. 4D, H) and andesite (Fig. 8E and F), indicate that hydrothermal alteration and mineralization were underway during volcanic dome emplacement. Hydrothermally altered clasts are also present in the hydrothermally altered volcano-sedimentary section, evidence that hydrothermal alteration was underway as volcano-sedimentary rocks accumulated. Hydrothermal alteration and mineralization in the Pueblo Viejo district were coeval with regional extension, batholith emplacement, tholeiitic island arc volcanism, volcanic dome emplacement, subsidence, and filling of a volcano-sedimentary basin.

9.8. Bedded massive sulfide mineralization

Sillitoe et al. (1996) and Hannington et al. (1998) described Pueblo Viejo as a high sulfidation VMS deposit. Their interpretation built on emerging isotopic evidence for magmatic sulfur and mineralogic evidence for advanced argillic alteration (cristobalite, pyrophyllite, kaolinite, opal-CT, native sulfur, alunite), as reported by Herzig et al. (1998), from submarine hydrothermal systems of the Lau back-arc spreading center. Support for links between epithermal and VMS deposits continued to build in following years with reports of advanced argillic alteration in other active submarine hydrothermal systems (e.g., Binns et al., 2007). Continued study of a growing number of active submarine hydrothermal systems has led to recognition of a transition between deep-water VMS mineralization and hybrid epithermal-VMS mineralization forming at shallow depths (e.g., Monecke et al., 2014).

VMS mineralization is well established in the Pueblo Viejo district. Dupéré and Paiement (2012) reported VMS mineralization at the La Lechoza deposit and Kesler et al. (1991b) reported VMS mineralization at the Loma la Mina deposit (Fig. 16). The Cerro de Maimón mine,

described as a VMS deposit by Lewis et al. (2000), Chénard (2006) and Torró et al. (2016) is located 10 km south of the Pueblo Viejo mine (Fig. 9).

Volcano-sedimentary beds in the Moore pit contain eroded clasts of bedded massive sulfide mineralization (Fig. 17D), clear evidence that the beds in which these clasts are found were exposed to erosion during deposition. These beds provide a firm marker of the paleosurface at the time of massive sulfide deposition.

Disseminated replacement sulfide mineralization is present at Pueblo Viejo but clasts of bedded massive sulfide clearly could not have formed by replacement. Massive sulfide beds and massive sulfide clasts at Pueblo Viejo are evidence for mineralization on the paleo-seafloor and indicate a strong link to volcanogenic massive sulfide mineralization.

Volcanogenic massive sulfide beds have been observed at two (stacked) levels in the volcano-sedimentary section, evidence that the basin was subsiding while volcano-sedimentary rock units were being deposited and while mineralization was underway.

9.9. Estimates of hydrothermal fluid temperature

Kesler et al. (1981) reported homogenization temperatures of 130 °C– 190 °C in low-salinity fluid inclusions and coexisting vapor-rich and liquid-rich inclusions, evidence that “boiling was a widespread event in the system.” Hydrothermal fluid temperatures at Pueblo Viejo have also been estimated from hydrothermal alteration mineral equilibria and sulfur isotope thermometry. Muntean et al. (1990) estimated temperatures of below 260 °C for stage I disseminated mineralization and above 285 °C for stage II vein-hosted mineralization.

The hydrothermal fluid temperatures estimated by Muntean et al. (1990) seem high considering the evidence presented here for deposition in a marginal-marine environment and the evidence for massive sulfide mineralization on the paleo-seafloor. However, temperature estimates to date have not accounted for metamorphic recrystallization. Metamorphic mineral assemblages, e.g., those involving pyrophyllite, need to be distinguished from hydrothermal mineral assemblages if the resulting hydrothermal fluid temperature estimates are to be considered reliable.

Hydrothermal pyrophyllite is present in the Pueblo Viejo district but it may not be a reliable indicator of fluid temperature. Low temperature hydrothermal solutions are typically supersaturated with silica relative to the concentration predicted by equilibria with quartz (e.g., Geilert et al., 2015). Under such conditions, pyrophyllite will form at temperatures below 260 °C.

If mineral equilibria can be modified to account for metamorphic recrystallization and if fluid temperatures based on those mineral equilibria can be adjusted for supersaturated silica, there remains an issue over the use of fluid temperature to estimate depth. Donaldson (1968) showed that pressure will increase, beyond hydrostatic, in a rising column of boiling fluid as a function of mass flow rate and permeability. Hydrothermal fluid temperatures of 260 °C will be lifted to depths of less than 200 m during periods of high fluid discharge (versus a depth of 560 m under hydrostatic conditions).

These factors help to explain the current disconnect between relatively high fluid temperatures estimated by hydrothermal mineral equilibria and the shallow depths indicated by a marginal marine environment of deposition and evidence for mineralization on the paleo-seafloor.

9.10. Post-mineral deformation and metamorphism

Evidence for deformation and metamorphism, well established in the Maimón Formation, is also present, though not to the same intensity, in the Los Ranchos Formation. At the Pueblo Viejo mine, Draper et al. (1996) reported “penetrative cleavage that is axial planar to asymmetric, northeast-verging folds in the metasedimentary rocks of the Pueblo Viejo member.” Nelson et al. (2020) reported greenschist facies

metamorphic rocks on Loma la Cuaba (Fig. 18).

Milky quartz veins are present in a strongly foliated sample from the Monte Negro pit that returned Re–Os dates on enargite of 111.9 ± 0.1 and 38 ± 4 Ma (Deyell et al., 2013; Vaughan et al., 2020). The older Re–Os date is consistent with Re–Os dates on mineralization reported by Kirk et al. (2014) and Nelson et al. (2015). The younger enargite date, however, suggests that enargite may have been re-mobilized by a

post-mineral tectonic or intrusive event.

9.11. Pueblo Viejo genetic model

Volcanic domes, derived from composite batholiths of tholeiitic composition, were emplaced during a period of extension (~ 108 to ~ 116) across an Early Cretaceous intraoceanic arc. Extension and

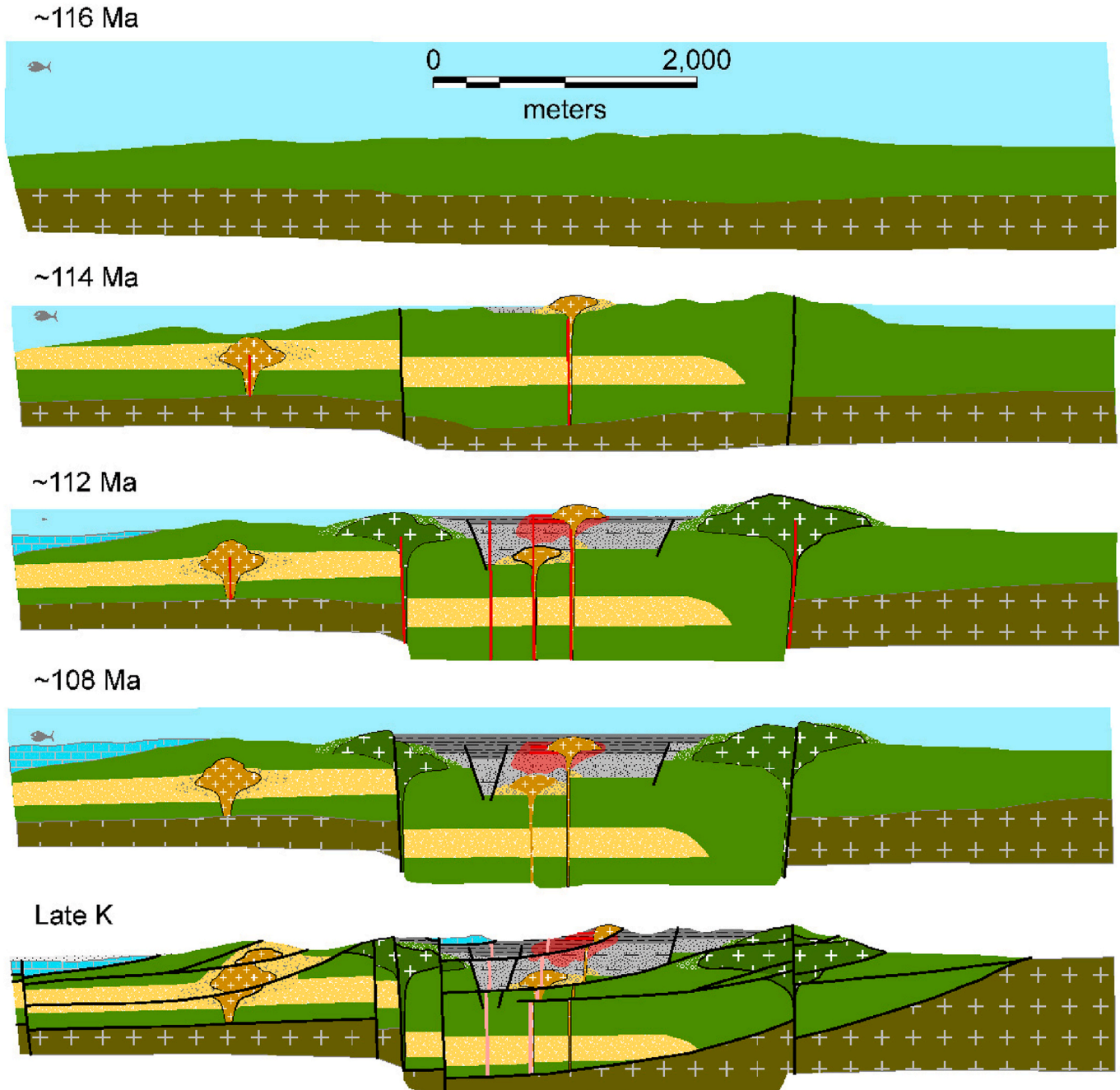


Fig. 22. Sequential cross sections, drawn at UTM 2094600N through the Moore deposit, show the Cretaceous evolution of the Pueblo Viejo district. See Fig. 3 for a rock unit legend. (~ 116 Ma) A tholeiitic, intraoceanic island arc is undergoing extension accompanied by emplacement of gabbroic phases of the Zambrana batholith. (~ 114 Ma) Extension across the arc continues, accompanied by emplacement of tonalitic phases of the Zambrana batholith, volcanic dome emplacement, emergence of the arc from the ocean, local subsidence, and the development of a marginal marine volcano-sedimentary basin. (~ 112 Ma) Main mineralizing event. High-angle normal faults act as hydrothermal feeders (vertical red lines) for massive sulfide beds (horizontal red lines) and for vein and disseminated Au–Ag–Cu–(Zn) ore deposits (red polygons). The basin continues to subside as mineralization continues; older volcanic domes are buried by younger volcano-sedimentary rocks, younger volcanic domes are emplaced higher in the volcano-sedimentary section, and; new massive sulfide beds form on the shallow seafloor. (~ 108 Ma) Au–Ag–Cu–(Zn) mineralization has ended. Basin subsidence and accumulation of volcano-sedimentary rocks continues. (Late K) Low-angle reverse faulting is accompanied by incipient to greenschist-facies metamorphic recrystallization and by milky quartz veining and replacement. Diorite dikes (pink), intruded at ~ 88.5 Ma, are sourced from a calc-alkaline pluton exposed less than a kilometer south of the cross section (Figs. 2 and 10).

volcanic dome emplacement were accompanied by the formation of shallow, marginal-marine basins filled by volcanoclastic sandstone, siltstone, and limy siltstone. As extension continued and the basins deepened, older volcanic domes were buried by younger volcano-sedimentary rocks (Fig. 22).

Massive andesite and dacite porphyry intruded carbonaceous, volcano-sedimentary host rocks along northerly-striking, high-angle structures. Contact metamorphic recrystallization adjacent to intrusive contacts drove off organic carbon and formed hornfels. Many intrusions breached the paleosurface and gave rise to coarsely-fragmental, epiclastic aprons that accumulated around the margins of newly-formed volcanic domes. Older volcanic domes were buried by as the volcano-sedimentary basin continued to subside. Volcanic dome emplacement and volcano-sedimentary basin development were coeval events in the Pueblo Viejo district.

The spatial association of Au–Ag–Cu–(Zn) deposits with volcanic dome margins at the Pueblo Viejo mine and elsewhere in the Pueblo Viejo district suggests a genetic link between volcanic dome emplacement and mineralization. Lithogeochemistry and radiometric dating (~108 to ~116 Ma for tholeiitic volcanic domes and diorite intrusions, ~112 Ma for mineralization) supports a link between tholeiitic magmatism, volcanic dome emplacement, and Au–Ag–Cu–(Zn) mineralization.

Volcano-sedimentary host rocks at the Pueblo Viejo mine contain algal matter, coral fragments, and terrestrial plant fossils, evidence for a shallow-water, marginal marine environment. Near-shore calcarenites of the conformably overlying Hatillo Limestone, deposited beginning in the late Aptian, and were covered by massive limestone as water depths increased through the mid-Albian (Myczynski and Iturralde, 2005; Bonilla-Rodríguez et al., 2014; Nelson et al., 2020).

Mineralization consists primarily of disseminated sulfides and cross-cutting, high-grade, massive sulfide veins. Volcano-sedimentary beds containing clasts of eroded massive sulfide provide a fix on the paleo-seafloor at the time of mineralization and indicate a link to VMS deposits. Stacked massive sulfide beds are evidence that the volcano-sedimentary basin was actively subsiding while hydrothermal alteration and mineralization were underway. Ore deposits in the Pueblo Viejo district display characteristics transitional between higher temperature VMS deposits and lower temperature epithermal deposits.

High-angle faults formed the basin margins, controlled the emplacement of volcanic domes, and served as conduits for hydrothermal solutions. Continued basin subsidence during a prolonged period of volcanic dome emplacement, hydrothermal alteration, and mineralization likely contributed to the extraordinary size of the Moore and Monte Negro ore deposits.

Advanced argillic alteration in the Pueblo Viejo district has been interpreted as a lithocap (Sillitoe et al., 2006). Molybdenite formed at ~112 Ma (Nelson et al., 2015), consistent with the ~112 Ma age for Pueblo Viejo ore deposits established by Kirk et al. (2014). However, volcanic domes that control the distribution of hydrothermal alteration and mineralization in the Pueblo Viejo district are tholeiitic in composition. Mineralization consists of disseminated sulfide, massive sulfide veins, and massive sulfide beds. Volcanic domes, widespread hydrothermal alteration, and an enormous amount of sulfide sulfur provide convincing evidence for a magma-driven hydrothermal system. Hydrothermal alteration and mineralization, however, are linked to tholeiitic volcanism, volcanic dome emplacement, and shallow water VMS mineralization rather than to calc-alkaline magmatism and porphyry deposits.

10. Conclusions

Geologic mapping at the Pueblo Viejo mine and across the surrounding district reveals massive andesite and dacite porphyry bodies that: 1) are homogeneous with a crystalline texture and no stratification, (2) are mushroom-shaped in cross section, and (3) narrow with depth

into intrusive feeders. Near intrusive contacts, volcano-sedimentary host rocks (4) are tilted and develop a contact metamorphic aureole defined by 5) a hornfels texture and 6) the presence of diopside, magnetite, and andalusite. Evidence that these intrusions breached the paleosurface includes: (7) coarsely-fragmental, epiclastic aprons, (8) sedimentary (conformable) contacts with overlying carbonaceous volcano-sedimentary rocks, (9) carapace breccias, and (10) peperites along sub-horizontal basal contacts. Massive andesite and dacite porphyry intrusions, given the evidence summarized above, breached the paleosurface thereby qualifying as volcanic domes. Volcanic domes are well exposed in the pits and throughout the Pueblo Viejo district.

Ore deposits in the Pueblo Viejo district formed in a volcanic dome field during a period of extension across an intraoceanic island arc. Volcanogenic massive sulfide beds were deposited on the paleosurface and became stacked, along with volcanic domes, as a subsiding basin filled with epiclastic volcano-sedimentary rocks. High-angle faults controlled the growth of the basin, the location of phreatomagmatic vents, and the emplacement of volcanic domes. These same high-angle faults provided feeders for mineralizing hydrothermal solutions. A shallow, marginal marine environment of deposition resulted in ore bodies with characteristics that are transitional between epithermal and volcanogenic massive sulfide deposits.

Ore deposits of the Pueblo Viejo district are not unique. Instead, the links demonstrated in this paper between a forty-million-ounce gold district, tholeiitic island arc volcanism, volcanic dome emplacement, and marginal-marine, hybrid epithermal - VMS mineralization contribute to a new model for large Au–Ag–Cu–(Zn) deposits in tholeiitic intra-oceanic island arcs. Rather than fit the Pueblo Viejo ore deposits to a porphyry model, an opportunity exists to construct a new model, building on the geologic setting described here, for Au–Ag–Cu–(Zn) mineralization in tholeiitic volcanic arcs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The senior author was introduced to the Pueblo Viejo mine on a 1980 visit while employed by Homestake Mining Company. Follow-up field work and sampling efforts were supported by a Fulbright faculty research grant (1987–1988). Detailed mapping in the pits took place from 1994 to 1997 and, on Loma la Cuaba, with the co-authors, from 2004 to 2008. District-scale mapping supported by Recursos del Caribe continued from 2012 through 2021. Field work by Dominguez, Carrasco, and Leonardo was supported by Evertor Resources Inc. During the period 2005 to 2014, Polanco has worked at the Pueblo Viejo mine for over forty years. Although Barrick Gold Corporation approved the participation of Polanco, Dominguez, and Leonardo as co-authors, the observations and conclusions presented here do not imply endorsement by the company. Jim Piper did the petrographic work. Victor Valencia separated zircons and supervised the U–Pb dating. This manuscript benefitted from helpful reviews by Issac Corral, Alan Galley, Patrick Hayman, Stephen Kesler, Steve Piercy, Norman Russell, and one anonymous reviewer. The collaboration and support of these individuals and organizations is gratefully acknowledged.

Data Availability

Supplementary data generated in the course of this investigation is contained in the appendices, available online at <https://doi.org/10.1016/j.jsames.2022.104158>.

Appendix I contains a description of sample preparation and analytical procedures along with major and minor element analytical

results for rock samples, standards, blanks, and replicates. **Appendix II** presents C1 Chondrite - normalized, primitive mantle – normalized, and N-MORB - normalized REE and minor element data. **Appendix III** contains complete U–Pb isotopic data used to calculate the radiometric ages.

References

- Binns, R.A., Barriga, F.J.A.S., Miller, D.J., 2007. 1. Leg 193 Synthesis: anatomy of an active felsic-hosted hydrothermal system, eastern Manus Basin, Papua New Guinea. In: Barriga, F.J.A.S., Binns, R.A., Miller, D.J., Herzig, P.M. (Eds.), *Proceedings of the ODP, Scientific Results, 193. Ocean Drilling Program, College Station, Texas*, pp. 1–71.
- Bonilla-Rodríguez, A.J., González, L.A., Walker, J.D., Santos, H., 2014. Strontium isotope ($^{87}\text{Sr}/^{86}\text{Sr}$) stratigraphy from the *Coalmana - Caprinuloidea* rudist assemblage in the Greater Antilles (Puerto Rico, Dominican Republic and Jamaica). *Cretac. Res.* 50, 97–109.
- Borst, R., Moore, C., Villeneuve, A., 2012. Technical Report on the Pueblo Viejo Project, Sanchez Ramirez Province, Dominican Republic: NI 43-101 Technical Report Prepared by Roscoe Postle. Associates Inc. for Barrick Gold Corporation. March 16, 2012.
- Bowin, C.O., 1966. Geology of the Central Dominican Republic (a case history of part of an island arc). In: Hess, H.H. (Ed.), *Caribbean Geological Investigations*, vol. 98. Geological Society of America Memoir, pp. 11–84.
- Brouwer, S.B., Brouwer, P.A., 1980. Geología de la región ambarífera oriental de la República Dominicana. In: *Transactions 9th Caribbean Geological Conference*, Santo Domingo, Dominican Republic, *Memorias*, pp. 303–322, 1.
- Cabanis, B., Lecolle, M., 1989. Le diagramme La/10-Y/15-Nb/8: un outil pour la discrimination des séries volcaniques et la mise en évidence de processus de mélange et/ou de contamination crustale: Comptes Rendus de l'Académie des sciences. Série II. Mécaniques. Physics. Chemistry. Space sciences. *Earth Sci.* 309, 2023–2029.
- Cardenas, R., Miranda, H., Krutzelmann, H., 2018. Technical Report on the Pueblo Viejo Mine, Sanchez Ramirez Province, Dominican Republic: NI 43-101 Report Prepared by Roscoe Postle. Associates Inc. for Pueblo Viejo Dominicana Corporation. March 19, 2018.
- Chang, Z., Vervoort, J.D., McClelland, W.C., Knaack, C., 2006. U-Pb dating of zircon by LA ICP-MS. *G-cubed* 7, Q05009. <https://doi.org/10.1029/2005GC001100>.
- Chénard, D., 2006. Evaluation of Seven Projects, Dominican Republic: NI 43-101 Report Prepared by Datac Geo-Consult Inc. for Globestar Mining and Corporación Minera Dominicana S.A. January 2006.
- Deyell, C.L., Stein, H., Cooke, D.R., Wurst, A.T., 2013. Direct Dating of High Sulfidation Gold Mineralization Using Rhenium-Osmium Isotopes: an Example from Pueblo Viejo, Dominican Republic (Abs. James Cooke University Economic Geology Research Unit (EGRU) Contribution, Townsville, Australia, 68).
- Donaldson, I.G., 1968. The flow of steam-water mixtures through permeable beds: a simple simulation of a natural undisturbed hydrothermal region. *N. Z. J. Sci.* 11, 3–33.
- Draper, G., Gutierrez, G., Lewis, J.F., 1996. Thrust emplacement of the Hispaniola peridotite belt: Orogenic expression of the mid-Cretaceous Caribbean arc polarity reversal? *Geology* 24, 1143–1146.
- Dupéré, M., Paiement, J.-P., 2012. Mineral Resource Estimation of the Ampliación Pueblo Viejo Property, Dominican Republic: an NI 43-101 Technical Report Prepared for Everton Resources. Inc., SGS Canada Inc.
- Escuder-Viruet, J., Díaz de Neira, A., Hernaiz Huerta, P.P., Montheil, J., García-Senz, J., Joubert, M., Lopera, E., Ullrich, T., Friedman, R., Mortensen, J., Pérez-Estaún, A., 2006. Magmatic relationships and ages of Caribbean Island arc tholeiites, boninites and related felsic rocks. *Dominic. Republ.: Lithos* 909, 61–186.
- Escuder-Viruet, J., Díaz de Neira, A., Hernaiz Huerta, P.P., García-Senz, J., Montheil, J., Joubert, M., Lopera, E., Ullrich, T., Friedman, R., Weis, D., Pérez-Estaún, A., 2007a. Implicaciones tectonomagmáticas y edad de las toleitas de arco-isla, boninitas y rocas ácidas relacionadas de la formación Los Ranchos, Cordillera Oriental. *Repúbl. Dominic.: Bol. Geol. Min.* 118, 195–220.
- Escuder-Viruet, J., Contreras, F., Joubert, M., Urien, P., Stein, G., Weis, D., Pérez-Estaún, A., 2007b. Tectónica y geoquímica de la Formación Amina: registro del arco-isla caribeño primitivo en la Cordillera Central. *Repúbl. Dominic.: Bol. Geol. Min.* 118, 221–242.
- Escuder-Viruet, J., Pérez-Estaún, A., Weis, D., Friedman, R., 2010. Geochemical characteristics of the Rio Verde complex, central Hispaniola: implications for the paleotectonic reconstruction of the lower Cretaceous Caribbean island-arc. *Lithos* 114, 168–185.
- García-Casco, A., Torres-Roldan, R.L., Iturralde-Vinent, M.A., Millan, G., Nunez Cambra, K., Lasaro, C., Rodriguez Vega, A., 2006. High pressure metamorphism of ophiolites in Cuba. *Geol. Acta* 4, 63–88.
- Geilert, S., Vroon, P.Z., Keller, N.S., Gudbrandsson, S., Stefansson, A., van Bergen, M.J., 2015. Silicon isotope fractionation during silica precipitation from hot spring waters: evidence from the Geysir geothermal field. *Iceland: Geochem. Cosmochim. Acta* 164, 403–427.
- Hannington, M.D., Poulsen, K.H., Thompson, J.F.H., Sillitoe, R.H., 1998. Volcanogenic gold in the massive sulfide environment. In: Barrie, C.T., Hannington, M.D. (Eds.), *Reviews in Economic Geology* 8, 319–350.
- Herzig, P.M., Hannington, M.D., Arribas Jr., A., 1998. Sulfur isotopic composition of hydrothermal precipitates from the Lau back-arc: implications for magmatic contributions to seafloor hydrothermal systems. *Miner. Deposita* 33, 226–237.
- Kesler, S.E., Galbraith, J.E., 1973. Los Cacaos Exploration Concession, Southern Sanchez Ramirez Province, Dominican Republic: 1:20,000 Scale Geologic Map Prepared for Rosario Resources Corporation.
- Kesler, S.E., Russell, N., Seaward, M., Rivera, J., McCurdy, K., Cumming, G.L., Sutter, J. F., 1981. Geology and geochemistry of sulfide mineralization underlying the Pueblo Viejo gold-silver oxide deposit. *Dominic. Republ.: Econ. Geol.* 76, 1096–1117.
- Kesler, S.E., Russell, N., Polanco, J., McCurdy, K., Cumming, G.L., 1991a. Geology and geochemistry of the early Cretaceous Los Ranchos Formation, central Dominican Republic. In: Mann, P., Draper, G., Lewis, J.F. (Eds.), *Geologic and Tectonic Development of the North American – Caribbean Plate Boundary in Hispaniola: Boulder, vol. 262. Geological Society of America Special Paper, Colorado*, pp. 187–201.
- Kesler, S.E., Russell, N., Reyes, C., Santos, L., Rodriguez, A., Fondeur, L., 1991b. Geology of the Maimón Formation, Dominican Republic. In: Mann, P., Draper, G., Lewis, J.F. (Eds.), *Geologic and Tectonic Development of the North American – Caribbean Plate Boundary in Hispaniola: Boulder, vol. 262. Geological Society of America Special Paper, Colorado*, pp. 173–187.
- Kesler, S.E., Campbell, I.H., Allen, C.M., 2005a. Age of the Los Ranchos Formation, Dominican Republic: Timing and tectonic setting of primitive island arc volcanism in the Caribbean region. *Geol. Soc. Am. Bull.* 117, 987–995.
- Kesler, S.E., Campbell, I.H., Smith, C.N., Hall, C.H., Allen, C.M., 2005b. Age of the Pueblo Viejo Gold-Silver Deposit and its significance to models for high sulfidation epithermal mineralization. *Econ. Geol.* 100, 253–272.
- Kirk, J.D., Ruiz, J., Kesler, S.E., Simon, A., Muntean, J.L., 2014. Re-Os age of the Pueblo Viejo epithermal deposit. *Dominic. Republ.: Econ. Geol.* 109, 503–512.
- Lewis, J.F., Amarante, A., Bloise, G., Jimenez, J., Dominguez, H.D., 1991. Lithology and stratigraphy of upper Cretaceous volcanic and volcanoclastic rocks of the Tireo Group, Dominican Republic, and correlations with the Massif du Nord in Haiti. In: Mann, P., Draper, G., Lewis, J.F. (Eds.), *Geologic and Tectonic Development of the North American-Caribbean Plate Boundary in Hispaniola: Boulder. Geological Society of America Special Paper 262, Colorado*, pp. 143–163.
- Lewis, J.F., Astacio, V.A., Espallat, J., Jimenez, J., 2000. The occurrence of volcanogenic massive sulfide deposits in the Maimón Formation, Dominican Republic: the Cerro de Maimón, Loma Pesada and Loma Barbutio deposits. In: Sherlock, R., Barsch, R., Logan, A. (Eds.), *VMS Deposits of Latin America*, vol. 2. Geological Society of Canada Special Publication, pp. 213–239.
- Lomas, S., 2005. Pueblo Viejo Project, Province of Sanchez Ramirez, Dominican Republic: NI 43-101 Technical Report and Qualified Person's Review Prepared for Placer Dome. Inc. by Amec Americas Ltd.
- Mann, P., Rogers, R.D., Gahagan, L., 2007. Overview of plate tectonic history and its unresolved tectonic problems. In: Bundschuh, J., Alvarado, G.E. (Eds.), *Central America: Geology, Resources and Hazards*, volume 1. Francis and Taylor Group, London, pp. 201–237.
- Martin, M., Canales, L., Ruiz, T., Lewis, J., Lopera, E., 2000. Memoria Geologica, Hoja: Hatillo (6172-I), escala 1:50,000: Programa de Desarrollo Geologico Minero (SYSMIN). In: *Convencion Lome IV*.
- Monecke, T., Petersen, S., Hannington, M.D., 2014. Constraints on water depth of massive sulfide formation: evidence from modern seafloor hydrothermal systems in arc-related settings. *Econ. Geol.* 109, 2079–2101.
- Mueller, A.G., Hall, G.C., Nemchin, A.A., O'Brien, D., 2008. Chronology of the Pueblo Viejo epithermal gold-silver deposit, Dominican Republic: formation in an Early Cretaceous intra-oceanic island arc and burial under ophiolite. *Miner. Deposita* 43, 873–890.
- Mullen, E.D., 1983. MnO/TiO₂/P2O₅: a minor element discriminant for basaltic rocks of oceanic environments and its implications for petrogenesis. *Earth Planet Sci. Lett.* 62, 53–62.
- Muntean, J.L., Kesler, S.E., Russell, N., Polanco, J., 1990. Evolution of the Monte Negro acid sulfate Au-Ag deposit, Pueblo Viejo, Dominican Republic: important factors in grade development. *Econ. Geol.* 85, 1738–1758.
- Myczynski, R., Iturralde, M., 2005. The Late Lower Albian invertebrate fauna of the Rio Hatillo formation of Pueblo Viejo, Dominican Republic. *Caribb. J. Sci.* 41, 782–796.
- Nelson, C.E., 2000a. Volcanic domes and gold mineralization in the Pueblo Viejo district, Dominican Republic. *Miner. Deposita* 35, 511–525.
- Nelson, C.E., 2000b. Volcanic dome emplacement and Au-Ag-Zn mineralization at the Moore deposit, Pueblo Viejo district, Dominican Republic, 2000b. In: Cluer, J.K., Price, J.G., Struhsacker, E.M., Hardyman, R.F., Morris, C.L. (Eds.), *Geology and Ore Deposits 2000: the Great Basin and beyond. Geological Society of Nevada Symposium Proceedings*, pp. 67–77.
- Nelson, C.E., Proenza, J.A., Lewis, J.F., Lopez-Kramer, J., 2011. The metallogenic evolution of the Greater Antilles. *Geol. Acta* 9, 229–264.
- Nelson, C.E., Stein, H.J., Dominguez, H., Carrasco, C., Barrie, T., Torró, L., Proenza, J., 2015. Re-Os dating of molybdenite from the Pueblo Viejo Au-Ag-Cu and Douvray Cu-Au districts. *Hispaniola: Econ. Geol.* 110, 1101–1110.
- Nelson, C.E., Polanco, J., Macassi, A., Dominguez, H., Proenza, J., Torró, L., Rhys, D., Iturralde-Vinent, M., 2020. The Hatillo limestone, Pueblo Viejo district, Dominican Republic: marginal reef or impermeable cap? *Bol. Soc. Geol. Mex.* 72, A011119. <https://doi.org/10.18268/BSGM2020v72n3a011119>.
- Pearce, J.A., Cann, J.R., 1973. Tectonic setting of basic volcanic rocks determined using trace element analysis. *Earth Planet Sci. Lett.* 19, 290–300.
- Pindell, J., Keenan, L., Maresch, W.V., Stanek, K.P., Draper, G., Higgs, R., 2005. Plate-tectonics and crustal dynamics of circum-Caribbean arc-continent interactions: tectonic controls on basin development in Proto-Caribbean margins. In: Avé Lallemant, H.G., Sisson, V.B. (Eds.), *Caribbean-South American Plate Interactions*, vol. 394. Geological Society of America Special Paper, Venezuela, pp. 7–52.
- Pindell, J., Maresch, W.V., Martens, U., Stanek, K., 2011. The Greater Antillean Arc: early Cretaceous origin and proposed relationship to Central American subduction

- mélanges: implications for models of Caribbean evolution. *Int. Geol. Rev.* <https://doi.org/10.1080/00206814.2010.510008>.
- Rojas-Agramonte, Y., Hu, H.Y., Iturralde-Vinent, M., Lewis, J., Mercier de Lepinay, B., García-Casco, A., 2021. A Late Cretaceous adakitic intrusion from Northern Haiti: additional evidence for slab melting and implications for migration of ridge-trench-trench triple junction during the Cretaceous in the Greater Antilles. *Int. Geol. Rev.* <https://doi.org/10.1080/00206814.2021.1998800>.
- Rollinson, H., 1993. *Using Geochemical Data: Evaluation, Presentation, Interpretation*. Longman Scientific and Technical, Longman Group UK Ltd.
- Russell, N., Kesler, S.E., 1991. Geology of the maar-diatreme complex hosting precious metal mineralization at Pueblo Viejo, Dominican Republic. In: Mann, P., Draper, G., Lewis, J.F. (Eds.), *Geologic and Tectonic Development of the North America – Caribbean Plate Boundary in Hispaniola*: Boulder, vol. 262. Geological Society of America Special Paper, Colorado, pp. 203–214.
- Sillitoe, R.H., Hannington, M.D., Thompson, J.F.H., 1996. High sulfidation deposits in the volcanogenic massive sulfide environment. *Econ. Geol.* 91, 204–212.
- Sillitoe, R.H., Hall, D.J., Redwood, S.D., Waddell, A.H., 2006. Pueblo Viejo high-sulfidation epithermal gold-silver deposit, Dominican Republic: a new model of formation beneath barren limestone cover. *Econ. Geol.* 101, 1427–1434.
- Smiley, C.J., 2002. Lower Cretaceous plants from Dominican Republic. In: Jackson, T.A. (Ed.), *Caribbean Geology, into the Third Millennium: Transactions of the Fifteenth Caribbean Geological Conference*. University of the West Indies Press, pp. 119–130.
- Smith, H.A., Stephenson, P.R., Butcher, M.G., Carr, C.A., 2008. Pueblo Viejo Gold Project, Dominican Republic: NI 43-101 Technical Report Prepared by. AMC Consultants for GoldCorp, Inc., May 1, 2008.
- Torró, L., Proenza, J.A., Melgarejo, J.C., Alfonso, P., Farré de Pablo, J., Colomer, J.M., García-Casco, A., Gubern, A., Gallardo, E., Cazañas, X., Chávez, C., Del Carpio, R., León, P., Nelson, C.E., Lewis, 2016. Mineralogy, geochemistry and sulfur isotope characterization of Cerro de Maimón (Dominican Republic), San Fernando and Antonio (Cuba) lower Cretaceous VMS deposits: formation during subduction initiation of the proto-Caribbean lithosphere within a fore-arc. *Ore Geol. Rev.* 72, 794–817.
- Torró, L., Proenza, J.A., Camprubí, A., Nelson, C.E., Dominguez, H., Carrasco, C., Reynoso-Villafañe, R., Melgarejo, J.C., 2017a. Towards a unified genetic model for the Au-Ag-Cu Pueblo Viejo District, central Dominican Republic. *Ore Geol. Rev.* 89, 463–494.
- Torró, L., Camprubí, A., Proenza, J.A., Leon, P., Stein, H.J., Lewis, J.F., Nelson, C.E., Chavez, C., Melgarejo, J.C., 2017b. Re-Os and U-Pb geochronology of the Dona Amanda and Cerro Kiosko deposits, Bayaguana district, Dominican Republic: looking down for the porphyry Cu-Mo roots of the Pueblo Viejo-type mineralization in the island-arc tholeiitic series of the Caribbean. *Econ. Geol.* 112, 829–853.
- Torró, L., Proenza, J.A., Marchesi, C., García-Casco, A., Lewis, J.F., 2017c. Petrogenesis of meta-volcanic rocks from the Maimón Formation (Dominican Republic): geochemical record of the nascent Greater Antilles paleo-arc. *Lithos* 278–281, 255–273.
- Torró, L., Proenza, J.A., Rojas-Agramonte, Y., García-Casco, A., Yang, J.-H., Yang, Y.-H., 2018. Recycling in the subduction factory: Archean to Permian zircons in the oceanic Cretaceous Caribbean island-arc (Hispaniola). *Gondwana Res.* 54, 23–37.
- Vaughan, J., Nelson, C.E., Polanco, J., García, V., Macassi, A., Garrido, G., 2020. The Pueblo Viejo Au-Ag-Cu-(Zn) deposit, Dominican Republic. In: Sillitoe, R.H., Goldfarb, R.J., Robert, F., Simmons, S.F. (Eds.), *Geology of the World's Major Gold Deposits and Provinces*, vol. 23. Society of Economic Geologists Special Publication, pp. 415–430.
- Williams, H., 1932. *The History and Characters of Volcanic Domes*, vol. 31. University of California Publications in Geological Sciences, pp. 51–146.
- Williams, I.S., 1998. U-Th-Pb geochronology by ion microprobe. In: Mckibben, M.A., Shanks III, W.C., Ridley, W.I. (Eds.), *Applications of Microanalytical Techniques to Understanding Mineralizing Processes: Reviews in Economic Geology* 7, 1–35.
- Zoppis de Sena, 1968. El depósito aurífero de pirita y blenda “Pueblo Viejo” en la Provincia Sanchez Ramirez, Republica Dominicana: prepared for Mineraleas Industriales, C. por A., Santo Domingo, República Dominicana.