Volcanic Dome Emplacement and Au-Ag-Zn Mineralization at the Moore Deposit, Pueblo Viejo District, Dominican Republic

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ABSTRACT

A total of 5.3 million ounces of gold and 24.4 million ounces of silver has been recovered from five open pits in the Pueblo Viejo district since mining commenced in 1975. Although oxide ore has been largely mined out, an underlying sulfide resource contains an additional 35 million ounces of gold, 203 million ounces of silver, 3 million tonnes of zinc, and 0.4 million tonnes of copper. Much of this resource (14 million ounces) is located in the Moore deposit, the largest of the sulfide gold ore deposits in the Pueblo Viejo district.

Gold, silver and zinc mineralization throughout the Pueblo Viejo district is spatially and temporally related to previously unrecognized Early Cretaceous volcanic domes that vary from basaltic andesite to dacite in composition. In the Moore deposit, gold mineralization surrounds a dacite porphyry volcanic dome and vent breccia. The dome's intrusive origin is indicated by tilting of flat-lying epiclastic carbonaceous sedimentary rocks adjacent to the dome margin, by the presence of crosscutting contacts between the dacite porphyry and surrounding sedimentary rocks, and, most importantly, by the presence of a baked contact metamorphic aureole adjacent to the dome margin. Steeply dipping reverse faults formed along the dome margin as the dacite porphyry shouldered its way through surrounding sedimentary rocks.

A genetic link between dome emplacement and gold mineralization is indicated by their spatial association and by evidence for coeval dome emplacement and hydrothermal alteration. Gold was likely derived by hydrothermal leaching of the accumulating volcanic pile and/or by condensation of volcanic gas.

INTRODUCTION

The geology of the Pueblo Viejo district has been described in a series of papers including Kesler et al. (1981); Cumming et al. (1982); Muntean et al. (1990); Kesler et al. (1991); Russell and Kesler (1991); Kettler et al. (1992); Vennemann et al. (1993). Mann et al.(1991) assemble pertinent regional studies. Readers are referred to these papers for a description of local and regional geology, for a description of hydrothermal alteration assemblages, and for isotope studies that bear on the origin of hydrothermal fluids.

This paper focuses on the Moore deposit, where geologic mapping by the author has identified an intrusive dacite porphyry dome and marginal hydrovolcanic vent breccia. The Moore dacite porphyry is one of a series of previously unrecognized volcanic domes in the Pueblo Viejo district.

PAST PRODUCTION AND CURRENT RESOURCE

Mining at Pueblo Viejo mine began in 1975 and continued almost continuously until 1999, when falling recovery related to depletion of the oxide reserve resulted in closure of the mine and carbon-in-leach (CIL) mill. Ruiz (1997) reports total production through 1996 of 5,335,918 ounces gold and 24,422,758 ounces silver.

Table 1 provides information on the size of the remainingsulfide gold resource at a number of cutoff grades. In spite of acknowledged difficulties with gold recovery, the sulfide resource is impressive. After more than twenty years of mining, Pueblo Viejo still contains close to 35 million ounces (1000 tonnes) at a cutoff grade of 1.0 g/t. Much of this resource (14.5 million ounces) is in the Moore deposit.

Metallurgical challenges presented by the sulfide gold resource include sulfide encapsulation, silica encapsulation, carbon competition, overall high arsenic content, and local high copper and zinc. Most of the gold in the Moore deposit occurs as electrum along growth zones in vein pyrite (Kesler et al., 1985; Muntean et al., 1990). Gold also occurs as inclusions of native gold and calaverite in disseminated pyrite (Muntean et al., 1990; Kettler et al., 1992). Sulfide sulfur content averages between eight and ten percent.

DISTRICT GEOLOGY

The Pueblo Viejo district occurs within the Los Ranchos Formation (Fig. 1), part of an Early Cretaceous intraoceanic island arc. Host rocks include basaltic andesite, andesite and dacite (Table 2). These rock units were spilitized by their interaction with seawater and were hydrothermally altered during gold mineralization. Figure 1 also shows the location of surrounding base and precious metal prospects.

Ore deposits in the Pueblo Viejo district are spatially associated with a series of volcanic domes (Nelson, in press). These domes are shown on Figure 2 and extend well outside of the map area. Gold prospects elsewhere in the Los Ranchos Formation (e.g. Managua, Guaimarote) are also associated with volcanic domes.

Northwest-striking thrust faults are common in the Moore deposit and throughout the Pueblo Viejo district (Figs. 1 and 2). Both volcanic and sedimentary rocks exhibit penetrative cleavage and are locally recrystallized to phyllite. Bowin (1966) proposed that metamorphism occurred during the Eocene. Draper et al. (1996) argue that metamorphic recrystallization and cleavage development was a Cretaceous event but that related thrust faults were reactivated during the Tertiary. Metamorphism occurred during Aptian-Albian abduction of oceanic crust when a northwest-facing arc replaced an Early Cretaceous southwest-facing arc.

TABLE 1. Pueblo Viejo District Sulfide Resource*.

Deposit size in millions of tonnes of ore	Average gold grade in grams per tonne	Average silver grade in grams per tonne	Contained gold in tonnes and (millions of troy ounces)	Cutoff grade in grams of gold per tonne
544.34	1.98	11.76	1078 (34.65)	1.0
321.42	2.50	14.47	80 (25.83)	1.5
188.92	3.06	17.63	578 (18.59)	2.0
69.81	4.17	25.13	29 (9.36)	3.0
28.30	5.29	33.98	150 (4.81)	4.0
12.99	6.31	41.94	82 (2.63)	5.0

*condensed from Ruiz (1997)

DACITE PORPHYRY DOME AND VENT BRECCIA

Geologic mapping by the author (Figs. 2 and 3) in the Pueblo Viejo district shows a dacite porphyry dome intruding epiclastic carbonaceous sedimentary rocks, host to the Moore gold deposit. This interpretation contrasts with previously published descriptions, all of which infer a pyroclastic origin for the dacite porphyry. Kesler et al. (1981) described this unit as quartz porphyry agglomerate. Muntean et al. (1990) and Russell and Kesler (1991) described this unit as a lapilli tuff.

The contact between dacite porphyry and surrounding carbonaceous siltstone is shown in Figure 4A and 4B. These figures show a baked contact metamorphic aureole surrounding the dacite porphyry and a steeply crosscutting contact with the host rocks. Both observations are incompatible with a pyroclastic origin. Gold mineralization mantles the northern margin of the dome (the southern margin is not exposed). The dome itself is mineralized only along its margin (Fig. 3).

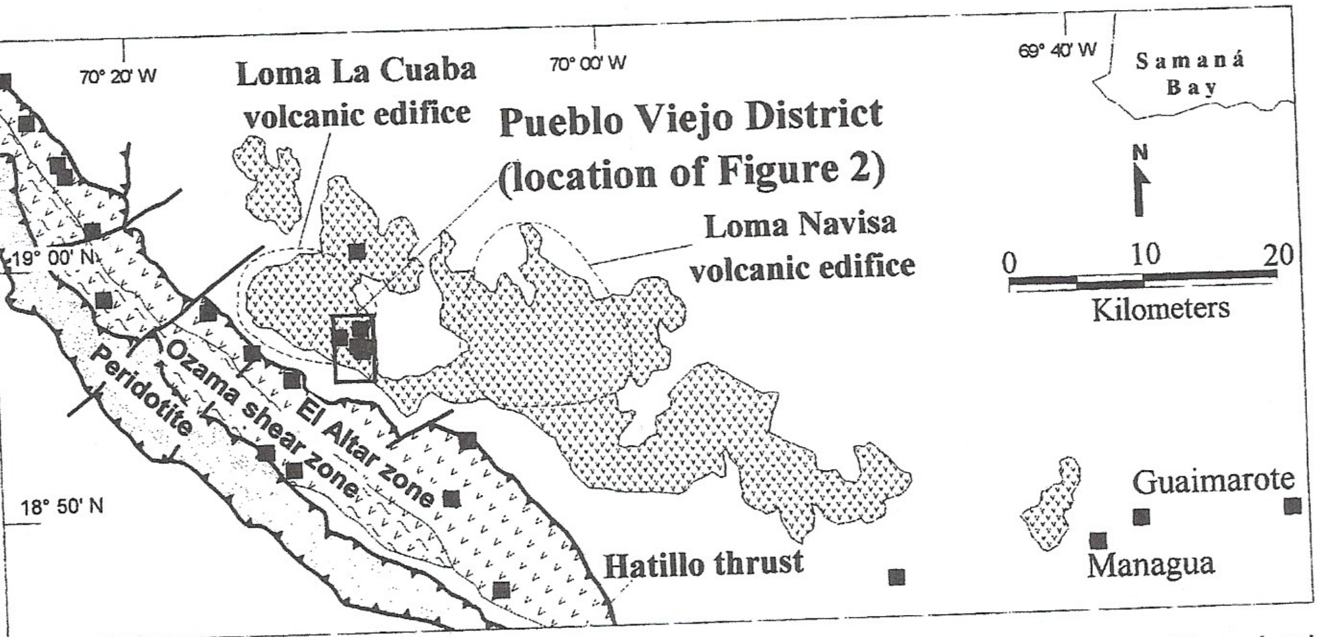
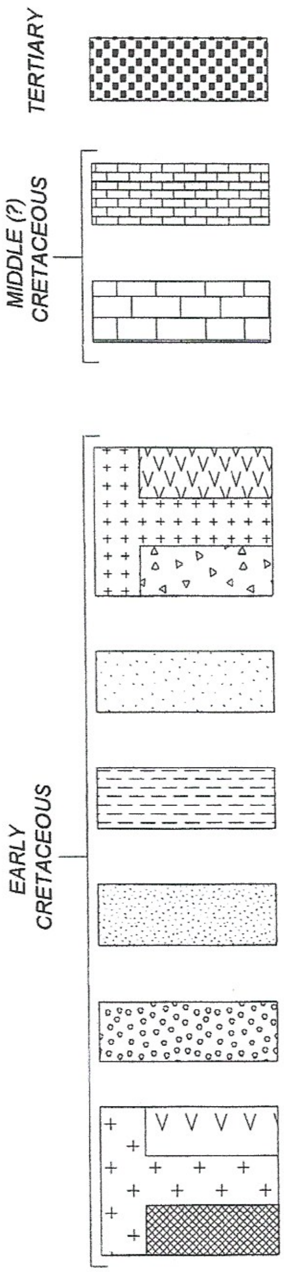


FIGURE 1. Location map of the Pueblo Viejo district and nearby base and precious metal prospects. The regional distribution of the Los Ranchos Formation is from Mann et al. (1991). The Ozama shear zone, the El Altar zone and bounding thrust faults are from Draper et al. (1996). The thrust-faulted southwestern boundary of the peridotite is from Toloczyki and Ramirez (1991).

TABLE 2. Stratigraphic section for the Pueblo Viejo District.

PUEBLO VIEJO STRATIGRAPHY



Fine-grained, unaltered diorite dikes and plugs.

Las Lagunas Formation
Thin to medium bedded calcareous shales and phyllites with interbedded limestone layers.

Hatillo Formation
Massively bedded reef limestones.

Los Ranchos Formation
Dacite dome and pyroclastic apron. Includes:

- massively-bedded lapilli tuff breccia with hydrothermally altered lithic fragments and quartz eyes (v pattern).
- massive dacite porphyry dome with quartz phenocrysts (+ pattern).
- matrix-supported dacite vent breccia (triangle pattern).

Medium-bedded (5-50cm) epiclastic carbonaceous sandstones with interbedded carbonaceous siltstones. Conglomeratic adjacent to domes.

Thinly-bedded (.5-5cm) epiclastic carbonaceous siltstones with interbedded carbonaceous sandstone. Coarser-grained adjacent to domes.

Epiclastic lapilli tuff breccias with interbedded carbonaceous sediments. Grades laterally into carbonaceous sandstone.

Coarsely-fragmental epiclastic crumble breccia containing abundant unsorted andesite clasts and lesser epiclastic sedimentary clasts. Occurs within and adjacent to exogenous basaltic andesite domes.

Andesite flows, domes, and pyroclastic aprons. Includes:

- massively-bedded lapilli tuff breccia with abundant mafic to intermediate fragments and no quartz eyes (v pattern).
- massive, crowded-feldspar porphyry domes and flows (+ pattern).
- steeply-dipping andesite dikes (shaded).

Reverse faults wrap around the dome's well-exposed northern margin and dip steeply towards the dome. Carbonaceous siltstones dip steeply away from the dome margin suggesting that surrounding rock units were tilted as the dacite porphyry dome shouldered its way through the epiclastic section. Xenoliths of carbonaceous siltstone can be observed within the dacite porphyry, especially near its contact with surrounding sedimentary rocks.

Quartz eyes are a distinctive characteristic of the dacite porphyry. The presence of bipyramidal outlines and resorbed borders indicate that most of the quartz eyes are phenocrysts. Although the dacite porphyry is generally massive and homogeneous, local flow banding and spherulitic devitrification occur. Figures 4C and 4D provide photos of the flow-banded dacite porphyry and marginal dacite porphyry vent breccia.

The margin of the dacite porphyry dome is marked by an unsorted, unbedded breccia that contains abundant lapilli-size fragments of dacite porphyry, andesite, and epiclastic carbonaceous siltstone. Hydrothermally altered fragments and quartz eyes are common. The breccia is irregularly exposed

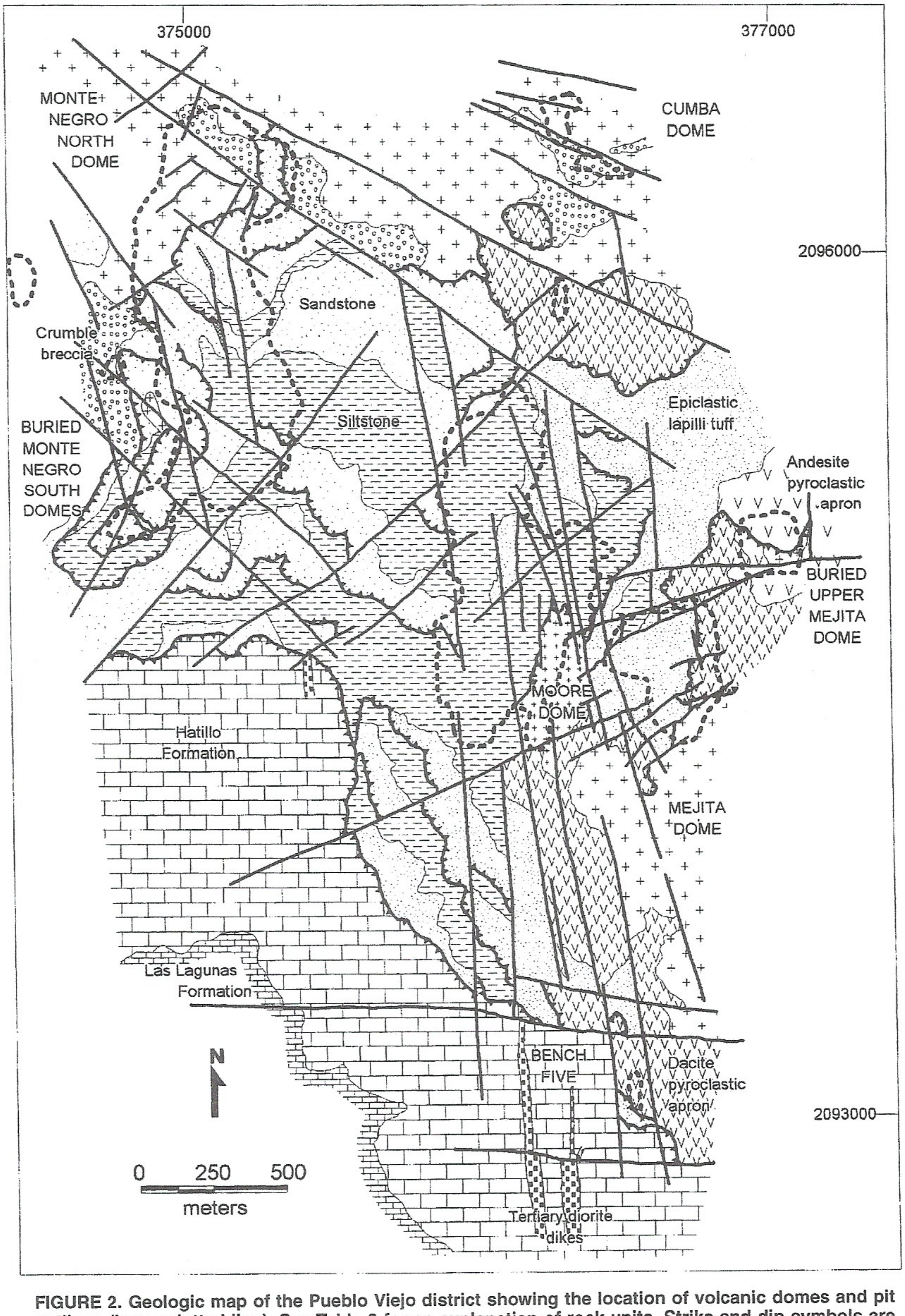


FIGURE 2. Geologic map of the Pueblo Viejo district showing the location of volcanic domes and pit outlines (heavy dotted line). See Table 2 for an explanation of rock units. Strike and dip symbols are omitted for clarity; sedimentary units are subhorizontal. See Figure 3 for a detailed geologic map of the Moore deposit.

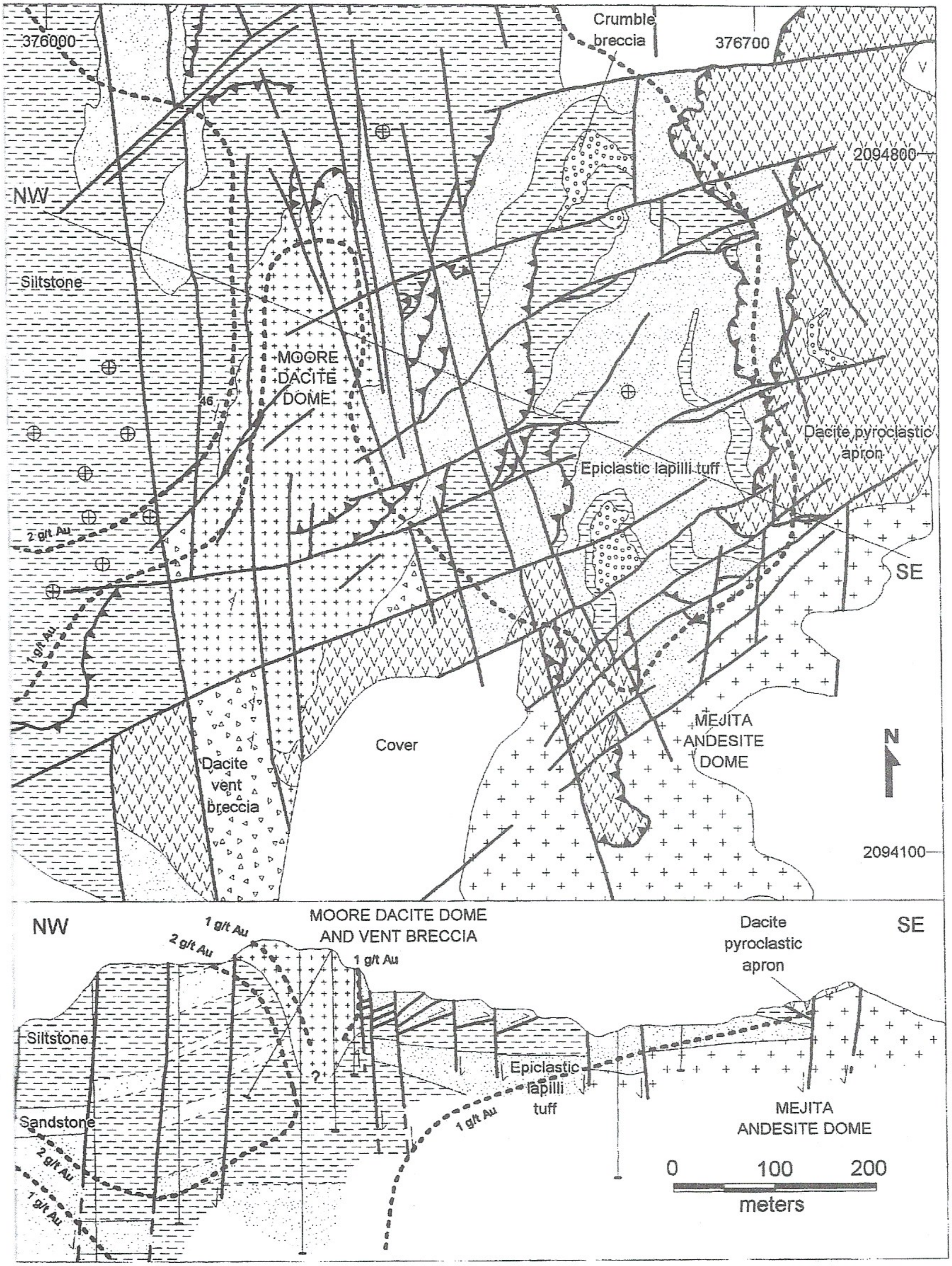


FIGURE 3. Geologic map and cross section of the Moore deposit, Pueblo Viejo district. There is no vertical exaggeration. Rock units too thin to be shown clearly on the section are omitted. Drill hole locations are plotted on the section. Grade contours are shown as heavy dotted lines.

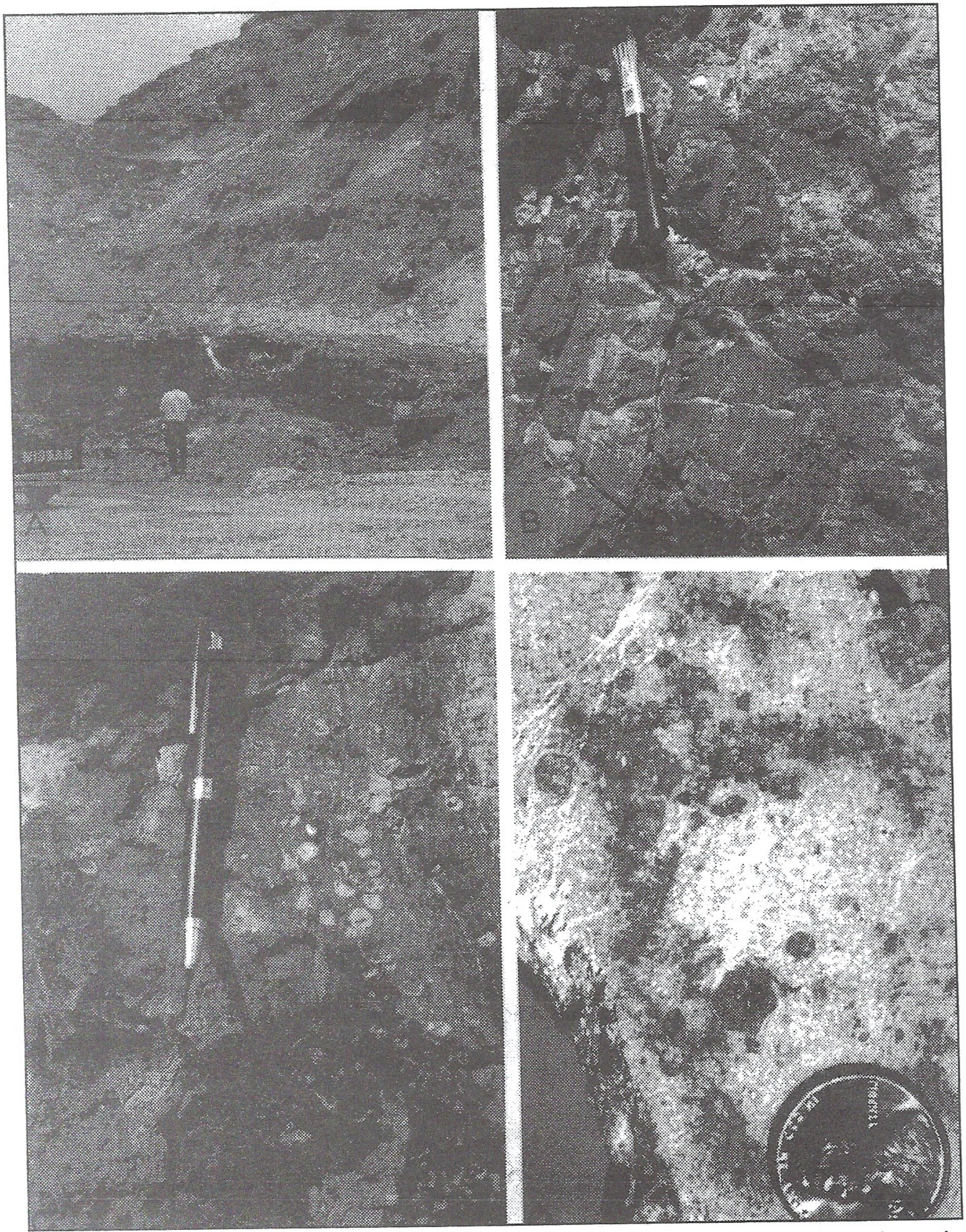


FIGURE 4. Dacite porphyry dome and its contact with surrounding epiclastic sedimentary rocks. A. Dacite porphyry dome (right) and baked contact (center right) in carbonaceous siltstone (left). B. Close-up photo showing a crosscutting contact between dacite porphyry (upper right) and baked carbonaceous sedimentary rocks (lower left). C. Flow-banding and spherulitic devitrification of the dacite porphyry. D. Dacite porphyry vent breccia with hydrothermally altered rock fragments and quartz eyes.

around the margin of the dacite porphyry dome and is interpreted here as a hydrovolcanic vent breccia. A pyroclastic apron, consisting of bedded lithic lapilli tuff breccia of dacite porphyry composition, is exposed at the top of the Mejita pit, 300 meters east of the Moore dacite porphyry.

Inclined core holes drilled in 1997 reveal a funnel-shaped contact (Fig. 3) with surrounding epiclastic carbonaceous sedimentary rocks, consistent with dacite porphyry intrusion. Elsewhere, the contact between dacite porphyry and carbonaceous siltstone is nearly horizontal (Kesler et al., 1981). There has also been offset of the dome by shallow dipping thrust faults (Figs. 2 and 3) which adds to the difficulty in identifying the still-controversial roots to this dome.

EPICLASTIC CARBONACEOUS SEDIMENTARY ROCKS

Thinly bedded, epiclastic, carbonaceous siltstones and sandstones surround the dacite porphyry dome in the Moore deposit. Bedding, clearly visible away from the intrusive contact, is obscured in the baked zone where siltstones exhibit a hardened, pale brown appearance (Figs. 4A, 4B). Carbonaceous sedimentary rocks are recrystallized but not silicified along the intrusive margin, resulting in a lighter color that is easily confused with the dacite porphyry.

Epiclastic carbonaceous sedimentary rocks near the dacite porphyry dome contain detrital quartz eyes and lenticular debris flows of dacite porphyry. Detrital quartz eyes can be found in the epiclastic section up to 200 meters from the dome margin. These observations are not inconsistent with dacite porphyry intrusion. Early phases of the dacite porphyry dome must have been exposed to erosion while epiclastic carbonaceous sediments accumulated and dacite porphyry intrusion continued. Hydrothermal alteration was also ongoing at the time, as indicated by the presence of altered and mineralized clasts in both the dacite porphyry vent breccia and the epiclastic sedimentary section.

Epiclastic carbonaceous sediments in the Moore deposit contain terrestrial plant fossils and exhibit well-developed soft sediment deformation and dewatering structures (Fig. 5). Sedimentary dikes and diapirs are common. These features indicate that the environment of deposition was subaqueous and that water depths were shallow. Pyroclastic "bombs" (Fig. 5B) provide evidence for nearby explosive volcanic activity during sedimentation. Given the evidence cited above, volcanic dome emplacement, epiclastic sedimentation, hydrothermal alteration, and gold mineralization must have been coeval events and must have occurred in a shallow subaqueous setting.

GOLD DEPOSITION

Gold mineralization in the Moore deposit (Fig. 6A) follows north-south striking normal faults that offset both the epiclastic sedimentary section and the margin of the dacite porphyry dome. Thick envelopes (as much as 30 m across) of gold-bearing disseminated sulfide minerals surround the high-angle feeder faults. Veins contain quartz, pyrite and variable amounts of sphalerite, galena and enargite (Fig. 6B, 6C). Gold is present as native gold, electrum and as calaverite (gold telluride).

Gold mineralization is associated with widespread secondary quartz and pyrophyllite alteration, an advanced argillic assemblage according to Corbett and Leach (1998). Muntean et al. (1990) report that hydrothermal fluid temperatures locally exceeded 285° C based on equilibria between pyrophyllite and coexisting diaspore. These temperatures are consistent with those reported by Vennemann et al. (1993) based on sulfur isotope geothermometry (over 250°C). Fluid-inclusion temperatures reported by Kesler et al. (1981) range from 135° to 195°C.

Sulfur isotopic studies have drifted with time away from a marine origin (Kesler et al., 1981) towards a magmatic origin (Vennemann et al., 1993). Kesler et al. (1981) suggest that base and precious metals were leached from the Los Ranchos Formation by circulating hydrothermal fluids. Vennemann et al. (1993) suggest that gold in the Pueblo Viejo district was introduced during bulk condensation of magmatic vapor. The two interpretations are not mutually exclusive. Circulating hydrothermal fluids could have leached gold from the glassy portion of an accumulating volcanic pile. Condensation of volcanic gas may have also provided gold to solution.

Massive sulfide layers are present within the epiclastic carbonaceous sedimentary section along the northern margin of the dacite porphyry dome (Fig. 6D). These layers contain mineralized clasts suggesting that they represent subaqueous sedimentary accumulations rather than replacements.

CONCLUSIONS

Geologic mapping at the Moore deposit in the Pueblo Viejo district indicates that gold mineralization was an Early Cretaceous event, coeval with the emplacement of a dacite porphyry volcanic dome and marginal vent breccia. Nelson (in press) reports a series of similar domes of andesitic composition from the nearby Monte Negro deposit (Fig. 2). This geologic setting is inconsistent with the maar basin proposed by Sillitoe and Bonham (1984) and adopted by Russell and Kesler (1991). Instead, domes and associated pyroclastic aprons describe a series of separate volcanic centers, which overlap one another and are surrounded by and interbedded with epiclastic sediments. The contrasting models are compared in Figure 7.

The coeval character of hydrovolcanism, hydrothermal alteration and gold mineralization is undoubtably related to the evolution of Pueblo Viejo as a world class deposit. Neither the composition of the domes (basaltic andesite to dacite) nor the proposed source of the gold (hydrothermal fluid circulation, leaching, and bulk condensation of magmatic vapor) is especially unique. The volcanic dome field at

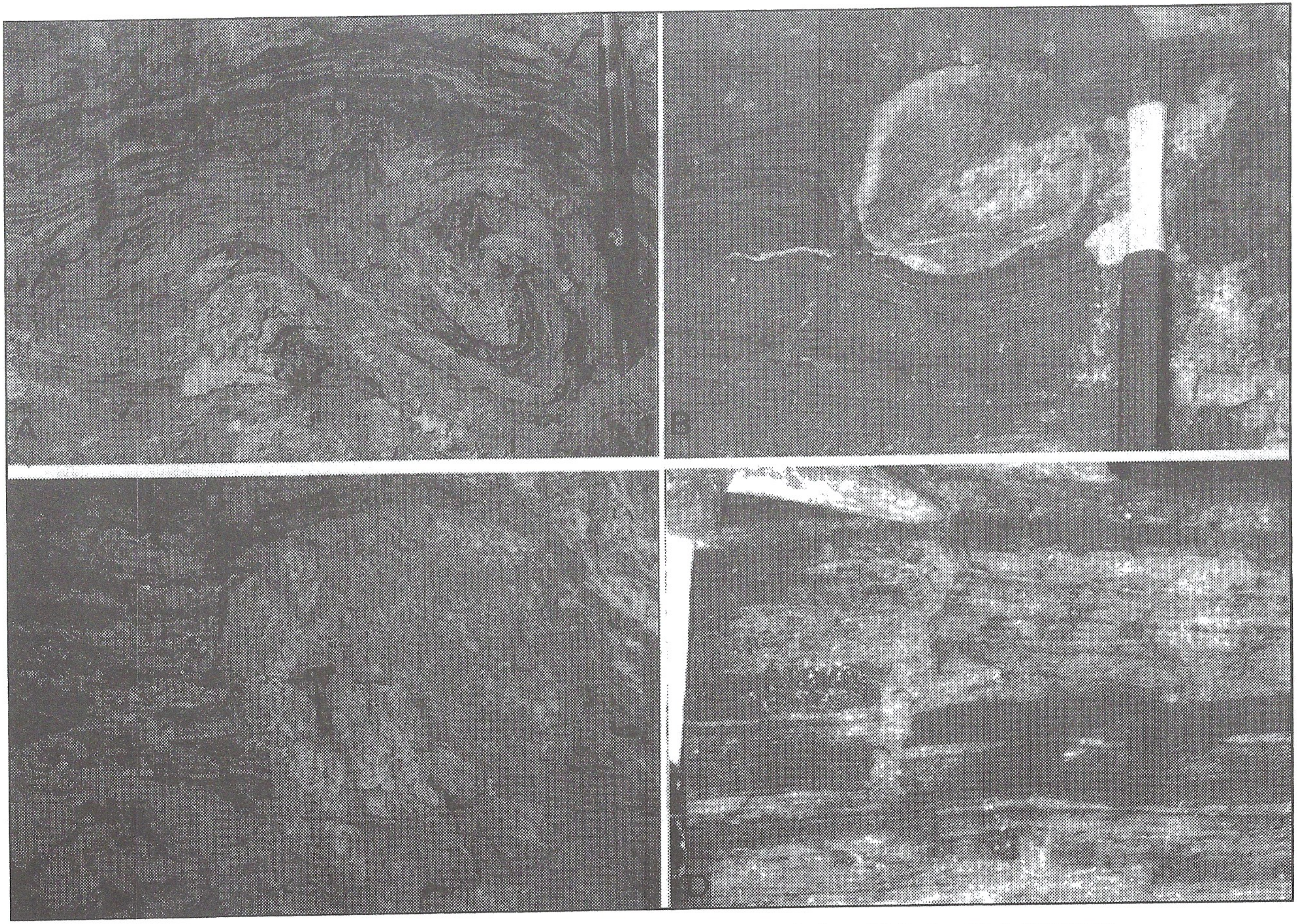


FIGURE 5. Structure in epiclastic carbonaceous siltstone from the Moore and adjacent Mejita deposits. A. Slump folds. B. Pyroclastic bomb from a nearby volcanic dome. C. Diapir of epiclastic lithic lapilli tuff. D. Sedimentary dike.

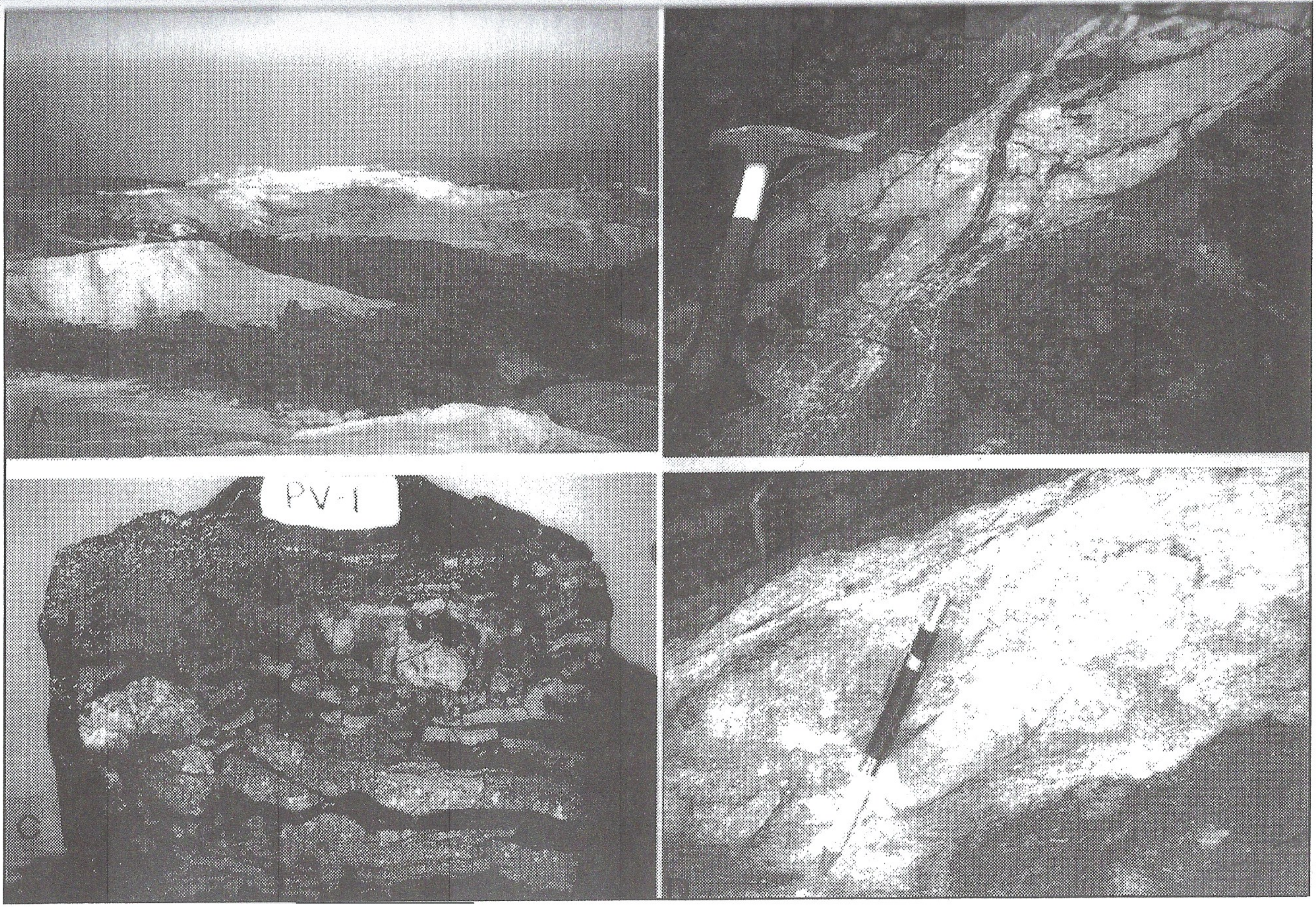


FIGURE 6. Gold mineralization at the Moore deposit. A. View southeast across the Moore deposit from the adjacent Monte Negro deposit. B. Typical, sulfide-rich, gold vein cutting carbonaceous siltstones. C. Close up photo of sulfidic gold vein. D. Massive sulfide layer interbedded with carbonaceous siltstones.

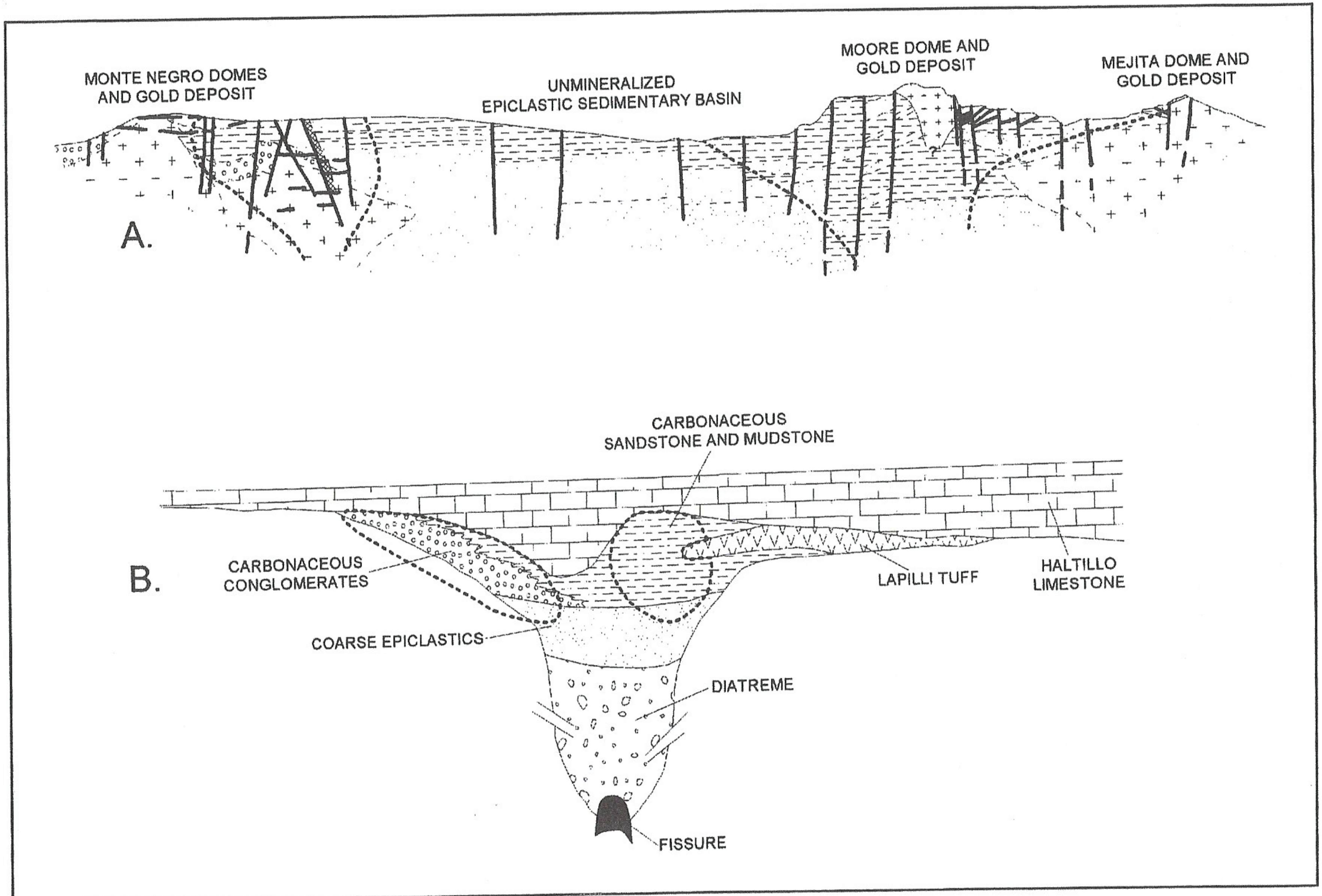


FIGURE 7. Contrasting geologic models for the Pueblo Viejo district. A. Schematic cross section looking north and showing volcanic domes (this paper). B. Schematic maar-diatreme model from Russell and Kesler (1991, Fig. 5C). Ore deposits are shown as heavy dotted lines.

Pueblo Viejo and a regional magnetic high beneath the adjacent Loma La Cuaba volcanic edifice provides strong evidence for an underlying magma chamber. However, there is as yet no evidence for an underlying porphyry copper deposit.

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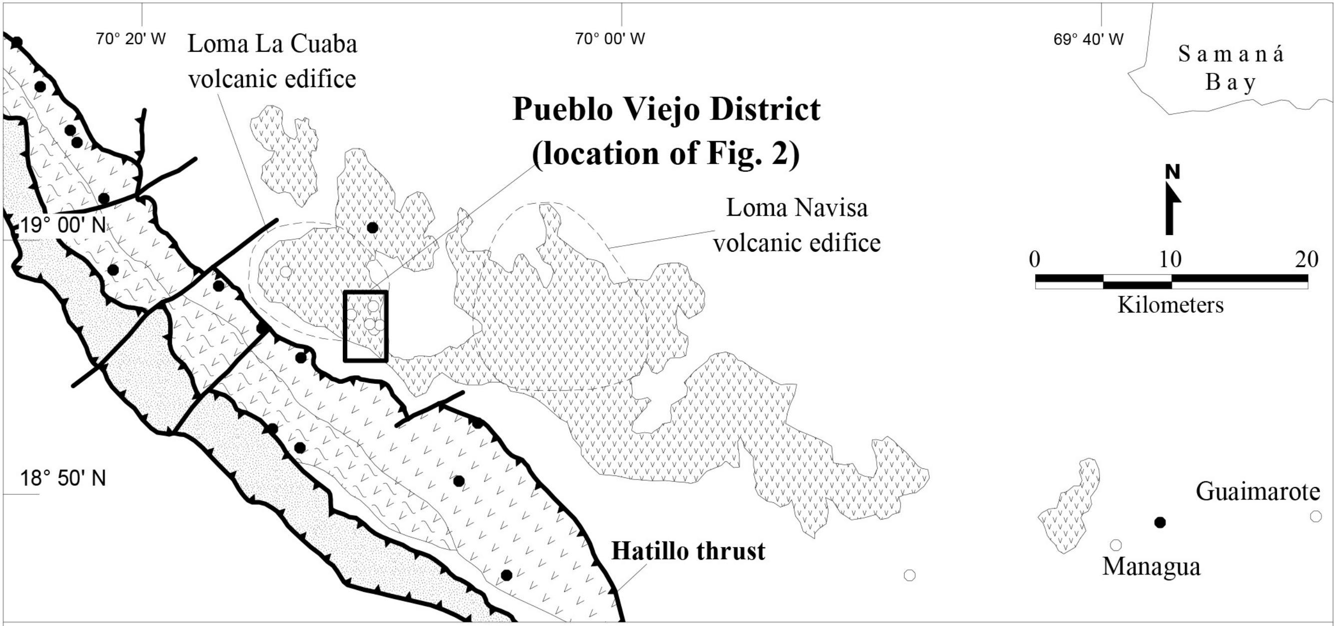
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70° 00' W
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volcanic edifice
Pueblo Viejo District
(location of Fig. 2)
Samaná
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Loma Navisa
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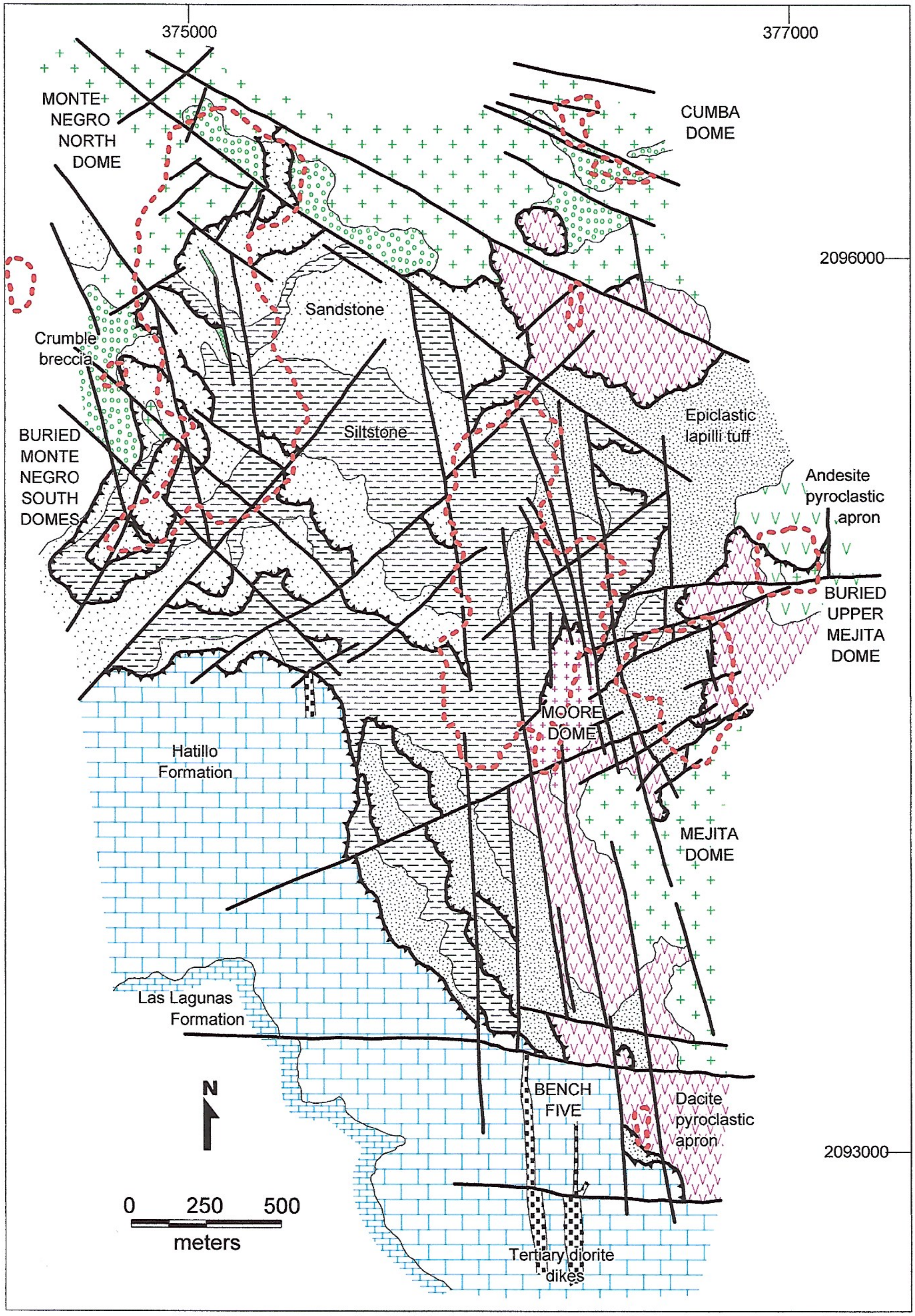
Managua
Hatillo thrust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MONTE NEGRO NORTH DOME
CUMBA DOME
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Siltstone
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BURIED MONTE NEGRO SOUTH DOMES
Andesite pyroclastic apron
BURIED UPPER MEJITA DOME
MOORE DOME
Hatillo Formation
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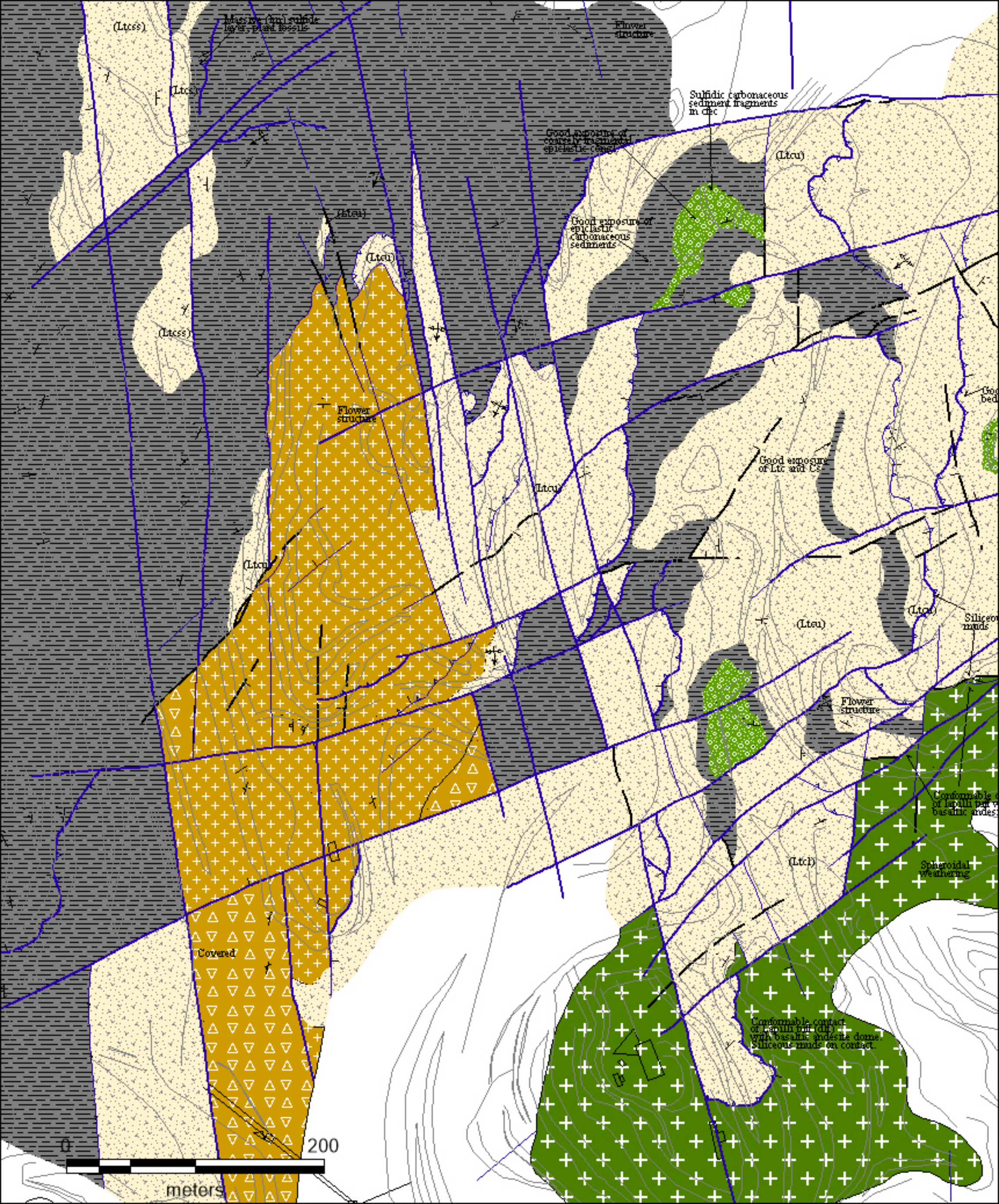

(Ltcss)
Flower structure
(Ltcss)
Sulfidic carbonaceous sediment fragments in clec
Good exposure of coarsely fragmental epiclastic congl.
(Ltcu)
(Ltcu)
Good exposure of epiclastic carbonaceous sediments
(Ltcu)
(Ltcss)
Flower structure
Good exposure of Ltc and Cs
(Ltcu)
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Flower structure
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Conformable contact of Lapilli tuff (dlt) with basaltic andesite dome. Siliceous muds on contact.
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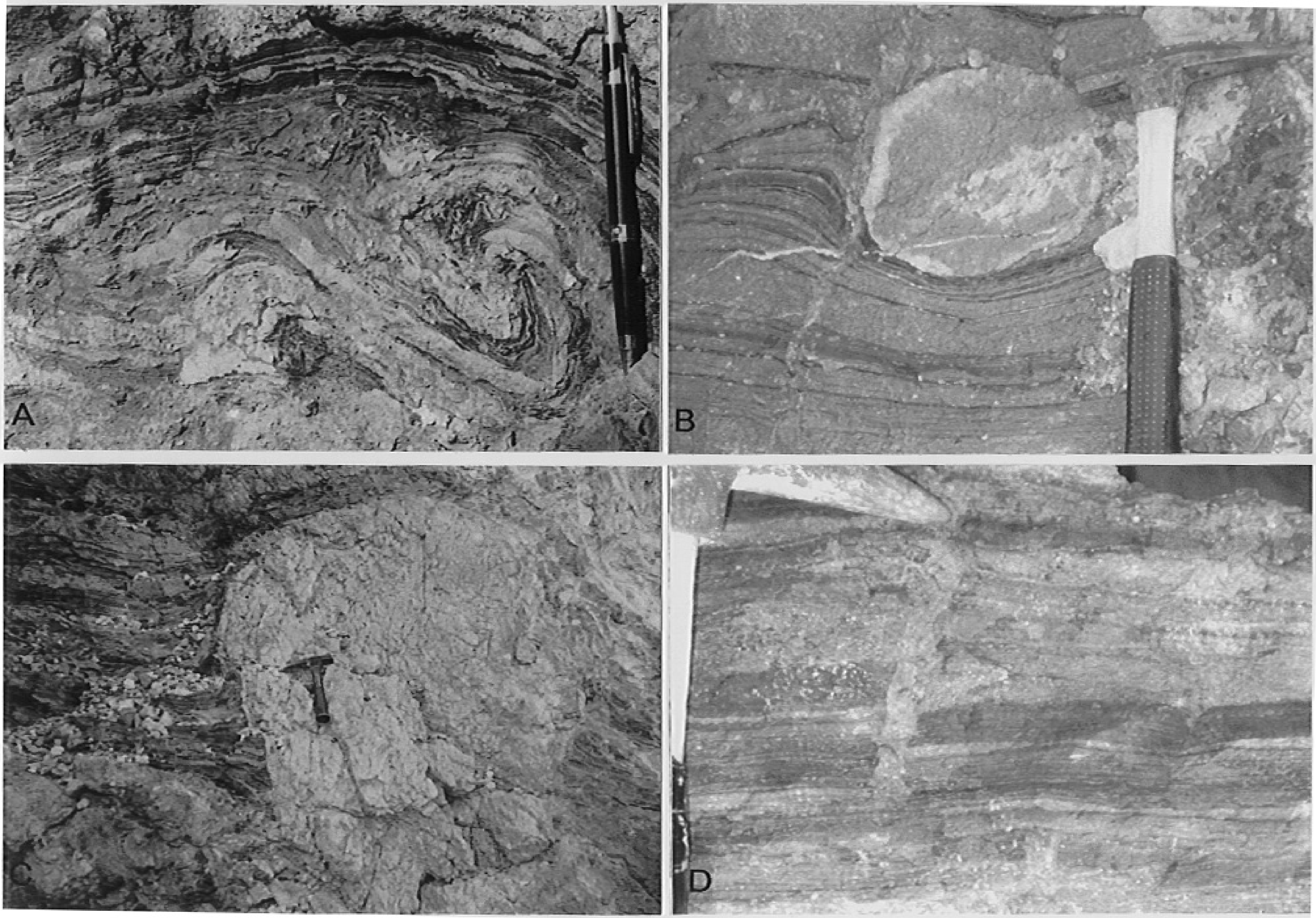
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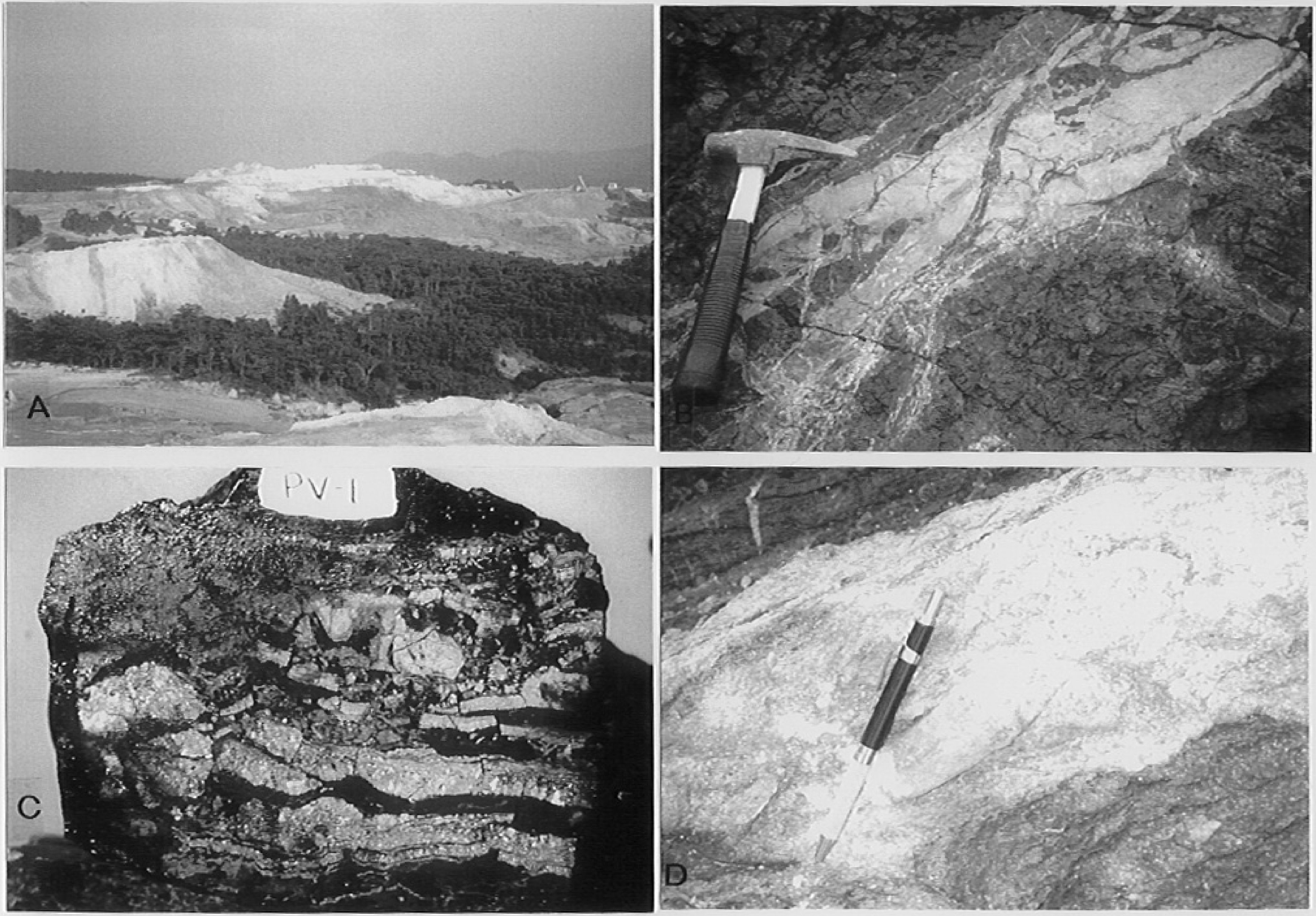
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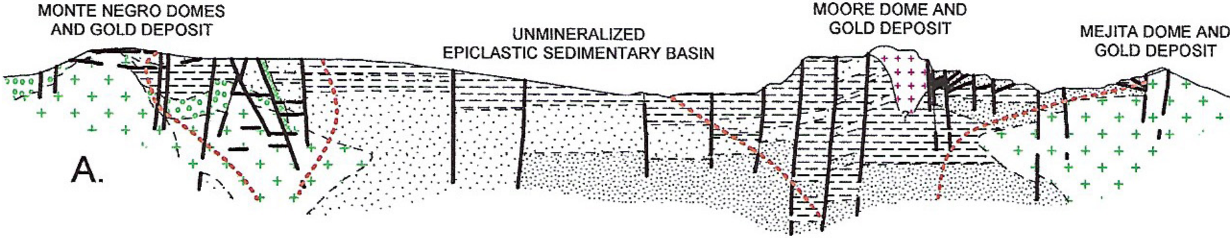
A.


MONTE NEGRO DOMES
AND GOLD DEPOSIT
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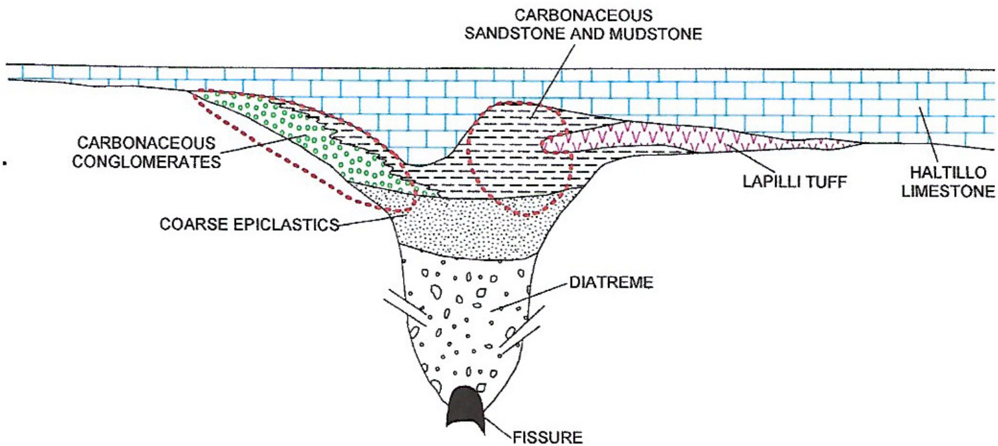
GOLD DEPOSIT

B.


CARBONACEOUS
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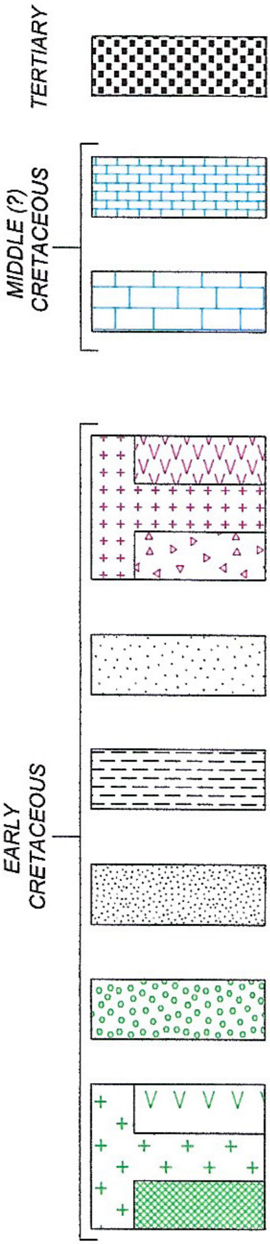
FISSURE

PUEBLO VIEJO STRATIGRAPHY



Fine-grained, unaltered diorite dikes and plugs.

Las Lagunas Formation
Thin to medium bedded calcareous shales and phyllites with interbedded limestone layers.

Hatillo Formation
Massively bedded reef limestones.

Los Ranchos Formation
Dacite dome and pyroclastic apron. Includes:
- massively-bedded lapilli tuff breccia with hydrothermally altered lithic fragments and quartz eyes (v pattern).
- massive dacite porphyry dome with quartz phenocrysts (+ pattern).
- matrix-supported dacite vent breccia (triangle pattern).

Medium-bedded (5-50cm) epiclastic carbonaceous sandstones with interbedded carbonaceous siltstones. Conglomeratic adjacent to domes.

Thinly-bedded (.5-5cm) epiclastic carbonaceous siltstones with interbedded carbonaceous sandstone. Coarser-grained adjacent to domes.

Epiclastic lapilli tuff breccias with interbedded carbonaceous sediments. Grades laterally into carbonaceous sandstone.

Coarsely-fragmental epiclastic crumble breccia containing abundant unsorted andesite clasts and lesser epiclastic sedimentary clasts. Occurs within and adjacent to exogenous basaltic andesite domes.

Andesite flows, domes, and pyroclastic aprons. Includes:
- massively-bedded lapilli tuff breccia with abundant mafic to intermediate fragments and no quartz eyes (v pattern).
- massive, crowded-feldspar porphyry domes and flows (+ pattern).
- steeply-dipping andesite dikes (shaded).