Geologica Acta: an international earth science journal
ISSN: 1695-6133
geologica-acta@ija.csic.es
Universitat de Barcelona
España

CORRAL, I.; GRIERA, A.; GÓMEZ-GRAS, D.; CORBELLA, M.; CANALS, À.; PINEDA-FALCONETT, M.; CARDELLACH, E.
Geology of the Cerro Quema Au-Cu deposit (Azuero Peninsula, Panama)
Geologica Acta: an international earth science journal, vol. 9, núm. 3-4, septiembre-diciembre, 2011, pp. 481-498
Universitat de Barcelona
Barcelona, España

Geologica Acta, Vol.9, Nos 3-4, September - December 2011, 481-498
DOI: 10.1344/105.000001742
Available online at www.geologica-acta.com

geologicaacta

Geology of the Cerro Quema Au-Cu deposit (Azuero Peninsula, Panama)

I. CORRAL [1] **A. GRIERA** [1] **D. GÓMEZ-GRAS** [1] **M. CORBELLA** [1] **À. CANALS** [2] **M. PINEDA-FALCONETT** [3] **E. CARDELLACH** [1]

[1] **Departament de Geologia, Universitat Autònoma de Barcelona (UAB)**
08193 Barcelona, Spain. Corral E-mail: Isaac.Corral@uab.cat Griera E-mail: Albert.Griera@uab.es
Gómez-Gras E-mail: David.Gomez@uab.es Corbella E-mail: Merce.Corbella@uab.es Cardellach E-mail: Esteve.Cardellach@uab.es

[2] **Facultat de Geologia, Universitat de Barcelona (UAB)**
08028 Barcelona, Spain. Canals E-mail: angelscanals@ub.edu

[3] **Departamento de Geografía, Universidad de Panamá**
082304747, Chitré, Panamá. Pineda-Falconett E-mail: mpineda@ancon.up.ac.pa

ABSTRACT

The Cerro Quema district, located on the Azuero Peninsula, Panama, is part of a large regional hydrothermal system controlled by regional faults striking broadly E-W, developed within the Río Quema Formation. This formation is composed of volcanic, sedimentary and volcano-sedimentary rocks indicating a submarine depositional environment, corresponding to the fore-arc basin of a Cretaceous–Paleogene volcanic arc. The structures observed in the area and their tectono-stratigraphic relationship with the surrounding formations suggest a compressive and/or transpressive tectonic regime, at least during Late Cretaceous–Oligocene times. The igneous rocks of the Río Quema Formation plot within the calc-alkaline field with trace and rare earth element (REE) patterns of volcanic arc affinity. This volcanic arc developed on the Caribbean large igneous province during subduction of the Farallon Plate. Mineralization consists of disseminations of pyrite and enargite as well as a stockwork of pyrite and barite with minor sphalerite, galena and chalcopyrite, hosted by a subaqueous dacitic lava dome of the Río Quema Formation. Gold is present as submicroscopic grains and associated with pyrite as invisible gold. A hydrothermal alteration pattern with a core of advanced argillic alteration (vuggy silica with alunite, dickite, pyrite and enargite) and an outer zone of argillic alteration (kaolinite, smectite and illite) has been observed. Supergene oxidation overprinted the hydrothermal alteration resulting in a thick cap of residual silica and iron oxides. The ore minerals, the alteration pattern and the tectono-volcanic environment of Cerro Quema are consistent with a high sulfidation epithermal system developed in the Azuero peninsula during pre-Oligocene times.

KEYWORDS | **Panama. Cerro Quema. Au-Cu High sulfidation epithermal deposit. Fore-arc basin. Arc-magmatism.**

INTRODUCTION

Central America is a region with important mineral resources such as gold, silver, copper, lead, zinc and aluminium. Precious metals (Au and Ag) and Cu are currently attracting the interest of mining companies. A significant portion of their investment is focused on gold-bearing epithermal vein deposits (e.g. Talavera, Bonanza and La Libertad, Nicaragua; Marlín, Guatemala), on porphyry copper deposits (e.g. Petaquilla and Cerro Colorado, Panama) and on base metal skarn and replacement deposits (e.g. Mochito, Honduras) (Nelson, 2007). Compared to other Central America countries such as Honduras, Guatemala, Belize, Costa Rica and Nicaragua, our knowledge of the geology and metallogeny of Panama is still limited. Gold and copper are the most economically important metals and are mainly related to epithermal and porphyry copper deposits respectively.

In 1965 a study of the geology and metallogeny of Panama was undertaken with the objective of evaluating Panama's mineral resource potential, financed by the United Nations Development Program (UNDP). One of the regions explored during the program was the Azuero Peninsula (Del Giudice and Recchi, 1969). The main results of this program were the discovery of areas with important copper and gold anomalies that were related to porphyry copper and epithermal deposits respectively. These findings were later confirmed by Ferencic (1970, 1971) and Kesler et al. (1977). In 1988, the Compañía de Exploración Mineral SA. (CEMSA), using data collected during the program, discovered an Au-Cu deposit at Cerro Quema which was considered a potentially mineable target. Between 1990 and 1994 Cyprus Amax carried out several exploration programs including both soil geochemistry and drilling campaigns. Results were presented in three unpublished reports by Leach (1992), Horlacher and Lehmann (1993) and Torrey and Keenan (1994). These latter authors reported gold resources of 10 Million tonnes (Mt) with an average gold grade of 1.26g/t.

Unraveling the geologic evolution of the area is the first step towards understanding the processes responsible for mineralization and associated hydrothermal alteration. In order to achieve this objective, a detailed geologic study of the Cerro Quema area was carried out. Fieldwork was complemented with geochemical analyses (major, trace element and REE) of regional rocks and the mineralogical characterization of the deposit was studied from surface and drill core samples. The lack of good exposures of hypogene mineralization and its apparent relationship to dacitic domes led to a debate about the origin of the Cerro Quema deposit. It was first considered a high sulfidation epithermal system possibly related to an underlying porphyry copper deposit (Leach, 1992; Nelson, 1995; Nelson and Nietzen, 2000). More recently, it has been suggested that it is an oxidized gold and copper deposit that shares characteristics of both epithermal and volcanogenic massive sulfide deposits (Nelson, 2007). Although epithermal style mineralization, high-level porphyry systems and volcanogenic massive sulfide deposits may be end-members of a continuum (Hannington, 1997), a better understanding of these different models may have important consequences for the discovery of new deposits in geologically similar areas.

GEOLOGICAL SETTING

Panama is situated in the southern part of Central America and represents the youngest segment of the land bridge between the North and South American plates. The closure of the Caribbean-Pacific seaway, which occurred during Late Pliocene to early Pleistocene times, had profound biological, oceanographic, and climatological consequences (Duque-Caro, 1990; Coates et al., 1992).

Panama is considered to be a tectonic block that lies at the junction of four tectonic plates, namely the Caribbean, South American, Cocos, and Nazca plates (Fig. 1A). The Panama microplate is considered to be part of the Caribbean plate but new GPS data indicates a decoupling motion and relative convergence between Panama and the Caribbean plate (Trenkamp et al., 2002). The northern boundary of the Panama microplate is defined by a system of thrust and transform faults known as the North Panama Deformed Belt (Adamek et al., 1988; Silver et al., 1990). Towards the West, these faults shift to the diffuse thrust belt of the Cordillera Central of Costa Rica (Marshall et al., 2003; Denyer and Alvarado, 2007). The eastern boundary with the South American continental plate is located along the dextral shear zone of the Atrato Valley (Taboada et al., 2000; Trenkamp et al., 2002). The southern edge is characterized by the subduction of the Nazca and Cocos oceanic plates beneath the Panama microplate. The initiation of the intra-oceanic subduction and the evolution of the magmatic island arc on the Azuero Peninsula is dated as Late Cretaceous and continued until Middle Miocene time (Buchs, 2008; Buchs et al., 2009, 2010; Wörner et al., 2009). Compression along the southern border of the Panama microplate controlled the formation of the South Panama Deformed Belt. Deformation is mainly accommodated by bending of the arc and sinistral NW-SE strike-slip faults (Mann and Corrigan, 1990; Coates et al., 2004).

The morphology of the subducting oceanic plates along the Central American Isthmus has a strong influence on the tectonics of the overriding plate and the supra-subduction magmatic processes. Subduction of relatively buoyant plates with irregular topographic highs (e.g. aseismic ridges and/or oceanic islands) causes the uplift and exposure of the fore-arc area along its margin (Fisher et al., 1998; Gardner et al., 2001; Sak et al., 2004). Such exposures provide the opportunity to study deep sections of the inner and outer fore-arc margin, which is composed of a complicated arrangement of arc-related volcanic rocks, accreted material and overlapped sequences (Buchs, 2008).

The Azuero Peninsula forms a pronounced prominence in the western Pacific coastline of Panama (Fig. 1B). The present configuration of the land bridge results from crustal mobility driven by escape tectonics and coastwise transport of fore-arc units (Krawinkel and Seyfried, 1994). The first regional mapping and stratigraphy definition was made through a joint program of the United Nations Development Program and the Dirección General de Recursos Minerales, 1976 (Del Giudice and Recchi, 1969; Metti et al., 1972; Metti and Recchi, 1976; Recchi and Miranda, 1977). The results of this work have been expanded upon in more recent contributions (Escalante, 1990; Krawinkel and Seyfried, 1994; Kolarsky and Mann, 1995; Kolarsky et al., 1995; Di Marco et al., 1995; Buchs, 2008; Buchs et al., 2009, 2010; Corral et al., 2008, and this study).

The basement of the Azuero Peninsula mainly consists of massive and pillowed basalt rocks with characteristic flat chondritic REE patterns which have been interpreted as tholeiitic basalts with plateau affinity (Hoernle et al., 2002, 2004; Hoernle and Hauff, 2007). Similar rocks have been identified in central and eastern Panama (i.e. Chagres and Darien regions) and along the Pacific onshore of Costa Rica (i.e Nicoya, Burrica and Osa Peninsula) and are interpreted as the western margin of the Caribbean large igneous province (Di Marco et al., 1995; Sinton et al., 1997; Hauff et al., 2000; Hoernle et al., 2002, Hoernle et al., 2004). Radiometric and paleontological ages range from 139 to 69Ma (Bourgois et al., 1982; Kolarsky et al., 1995; Kerr et al., 1997; Sinton et al., 1997, 1998; Revillon et al., 2000; Hauff et al., 2000; Hoernle et al., 2002, Hoernle et al., 2004; Lissinna, 2005; Buchs, 2008; Buchs et al., 2009, 2010). Although these rocks were interpreted initially as accreted oceanic terranes by Goossens et al. (1977), the current accepted interpretation is that they represent uplifted portions of the western margin of the Caribbean plate (Hauff et al., 2000; Hoernle et al., 2002, Hoernle et al., 2004).

In spite of the abundance of radiometric studies of the igneous rocks of the area (e.g. Del Giudice and Recchi, 1969; Lissinna, 2005), the age of the onset of subduction and the development of the volcanic arc remains a matter of debate. Proposed ages of arc initiation range between 88Ma (Lissinna et al., 2006) to 66Ma (Hoernle et al., 2002; Wörner et al., 2006). Recently, intermediate ages between both extremes have been proposed, (69-71Ma by Wenger et al., 2011; 84-71Ma by Pindell and Kenan, 2009). Buchs (2008) and Buchs et al. (2010) reported unusual

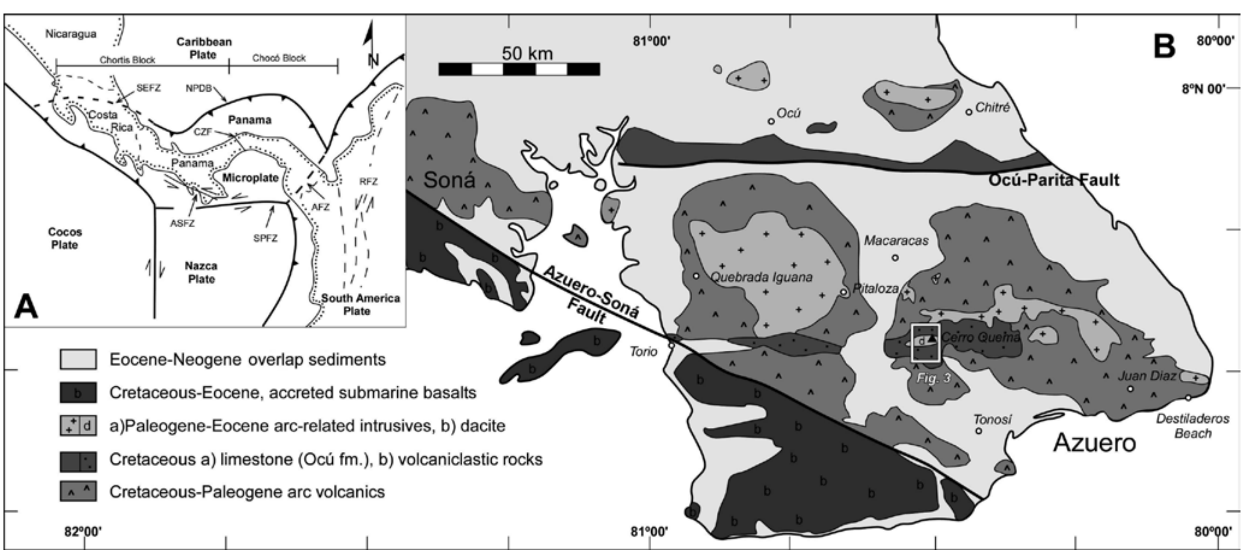

FIGURE 1 | **Present-day tectonic setting of Southern Central America and the Azuero Peninsula. A) North Panama Deformed Belt (NPDB), South Panama Fault Zone (SPFZ), Santa Elena suture (SEFZ), the Atrato Fault Zone (AFZ), Canal Fracture Zone (CFZ), Romeral Fault Zone (RFZ); (after Duque-Caro, 1990; de Boer et al., 1995; Kellogg et al., 1995; Mann and Kolarsky, 1995; Harmon, 2005). B) Geological map of Azuero Peninsula (after DGRM, 1976).**

geochemical compositions for basaltic lava flows and dikes emplaced in the Azuero basement with intermediate signatures, ranging from typical oceanic plateau to intra-oceanic island arc. These authors defined these rocks as the "Azuero Proto-arc Group" and interpreted them to have developed from early magmatism produced during the onset of subduction at 73-75Ma. These rocks are equivalent to those described by Wörner et al. (2009) as "enigmatic Caribbean large igneous province -arc rocks" and to some of the samples described by Wenger et al. (2011) as "Sona-Azuero Arc". These observations suggest a possible overlap in ages between plateau and arc magmatism during early stages of subduction.

Subsequently, arc-magmatism was developed on top of the Azuero basement and proto-arc rocks. The Azuero Arc Group (Buchs et al., 2010) is composed of an arc-related sequence of volcanic rocks and associated tuffites and volcaniclastic rocks. Their ages indicate that the arc is, at least, Maastrichtian (~71Ma) in age and expands up to ~40Ma (Del Giudice and Recchi, 1969; Maury et al., 1995; Lissinna, 2005; Lissinna et al., 2002, 2006; Wörner et al., 2005, 2006, 2009; Wegner et al., 2011). Maturation of magma sources during growth of the volcanic arc is not well constrained, although radiometric ages suggest an overlap of basic and acid igneous rocks (Buchs et al., 2010; Wörner et al., 2009).

The study area, part of the Cerro Quema district and surrounding areas, is situated in the central part of the Azuero Peninsula (see Fig. 1B) and mainly consists of andesites, dacites, limestones, basalts and turbidites, developed in a fore-arc basin environment. First studies by Del Giudice and Recchi (1969) and Weyl (1980) did not distinguish between different stratigraphic units and assigned all units to the Ocú Formation. They made this assignment because of the similarities between the limestones that occur in the Cerro Quema area and the grayish-white micritic limestones that crop out in the northern part of the Azuero Peninsula (Ocú locality, see Fig. 1B). Based on microfossil biostratigraphy and field observations, Weyl (1980) proposed a Campanian-Maastrichtian age for these rocks. Later, Horlacher and Lehmann (1993), after field mapping of the area, distinguished two units: 1) the Ocú Formation that included all limestones and volcano-sedimentary rocks, and 2) the Quema Formation, that was restricted to dacites and massive andesites.

STRATIGRAPHY

The Ocú Formation was initially described as well bedded fine-grained limestones with locally interbedded siltstones, tuffs and intermediate lava flows, deposited on top of basaltic basement rocks (Del Giudice and Recchi, 1969). The assumed age for the Ocú Formation is late Campanian-Maastrichtian on the basis of the association of planktonic foraminifera (*Globotruncana Lapparenti, Globotruncana ventricosa* and *Globotruncana contusa*) as first noted by Del Giudice and Recchi (1969), Weyl (1980) and Bourgois et al. (1982). Kolarsky et al. (1995) defined the Ocú Formation as thin to medium-bedded grayish-white limestone and calcareous siltstone, and light brown, fine grained calcareous siltstone and sandstone, mainly interbedded with basaltic rocks with 1,500m of apparent thickness. Del Giudice and Recchi (1969) and Weyl (1980) and other recent studies (Buchs, 2008; Buchs et al., 2010) describe interbedded basaltic lava flows within the Ocú Formation (e.g. Coiba Island) locally crosscut by basaltic dikes of the Azuero Proto-arc Group. The limestones of the Ocú Formation which show syn-volcanic soft deformation were dated by Buchs et al. (2010) as Late Campanian (~75-73Ma) in agreement with two limestone samples from the Ocú type locality which gave a Campanian age.

The rocks in the Cerro Quema district neither correspond with the classical definition of the Ocú Formation nor have the same genetic implications. Therefore, the rocks cropping out in the study area need to be defined and reinterpreted as a new lithostratigraphic unit. Our data, together with the work of previous authors, allow us to propose a new formation, named hereafter the Río Quema Formation, consisting of volcanic and volcaniclastic sediments interbedded with hemipelagic limestones, submarine dacite lava domes and crosscut by basaltic to andesitic dikes. The Río Quema Formation is interpreted as the infill sequence of the fore-arc basin of the Cretaceous–Paleogene volcanic arc and is integrated within the five major units of the Azuero Peninsula as follows: 1) Azuero Igneous Basement, 2) Azuero Proto-arc Group, 3) Río Quema Formation, 4) arc-related intrusive rocks, and 5) Tonosí Formation. The main characteristics of these units are described below and shown in Figure 2.

1) The Azuero Igneous Basement (Fig. 2A) is composed of massive, agglomerate and pillowed basaltic lavas, diabases, gabbros, minor occurrences of hemipelagic sediments interlayered with lavas, and basaltic dikes crosscutting all materials. Geochronological dating of the basalts indicates ages ranging from Turonian to Santonian (Lissinna, 2005) and is consistent with a Coniacian age obtained from interlayered radiolarian sediments (Kolarsky et al, 1995), recently revised by Buchs et al. (2009) who reported a Coniacian-Early Santonian age.

2) The Azuero Proto-arc Group locally overlies the Azuero Igneous Basement. In the Río Quema stratigraphical section it is composed of massive and pillowed basaltic lavas of irregular thickness (0-40m?) overlain by well bedded greenish shales, cherts and thin basaltic lava flows.

These volcanic rocks were described by Buchs (2008) and Buchs et al. (2010) as basaltic trachyandesitic lava flows and dikes, locally interbedded with hemipelagic limestones of the Ocú Formation.

3) The Río Quema Formation includes all sedimentary, volcaniclastic and extrusive volcanic units deposited in a fore-arc basin, overlying both the Azuero Igneous Basement and locally the Azuero Proto-arc Group. The total thickness of the Río Quema Formation is approximately 1,700m. The following units have been distinguished in the Cerro Quema district:

-A Lower Unit, made up of andesitic lava flows (0.20-2m thick) and well bedded crystal-rich sandstone to siltstone turbidites interbedded with hemipelagic thin limestone beds (Fig. 2B). W-SW paleocurrents were deduced from cross bedding, ripples and tool marks.

-A Limestone Unit, corresponding to a 100-150m thick light grey biomicritic hemipelagic limestone which is interlayered with well bedded cherts, thinly bedded turbidites and ash layers (Fig. 2C). The presence of planktonic foraminifera (*Globotruncana sp*., *Globotruncanita sp*., and *Globotruncanella sp*.) indicates a Late Cretaceous age. The similarities with the foraminifera found in the limestones described by Del Giudice and Recchi (1969), Tournon et al. (1989), Di Marco et al. (1995) and Buchs et al. (2010) allow us to infer a late Campanian–early Maastrichtian age. Similar limestone beds have also been found in the

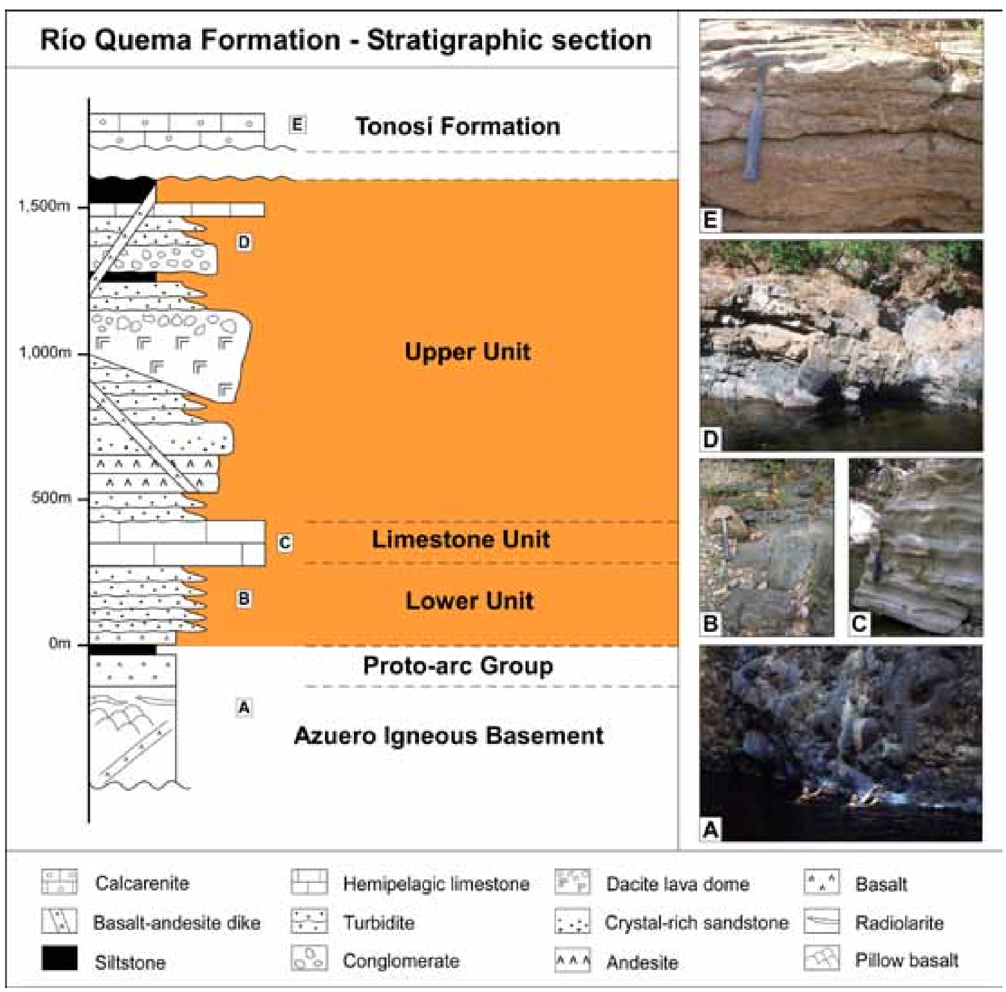

FIGURE 2 | **Idealized stratigraphic section of the Río Quema Formation. A) Pillow basalts of the Azuero Igneous Basement at Río Joaquín. B) Volcaniclastic sediments of the Río Quema Formation lower unit at Río Quema. C) Hemipelagic limestones from the Río Quema Formation limestone unit south of Río Quema. D) Volcaniclastic and hemipelagic sediments crosscut by a basaltic-andesitic dike of the Río Quema Formation upper unit north of Río Quema. E) Fossiliferous calcarenite of the Tonosí Formation at Río Güerita.**

Torio and Güera rivers, following the southernmost E-W trend fault zone of the Azuero Peninsula.

-An Upper Unit, which crops out both in the northern and southern part of the Río Quema section. The northern part is composed of volcaniclastic sediments interlayered with massive to laminar andesitic lava flows (1 to 3m thick), andesitic hyaloclastites (0.1 to 0.5m thick), and massive dacites overlain by dacite lava flows and dacitic and resedimented hyaloclastites (the latter up to 3m thick). However, in the southern part, this unit is characterized by volcaniclastic turbidites, crystal rich sandstones (up to 1m thick), siltstones and thin pelagic limestone beds (up to 0.2m). Whereas massive lava flows and extrusive rocks prevail in the northern part of the section, volcaniclastic turbidites are dominant in the southern region. W-SW paleocurrents are deduced from cross bedding. Basaltic-andesitic dikes intrude part of the series (Fig. 2D), but are more common in the northern part of the study area (Fig. 3).

4) The arc-related intrusive unit is composed of diorites, quartz-diorites and granodiorites. They are exposed as large batholiths in the central and northern part of the Azuero Peninsula, although small quartz-diorite stocks and/or dikes occur South of Cerro Quema. Ages of these igneous rocks range from 66 to 42Ma (Maury et al., 1995; Lissinna, 2005; Wörner et al., 2009; Wenger et al., 2011).

5) The Tonosí Formation consists of a sedimentary sequence unconformably overlapping all of the previous units. Recchi and Miranda (1977) defined the Tonosí Fm. as conglomerates, reefal limestones and associated calcarenites of Middle Eocene to Early Oligocene age, overlying the basaltic basement northeast of the Azuero-Soná fault zone. More recent studies (Kolarsky et al., 1995; Krawinkel and Seyfried, 1994) divided the formation into two major lithological units: 1) A lower unit composed of minor coal seams, conglomerate, coarse sandstone and reefal limestone, and 2) an upper unit composed of deeper marine interbedded sandstone, siltstone and calcarenite. Ages for the Lower unit range from Middle Eocene to Early Oligocene (~40 to 30Ma) and for the Upper unit from Late Oligocene to Early Miocene (~30 to 15Ma) (Kolarsky et al., 1995; Krawinkel and Seyfried, 1994; Krawinkel et al., 1999).

Our interpretation assumes that the Azuero Igneous Basement is equivalent to the Caribbean large igneous province described by Hauff et al. (2000), Hoernle et al. (2002, 2004), and represents the autochthonous basement of the Azuero Peninsula at the onset of subduction. At the initial stages of magmatism, a Proto-arc was developed locally on top of the Azuero Igneous Basement (Buchs, 2008; Buchs et al., 2009, 2010). Simultaneously, the deposition of the Ocú Formation took place (this formation does not crop out in the study area). The Río Quema Formation is the expression of a fore-arc basin infill submarine sequence of a more mature volcanic arc. The Lower Unit, formed by andesitic lava flows, crystal-rich sandstones and turbidites interbedded with hemipelagic limestone beds, represents a proximal depositional environment with respect to the volcanic front. The Limestone Unit records a period of time with minor volcanic activity in which autochthonous sedimentation was dominant over volcanic sedimentation. The Upper Unit records both distal and proximal depositional environments due to the presence of submarine dacite lava domes which played a paleo-barrier role in terms of sedimentation. These dacite lava domes compartmentalized the fore-arc basin, producing changes in the sedimentation. The northern slope of the dacitic domes is mainly composed of massive volcanic rocks, minor turbidites, limestone layers and abundant basaltic-andesitic dikes, suggesting a proximal depositional environment with respect to the volcanic front. In contrast, the southern slope is characterized by a large fraction of volcaniclastic sediments, turbidites, shales and siltstones and by a minor presence of andesitic lava flows, suggesting a distal depositional environment near the volcanic front. The arc-related intrusive unit represents a period of time characterized by quartz-diorite and granodiorite intrusions. These intrusions are abundant to the North of the study area, but minor quartz-diorite batholiths are also present in the southern part. The intrusions produced contact metamorphism on the Río Quema Formation close to the batholiths. Finally, the sedimentary sequence of the Tonosí Formation represents a regional transgressive event that affected the Azuero Peninsula (Kolarsky et al., 1995; Krawinkel et al., 1999).

STRUCTURE

A large network of faults can be recognized in the area. Predominant faults trend NW-SE and NE-SW, show sub-vertical dip and normal sense of offset. A left-lateral strike-slip component has been observed along faults which trend NW-SE trend. Another main tectonic structure of the area is the Río Joaquín fault zone, a 30km regional scale fault zone with a broad E-W orientation (Fig. 3). It was originally identified by Buchs (2008) combining fieldwork and interpretation of satellite images. In the Cerro Quema area, our observations indicate that the Río Joaquín fault zone maintains the general E-W orientation and does not change to a NE-SW trend as proposed by Buchs (2008). Along the Río Joaquín fault, the Azuero igneous basement is directly in contact with the upper series of the Río Quema Formation (see Fig. 3, cross section). A reverse dip-slip motion is observed at the Río Joaquín fault with the southern block uplifted with respect to the northern block. The inferred minimum vertical offset is 300-400m.

Faulting caused a strong deformation, forming cataclasites and a network of tension gashes oblique to the fault.

In addition, ENE-WSW trending folds and minor faults parallel to E-W trending lithological boundaries have also been identified in the area. All these structures are slightly oblique to the Río Joaquín fault zone and are partly cut by it. The northern part of the area is characterized by abundant decametric open folds with moderate limb dips and fold axes gently plunging to the SW. The southern area is characterized by a kilometer-scale E-W trending syncline that affects the entire fore-arc basin (see Fig. 3, cross section). All these structures are covered by the Tonosí Fm., which overlaps the Azuero

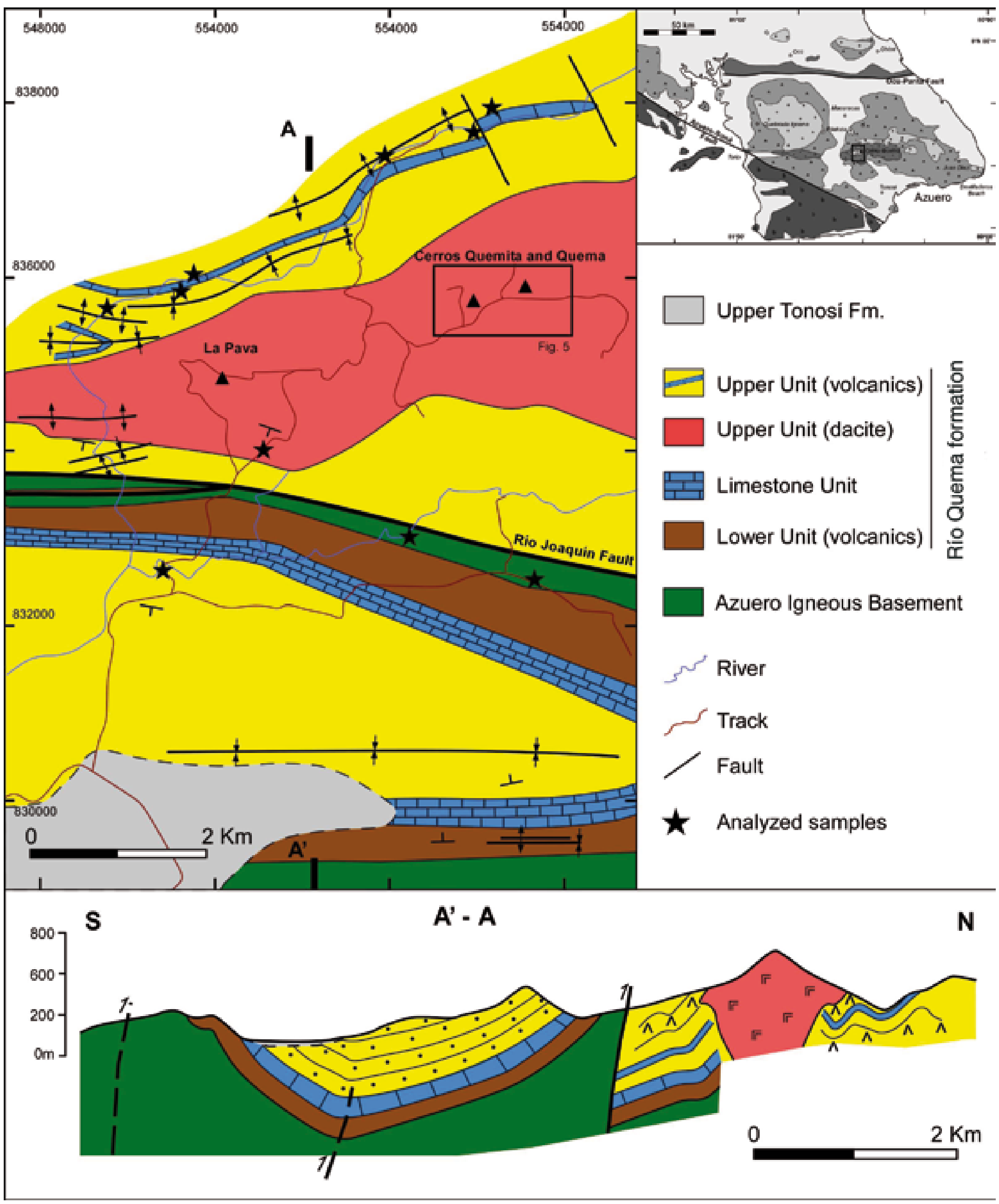

FIGURE 3 | **Geologic Map of the West Cerro Quema area.**

Igneous Basement, the Río Quema Fm. and the arc-related intrusions.

GEOCHEMISTRY

Whole rock analysis (major, trace and REE elements) was performed on 20 representative samples of unaltered igneous and volcaniclastic rocks of the Cerro Quema district and surrounding areas. Samples were cut, crushed and reduced to powder using a tungsten carbide mill. Analyses were carried out by Actlabs (Canada) using X-ray fluorescence (XRF) and inductively coupled plasma-mass spectrometry (ICP-MS). Results are presented in Table I available in www.geologica-acta.com.

As shown by the Total Alkali-Silica (TAS) diagram, the analyzed igneous rocks belong to the sub-alkaline type, spanning the entire compositional range from basalt to dacite (Fig. 4A). According to the AFM (Al_2O_3, FeO, MgO) plot, quartz-diorites from the northern part of the Cerro Quema district and volcaniclastic sediments, andesites, dacites and basaltic-andesitic dikes of the Río Quema Formation have calc-alkaline affinity whereas basalts, pillow basalts and basaltic dikes of the Azuero Igneous Basement show tholeiitic affinity (Fig. 4B).

Two distinct rock groups are recognized using the trace element and REE signatures that match up with the major element data. The first group consists of basalts, andesites and dacites of the Río Quema Formation and the quartz-diorites from the northern part of the Cerro Quema area, displaying characteristic features of rocks with volcanic arc affinities (i.e. variably enriched fluid-mobile elements and depleted in heavy REEs; Fig. 4C and 4D). The second group is represented by basalts with flat or slightly enriched trace elements (i.e. Ba, Sr and Zr) and REE patterns, compatible with compositions of oceanic plateau-like affinities as reported for the Caribbean large igneous province (Fig. 4E) and similar to the rocks of the proto-arc group described by Buchs (2008) and Buchs et al. (2010).

HYDROTHERMAL ALTERATION AND MINERALIZATION

The Río Quema Formation constitutes the most economically interesting geological formation in the Azuero Peninsula because it locally hosts Au-Cu mineralization. The mineralization crops out not only in the Cerro Quema area (e.g. Cerro Quema, Cerro Quemita, Cerro La Pava) but also further East (e.g. Juan Díaz) and West (e.g. Pitaloza and Quebrada Iguana), always to the North of the Río Joaquín fault zone. Ore minerals are rarely seen in outcrops and have been mostly studied in samples from 12 drill cores (2 from Cerro Quemita, 6 from Cerro La Pava and 4 from the area between both hills). Surface sampling and eroded cobbles accumulated in creeks were also used to complete the mineralogical study.

The Río Quema Formation is affected by regional-scale hydrothermal alteration (approximately from Torio village, West of the Azuero Peninsula to the Destiladeros Beach, East of the Azuero Peninsula, Fig. 1). The most prominent hydrothermal alteration is silicification, which is readily observed in the field.

Previous studies in the Cerro Quema area (Torrey and Keenan, 1994) described three hydrothermal alteration types: 1) Silica–pyrite, characterized at surface by highly fractured, vuggy, locally brecciated rock composed of silica and iron oxides and, at depth, by abundant pyrite (up to 35% of the rock volume). The mineral assemblage includes alunite, pyrite, dickite, quartz, pyrophyllite, barite, interlayered illite-smectite, illite, kaolinite, apatite and rutile. 2) Clay–pyrite, containing illite, kaolinite and hematite with disseminated pyrite at depth. 3) Propylitic, at the outer margins of the alteration halo and characterized by chlorite, calcite, siderite, halloysite, laumonite, hematite and illite.

The alteration zones defined by Torrey and Keenan (1994) have not been confirmed by our detailed mapping or by the analytical data from outcrop and drill-core samples. According to our observations, the alteration pattern in Cerro Quema is clearly fault controlled, following the ENE-WSW trending regional faults. Nevertheless, concentric zoning of alteration was observed (Fig. 5A), mainly within dacitic domes but also in andesites. From the microscopic study of thin and polished sections and SEM-EDS and XRD analyses of minerals, a new alteration pattern in the Cerro Quema area is proposed:

1) An inner alteration assemblage, which is characterized at surface by the presence of vuggy silica with hematite, goethite and rutile (Fig. 5B). At depth this alteration zone contains quartz, alunite-natroalunite, aluminium-phosphate-sulphate minerals (APS), dickite, barite, pyrite, enargite and rutile (Fig. 5C, D). This assemblage corresponds to an advanced argillic alteration zone.

2) An external assemblage with kaolinite, illite, smectite and interlayered illite-smectite in both surface exposures and at depth, corresponding to the argillic alteration zone (Fig. 5E). The limit between the two zones can be transitional and they locally overlap.

3) A propylitic alteration assemblage related to mineralization, containing pyrite, chlorite, calcite and siderite has only been found in some drill cores, unrelated

TABLE 1 | **Analyzed samples for major and trace elements and REE**

Sample:	RQ 9A	RQ 15AND	RQ 24	RQ 12	RQ 13	RQ 11	RQ 07	RQ 03	RQ 26	Gue 5Bis
Region:					Río Quema					Tonosí Road
Latitude	N7 34.072	N7 33.602	N7 34.702	N7 33.770	N7 33.717	N7 33.770	N7 34.245	N7 34.528	N7 34.704	N7.54121
Longitude	W80 31.959	W80 33.458	W80 31.216	W80 32.975	W80 33.030	W80 32.975	W80 31.905	W80 31.788	W80 31.121	W80.59680
Lithology:	Dacite	Andesite	Basalt	Andesite	Andesite	Andesite	Basalticandesite	Basalticandesite	Basalt	Basalt
SiO_2	64.56	57.94	54.01	58.27	57.86	55.55	55.32	51.67	45.86	48.7
Al_2O_3	14.37	14.61	16.01	13.69	14.44	15.13	15.08	18.34	14.82	13.81
Fe_2O_3(T)	5.79	7.84	8.45	8.50	7.85	10.21	10.05	8.80	11.46	12.02
MnO	0.148	0.107	0.16	0.08	0.15	0.14	0.14	0.17	0.159	0.19
MgO	1.87	4.23	4.36	5.48	5.47	4.54	4.60	4.93	6.42	7.84
CaO	4.31	6.77	7.29	1.87	2.93	7.09	7.02	4.65	12.66	10.89
Na_2O	3.65	3.1	2.89	4.04	4.12	3.16	3.12	4.43	1.99	3.03
K_2O	0.6	0.46	1.25	1.50	1.43	1.13	1.11	1.71	0.05	0.07
TiO_2	0.735	0.334	0.64	0.30	0.34	0.76	0.77	0.54	1.479	1.25
P_2O_5	0.32	0.1	0.11	0.06	0.08	0.13	0.13	0.07	0.16	0.08
LOI	4.24	4.23	4.73	4.81	5.27	2.78	2.78	4.68	5.24	2.43
Total	100.6	99.72	99.92	98.60	99.93	100.60	100.10	99.98	100.3	100.3
Cs	4.76	42.86	47.62	19.05	33.33	19.05	23.81	33.33		
Rb	18.33	15.00	38.33	43.33	26.67	20.00	25.00	33.33	10.00	6.67
Ba	44.85	27.88	71.06	123.79	50.61	68.18	68.18	72.58	13.48	7.12
Th	8.55	8.43	26.92	8.43	8.68	9.56	9.69	5.66	6.16	3.27
U	13.30	16.26	31.03	14.78	16.26	15.27	15.27	9.36	7.39	4.43
Nb	9.27	2.28	3.04	7.29	2.13	3.34	5.93	2.43	8.81	7.90
La	12.81	6.27	14.38	6.60	6.56	9.29	9.03	6.02	9.68	5.40
Ce	11.04	4.92	10.87	4.75	4.98	7.28	7.10	4.56	8.84	5.28
Pr	11.57	4.88	10.16	4.53	5.00	7.72	7.44	4.88	9.21	5.55
Nd	11.60	4.39	9.04	3.94	4.55	7.42	6.98	4.75	9.20	5.77
Sr	14.97	15.83	20.60	12.91	11.86	23.97	25.18	18.54	10.40	16.78
Sm	11.11	3.45	7.22	3.33	3.77	6.55	6.26	4.11	9.11	6.13
Zr	8.57	4.48	8.19	4.67	4.29	6.95	6.57	3.81	13.05	7.33
Hf	6.01	3.13	5.48	3.39	2.87	4.70	4.96	2.61	8.36	4.96
Ti	3.63	1.67	3.17	1.49	1.67	3.74	3.82	2.66	7.33	6.20
Eu	9.29	2.79	5.42	2.14	2.86	5.47	5.05	3.71	8.44	6.16
Gd	10.20	2.70	5.94	2.59	2.90	5.57	5.40	3.62	8.71	6.27
Tb	10.00	2.42	5.86	2.42	2.63	5.56	5.15	3.54	8.99	6.57
Dy	9.15	2.24	5.24	2.20	2.36	5.10	4.76	3.18	8.16	5.95
Ho	8.66	2.15	4.83	2.01	2.28	4.70	4.43	2.89	7.79	5.44
Y	8.14	1.86	4.65	1.63	2.09	4.42	4.42	3.02	6.98	5.12
Er	8.90	2.31	5.07	2.17	2.44	4.82	4.66	3.04	7.60	5.53
Tm	9.12	2.51	5.18	2.40	2.59	5.09	4.84	3.18	7.66	5.50
Yb	9.30	2.68	5.31	2.54	2.77	5.31	5.06	3.33	7.66	5.51
Lu	8.87	2.67	5.23	2.50	2.80	5.05	4.86	3.29	7.14	5.16

TABLE 1 | **Continued**

Sample:	PA 01	LI 01	AN 02	AN 04	TRI 01	LP 204	LP 111	PIT 02	RJ 13B	RJ 11
Region:	París	Limón	Finca AN	Finca AN	Trinidad	Cerro La Pava	Qda. Quema	Pitaloza	Río Joaquín	Río Joaquín
Latitude	N7 59.652	N8 03.452	N7 31.773	N7 31.450	N7.63192	N7 32.698	N7.5265667	N7.55377	N7 31.927	N7 31.630
Longitude	W80 31.629	W80 46.312	W80 30.676	W80 30.274	W80.66756	W80 32.543	W80.551737	W80.54827	W80 28.120	W80 28.120
Lithology:	Quartzdiorite	Quartzdiorite	Basalt	Trachyandesite	Quartzdiorite	Dacite	Andesite	Quartzdiorite	Basalt	Basalt
SiO_2	61.23	62.92	47.87	53.48	56.03	62.9	56.15	60.36	49.09	50.33
Al_2O_3	15.32	15.74	13.34	16.76	17.07	13.61	12.57	15.31	16.53	14.18
Fe_2O_3(T)	6.33	5.41	13.5	8.24	8.03	7.33	7.85	7.24	9.63	12.82
MnO	0.112	0.13	0.17	0.167	0.151	0.132	0.145	0.08	0.16	0.19
MgO	2.09	2.03	7.51	3.4	3.84	3.55	5.71	3.32	5.96	4.53
CaO	6	3.52	7.07	7.87	8.43	3.56	7.11	6.49	11.59	8.74
Na_2O	3.29	4.49	3.91	3.2	2.9	3.99	1.62	2.78	3.11	4.06
K_2O	1.01	1.82	0.1	2.13	0.82	2.91	0.53	0.84	0.28	0.09
TiO_2	0.806	0.794	1.09	0.691	0.721	0.216	0.256	0.24	1.32	2.05
P_2O_5	0.13	0.24	0.09	0.32	0.13	0.07	0.06	0.07	0.14	0.29
LOI	2.12	2.47	3.82	2.36	1.15	2.47	6.59	2.01	2.93	2.66
Total	98.43	99.56	98.49	98.61	99.27	100.7	98.59	98.75	100.70	99.95
Cs	14.29	52.38		9.52	14.29	14.29	4.76	19.05	9.52	
Rb	30.00	61.67	8.33	78.33	25.00	58.33	18.33	28.33	8.33	
Ba	62.42	98.48	9.55	155.15	53.79	96.67	25.76	29.85	20.30	5.45
Th	30.19	30.69	4.65	24.03	17.61	13.46	5.66	7.42	2.77	6.67
U	38.42	45.32	5.42	39.90	23.65	19.70	10.34	10.84	3.94	9.36
Nb	19.30	38.30	7.60	10.79	3.80	3.80	3.04	2.28	4.56	7.60
La	21.91	25.93	4.85	25.62	11.54	11.19	5.37	5.83	6.22	11.47
Ce	17.43	19.82	4.57	17.73	8.90	8.00	3.99	4.44	6.45	10.93
Pr	15.87	17.48	4.88	15.55	8.43	7.56	3.86	4.41	7.48	12.13
Nd	13.68	15.04	5.13	13.12	7.76	6.45	3.34	3.84	8.08	12.56
Sr	11.61	15.28	6.53	47.14	14.52	25.43	18.59	14.87	14.42	8.64
Sm	11.06	11.72	6.08	9.31	6.72	4.63	2.73	3.05	8.65	12.22
Zr	18.95	20.19	8.57	9.90	8.00	5.05	5.14	4.19	10.86	13.62
Hf	12.27	12.27	6.01	6.01	5.48	3.39	3.39	2.87	6.79	8.62
Ti	4.07	3.97	5.49	3.49	3.61	1.07	1.29	1.20	6.51	10.21
Eu	6.88	8.70	5.95	7.60	5.38	3.47	2.05	2.37	8.38	11.43
Gd	9.41	9.45	6.95	6.99	5.72	2.94	1.89	2.44	8.25	11.29
Tb	9.19	8.89	7.68	6.36	5.66	2.32	1.82	2.32	8.59	11.01
Dy	8.22	7.85	7.58	5.59	5.19	1.82	1.57	2.11	7.66	10.07
Ho	7.45	6.98	7.25	5.10	4.70	1.54	1.48	2.01	6.85	8.93
Y	8.37	6.98	6.98	4.88	4.65	1.63	1.16	1.40	6.74	8.60
Er	7.63	7.15	7.72	5.25	4.86	1.60	1.6	2.21	7.01	8.97
Tm	7.72	7.47	8.12	5.47	4.97	1.71	1.78	2.44	7.18	9.01
Yb	7.78	7.66	8.14	5.56	5.01	1.86	1.93	2.74	7.12	8.93
Lu	7.30	7.24	7.75	5.26	4.90	1.81	1.88	2.80	6.56	8.18

to the other alteration zones (Fig. 5F). Contrary to the reports by Torrey and Keenan (1994) it has not been observed in surface outcrops, suggesting that its extension is limited.

The intense weathering typical of tropical latitudes affects all rocks of the area. The superimposition of this supergene alteration to the hydrothermally altered terrains results in a thick cap (up to 150m) of silica and iron oxides (Fig. 5G).

In the Cerro Quema area several mineable gold deposits have been identified: La Pava in the West and Cerro Quemita and Cerro Quema in the East of the

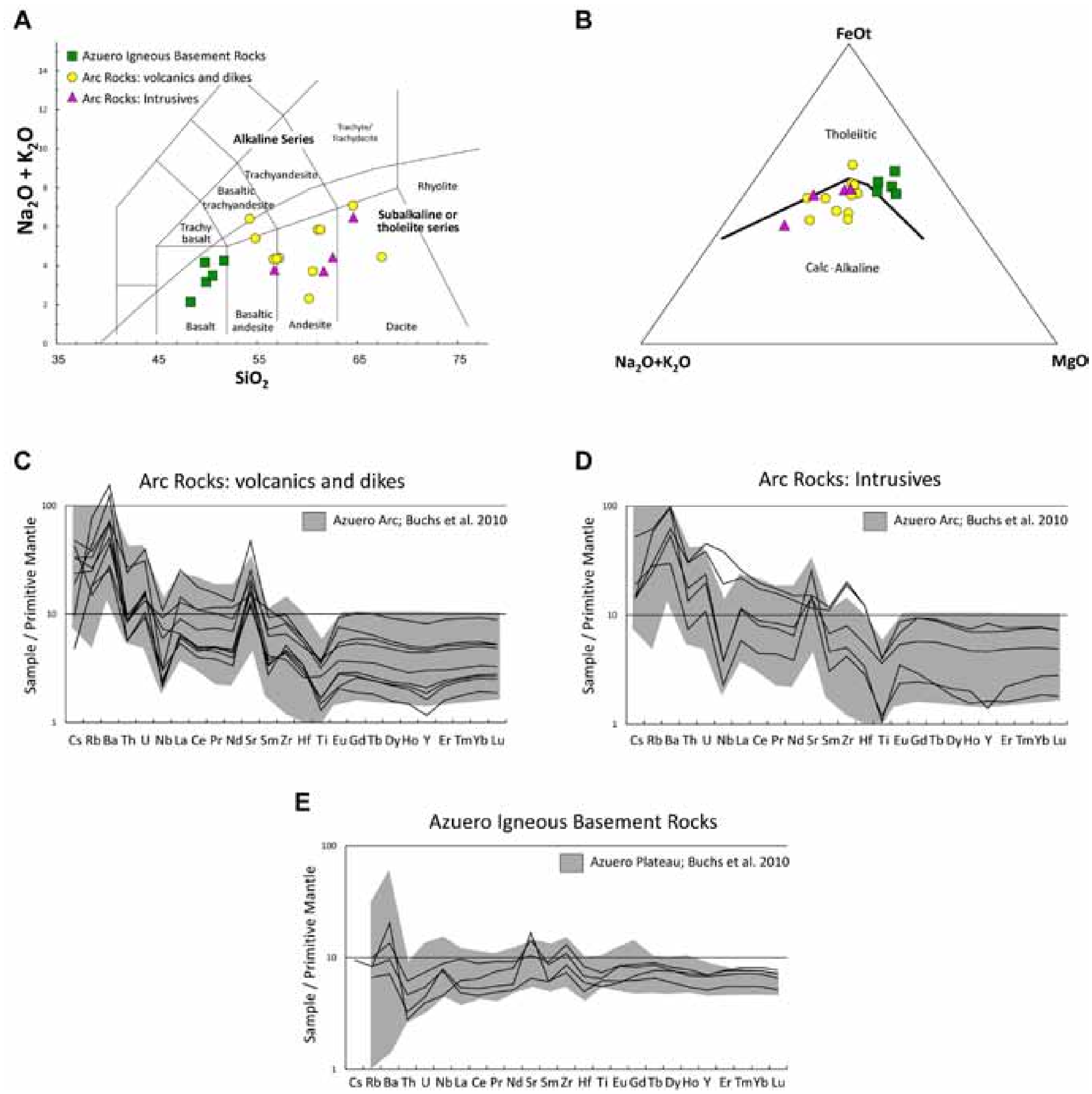

FIGURE 4 | **Major element geochemistry, chondrite-normalized (Sun and McDonough, 1989) trace element and REE concentrations of Cerro Quema area igneous rocks A) Chemical composition of igneous rocks in Total Alkali-Silica (TAS) diagram (Le Maitre et al., 1989). B) AFM diagram, Irvine and Baragar (1971). C) Arc Rocks of the RQF: Volcanic, volcaniclastic rocks and dikes. D) Arc Rocks of the RQF: Quartz-diorites and dacites. E) Azuero Igneous Basement rocks.**

area. Estimated total gold resources are 10Mt with an average gold grade of 1.26 g/T (Torrey and Keenan, 1994). The mineralization consists of disseminated pyrite, local enargite and a poorly developed stockwork of quartz, pyrite, chalcopyrite and barite with traces of galena and sphalerite. Gold occurs as disseminated submicroscopic grains and as invisible gold within the crystalline structure of pyrite (Corral, 2008), especially in the advanced argillic alteration zone. Strong supergene alteration (oxidation cap or gossan) released the gold contained in the structure of pyrite allowing the deposit to be economically profitable, as well as the mechanical transport of gold into nearby stream sediments.

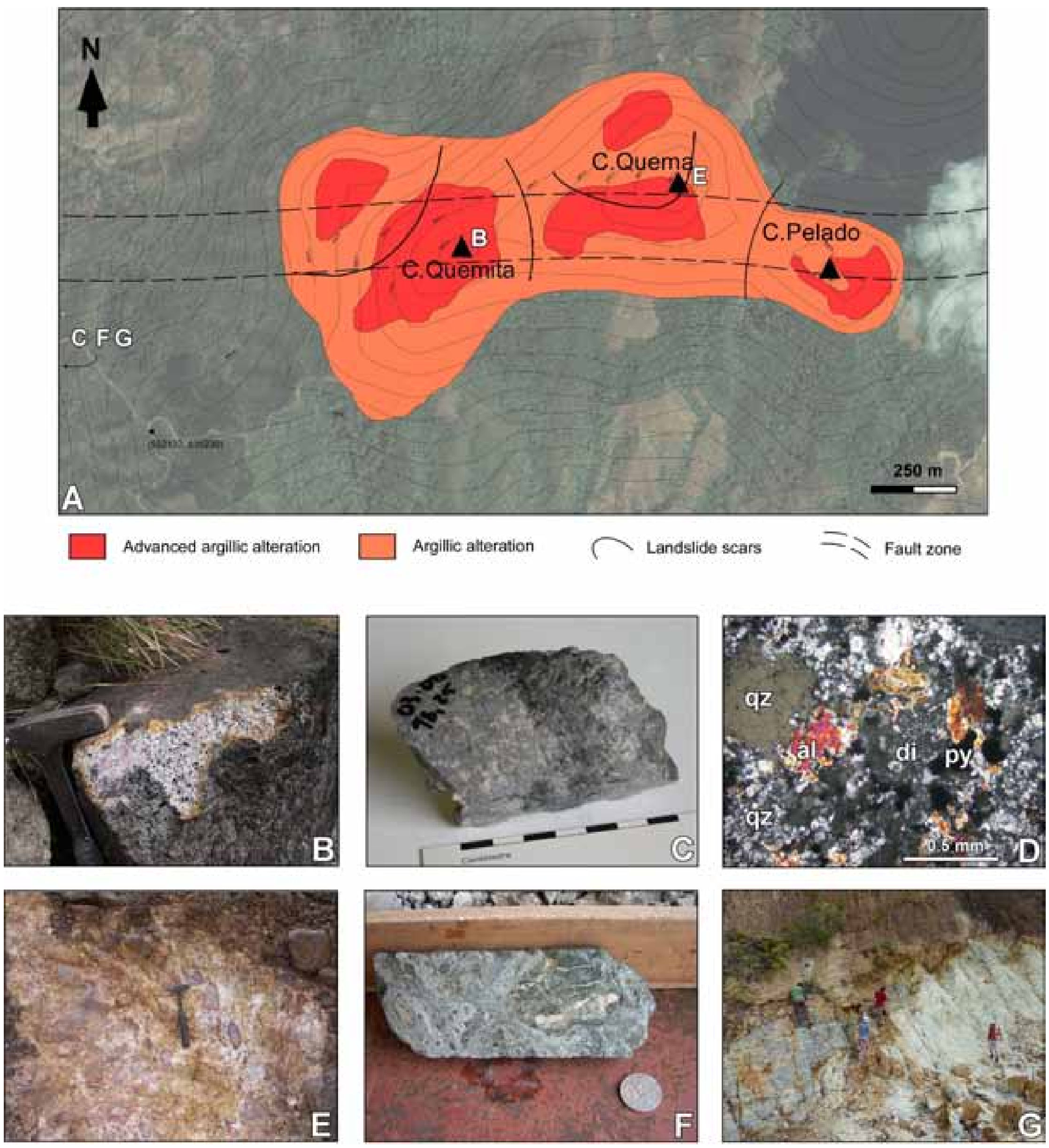

FIGURE 5 | **Alteration pattern at Cerro Quemita, Cerro Quema and Cerro Pelado. A) Hydrothermal alteration map. B) Vuggy silica at Cerro Quemita. C) Drill core sample of advanced argillic alteration, quartz-alunite-dickite crosscut by pyrite-enargite veins (dark gray). D) Thin section of the advanced argillic alteration. (py: pyrite, qz: quartz, al: alunite, di: dickite). E) Argillic alteration at Cerro Quema, kaolinite ± smectite ± illite. F) Propylitic alteration in a drill core sample, chloritized dacite with calcite veins and siderite. G) Red-ox boundary at Cerro Quemita (red-brown: oxidized zone, light gray: unoxidized zone).**

DISCUSSION

This work has focused on the study of the tectono-volcanic environment of the Cerro Quema area and on the mineralogy and spatial distribution of hydrothermal alteration related to gold and copper mineralization. Stratigraphic, petrologic and tectonic evidences suggest that the volcano-sedimentary Río Quema Formation was deposited in a submarine fore-arc basin from late Cretaceous to Eocene times. The fore-arc basin is limited to the North of Cerro Quema by arc-related intrusives of Paleogene age (Fig. 1). The southern limit is not clear, though we infer that the basin was limited by the Cretaceous subduction trench, which has not been identified in the field yet, or that it was subducted during later stages. Our geochemical data confirm that the Azuero Igneous Basement at the Cerro Quema district is chemically similar to the tholeiitic basalts of the Caribbean large igneous province (Goossens et al., 1977; Hauff et al., 2000; Hoernle et al., 2002; Hoernle et al., 2004). The less incompatible trace elements and REE show similar abundances and flat pattern tendencies to those reported for the Caribbean large igneous province (Hoernle et al., 2004; Wörner et al., 2009). Therefore, the igneous basement of the Azuero Peninsula cannot be interpreted as an accreted terrane (Goossens et al., 1977). Conversely, it represents the autochthonous basement of the upper plate, uplifted and exhumed during convergence tectonics. The recognition of the autochthonous basement of the Río Quema Formation allows us to describe the depositional environment from the onset of intra-oceanic subduction to the geochemical and geodynamic maturation of the magmatic arc.

The Proto-arc Group is interpreted to have formed at the initial stages of the magmatic arc which developed on top of the Azuero igneous basement. Its voluminous sheet flows and pillowed non-vesicular basalts and andesites associated with cherts and shales indicate extrusion/deposition in a deep marine environment proximal to the volcanic centre. Its geochemical composition is unusual and its signature is intermediate between typical oceanic plateau and intra-oceanic island arc (i.e. variably enriched in fluid-mobile elements and depleted in heavy REEs). Our interpretation of a magmatic arc on top of an oceanic plateau, such as the Caribbean large igneous province at the initial stages of subduction, would explain the presence of the so-called "enigmatic arc rocks" in the Caribbean large igneous province by Wörner et al. (2009) and some samples of the Sona-Azuero Arc described by Wegner et al. (2011). Our results are in agreement with those of Buchs (2008), Buchs et al. (2009, 2010) and Wörner et al. (2009). The Proto-arc Group rocks are true arc-related rocks, and could be associated to the initial magmatic arc generated at the onset of the Farallon plate subduction beneath the Caribbean Plate during Late Cretaceous-Paleogene times.

The classical interpretation of the Ocú formation assumes limestone deposition before the initiation of arc magmatism (Del Giudice and Recchi, 1969; Weyl, 1980; Kolarsky et al., 1995; Buchs, 2008; Buchs et al., 2010). However, in the Cerro Quema area, limestones overlie early volcanic arc rocks whose deposition followed the initiation of island arc magmatism. Therefore, the Cerro Quema limestones and equivalent calcareous layers observed at the Torio and Güera Rivers (West of Azuero; Buchs, 2008) do not belong to the Ocú Formation. Consequently, they are not indicative of the onset of subduction, being possibly a bit younger. Therefore we suggest the restriction of the so-called Ocú Formation to only the grayish foraminifera-bearing hemipelagic limestones deposited on top of basaltic basement rocks and/or interbedded with the Proto-arc Group.

The Río Quema Formation is interpreted as a fore-arc basin infill sequence accumulated during the geochemical and geodynamic maturation of the arc. The presence of andesites and dacites in the Río Quema Formation are indicative of magmatism of intermediate to acid composition. The abundance of hyaloclastites in both types of rocks, the scarcity of vesiculation and the presence of turbidites grading up into fine beds of hemipelagic sedimentary rocks indicate a submarine environment. However, the emplacement of dacites acted as a paleo-barrier to sedimentation producing the compartmentalization of the forearc basin (Fig. 6). The facies found on the northern slopes of the dacitic domes are characterized by the presence of massive volcanic rocks, minor turbidites, limestone layers with wave imprints, and abundant basaltic-andesitic dikes. These features allow us

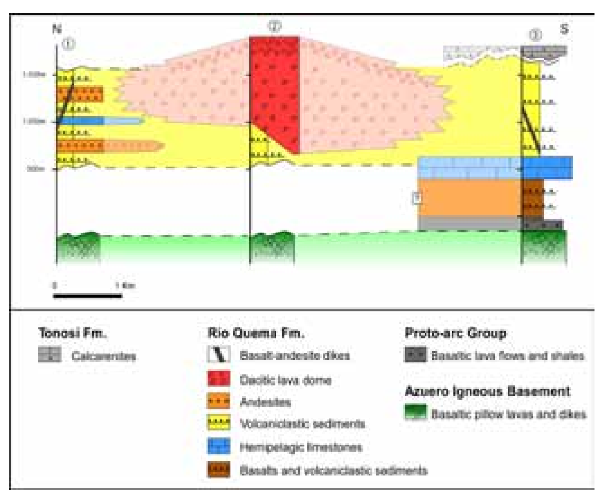

FIGURE 6 | **Schematic stratigraphic section across the Cerro Quema area. 1) North Cerro Quema area. 2) Central Cerro Quema area. 3) South Cerro Quema area.**

to interpret this part of the series as proximal to the volcanic front, so that the northern volcano-sedimentary sequence defines the inner fore-arc basin. On the other hand, the facies observed on the southern slopes of the dacitic domes with a large fraction of volcanoclastic sediments, turbidites, shales and siltstones and a small presence of andesitic lava flows are interpreted as distal and deeper facies. Hence, the southern sedimentary sequence would define the outer section of the fore-arc basin, consistent with the SW to W paleocurrents observed in turbidite sediments, indicative of axial transport in the basin.

The main tectonic structures recognized in the area are the E-W Río Joaquín fault zone, ENE-WSW folds and late sinistral NW-SE strike-slip faults. All these structures are compatible with a compressive and/or a transpressive tectonic regime. Since the Tonosí Formation unconformably overlies tectonic features and igneous rock units, we infer a minimum pre-Oligocene age for the main tectonic phase. However, additional field and geochronological data are required to better constrain the timing of tectonism.

Hydrothermal alteration has been mainly recognized in dacites, but also in andesites further East, which have a similar age to that of the Río Quema Fm. No hydrothermal alteration has been observed affecting the sediments of the Tonosí Fm. (Oligocene). Therefore, the hydrothermal event related to mineralization must have occurred between the Late Cretaceous and the Oligocene, probably associated to one or more of the magmatic events that show up in the intrusive unit rocks (diorites, quartz-diorites and granodiorites) or to a possible porphyry system associated to the intrusion of the dacitic domes.

The mineralogy and spatial distribution of hydrothermal alteration observed in Cerro Quema fit well within the classical high sulfidation epithermal gold deposits model described by Hedenquist (1987), Berger and Henley (1989), Sillitoe (1989, 1995), White (1991), Ginggenbach (1992), Rye (1993), Hedenquist and Lowenstern (1994) and Arribas et al. (1995). Hydrothermal alteration is related to the circulation of acidic fluids of magmatic origin and to the presence of a porphyry copper system at depth in a calc-alkaline volcanic arc in both, sub-aerial and submarine environment (Sillitoe et al., 1996; Herzig et al., 1998; Paulick et al., 2004; Binns et al., 2007). Despite the mineralogy, the spatial distribution and tectono-volcanic environment of the Cerro Quema deposit are in agreement with the model, the possible presence of porphyry copper at depth could not be proved. On the other hand, a model based on an oxidized gold and copper deposit that shares characteristics of both epithermal and volcanogenic massive sulfide deposits (Nelson, 2007) can be discarded, as no signs of bedded massive sulfides have been found in the alteration zones, in the vicinity of the dacitic lava domes or associated hyaloclastitic sediments.

Some of the characteristics of the Cerro Quema deposit (presence of dacitic domes, geological setting, hydrothermal alteration pattern…) are shared with the Pueblo Viejo gold deposit (Dominican Republic), the largest mineable high sulfidation epithermal gold deposit of the Caribbean (Kesler et al., 1981, 2005; Nelson, 2000; Sillitoe et al., 2006). Considering that similar hydrothermal alteration related to E-W faults has been observed towards the East and West of Cerro Quema (Juan Díaz district and Pitaloza district respectively) we can conclude that the hydrothermal flow was a large-scale structurally controlled event that affected materials of different composition. Recognition of structurally controlled high sulfidation epithermal deposits in the studied area may have important consequences for mineral exploration. Prospection should be focused at, or close to the E-W trending faults regardless of the enclosing rock type, as hydrothermal systems seem to be related to these structures situated to the North of the Río Joaquín fault.

CONCLUSIONS

The general conclusions of this study can be summarized in the following points:

1) The stratigraphy and petrology of the volcano-sedimentary rocks of the Cerro Quema area denote a submarine depositional environment. The tectonic setting corresponds to the fore-arc basin associated to a Late Cretaceous–Paleogene intra-oceanic volcanic arc.

2) A new lithostratigraphic unit, the Río Quema Formation, is proposed to describe the volcano-sedimentary sequence that crops out in the central Azuero Peninsula and corresponds to the fore-arc basin infill sequence of the Cretaceous–Paleogene volcanic arc. The igneous rocks within this formation belong to the calc-alkaline family, with trace and REE element patterns compatible with volcanic arc affinity. The volcanic arc developed on top of a tholeiitic igneous basement (Azuero Igneous Basement) and was originated by the subduction of the Farallon Plate. The Azuero Igneous Basement's geochemistry is similar to that of the Caribbean large igneous province.

3) The Río Joaquín fault zone, a major regional scale fault zone with broad E-W orientation and reverse-sense motion, has been recognized in the study area and mapped with a slightly different trend from that proposed by Buchs (2008). Along this structure, the Azuero Igneous Basement is in direct contact with the Upper Unit of the Río Quema Formation. In addition, kilometric to decametric ENE-WSW folds and late sinistral NW-SE strike-slip faults have also been identified. These structures suggest a

compressive and/or transpressive tectonic regime, at least during Late Cretaceous–Oligocene times.

4) The Cerro Quema mineral district comprises the hydrothermally altered dacite hills of Cerro Quema, Quemita and La Pava, all included in the Río Quema Formation. An inner core of advanced argillic alteration (vuggy silica, alunite-natroalunite and dickite) and an outer halo of argillic alteration (kaolinite, illite and illite-smectite) have been recognized, both in outcrops and drill core samples. A propylitic alteration zone has only been observed in a few drill core samples.

5) Mineralization at Cerro Quema consists of disseminated pyrite, chalcopyrite and locally enargite, with a poorly developed stockwork of pyrite, chalcopyrite and barite with minor galena and sphalerite. Gold is found as disseminated submicroscopic grains both alone and within the crystalline structure of pyrite (invisible gold). It is principally concentrated within vuggy silica of the advanced argillic alteration zone.

6) The mineralogy and hydrothermal alteration pattern in the Cerro Quema area as well as the tectono-volcanic environment correspond to a high sulfidation epithermal system. The Cerro Quema deposit is part of a larger hydrothermal system related to E-W trending faults that affected different lithologies further East and West of the Azuero Peninsula.

7) The exploration criteria for finding new gold deposits in the area should be focused at or close to the E-W trending regional faults, regardless of the enclosing rock type, as hydrothermal systems seem to be related to these structures which are always situated to the North of the Río Joaquín fault zone.

ACKNOWLEDGEMENTS

This study was supported by the Spanish Ministry of Science and Education (MEC) project CGL2007-62690/BTE, a pre-doctoral grant of the "Departament d'Universitats, Recerca i Societat de la Informació (Generalitat de Catalunya)". The corresponding author would like to express his gratitude to the SEG Foundation and the SEG Canada Foundation for the 2009 and 2010 student research grants (Hugh E. McKinstry) which supported part of the field and related laboratory research expenses. This study has been performed within the framework of the Ph.D. program in Geology of the Universitat Autònoma de Barcelona. We thank Bellhaven Copper and Gold Inc. for access to mine samples and drill cores used in this study. Discussions with David Buchs about the geology of the Azuero Peninsula were very fruitful. Fieldwork comments and help by Stuart Redwood and Carl Nelson are greatly appreciated. Finally, we want to show our gratitude to Mark Jessell for the final revision of the manuscript.

REFERENCES

Adamek, S., Frohlich, C., Pennington, W.D., 1988. Seismicity of the Caribbean-Nazca boundary; constraints on microplate tectonics of the Panama region. Journal of Geophysical Research, 93, 2053-2075.

Arribas, A.Jr., Hedenquist, J.W., Itaya, T., Okada, T., Concepcion, R.A., Garcia, J.S.Jr., 1995. Contemporaneous formation of adjacent porphyry and epithermal Cu-Au deposits over 300 ka in northern Luzon, Philippines. Geology, 23, 337-340.

Berger, B.R., Henley, R.W., 1989. Advances in the understanding of epithermal gold-silver deposits, with special reference to the Western United States. Economic Geology Monographs, 6, 405-423.

Binns, R.A., Barriga, F.J.A.S., Miller, D.J., 2007. 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 Ocean Drilling Program, Scientific Results. Texas, College Station, Ocean Drilling Program, 193, 1-71.

Bourgois, J., Azema, J., Tournon, J., Bellon, H., Calle, B., Parra, E., Toussaint, J.F., Glacon, G., Feinberg, H., Dewever, P., Origlia, I. 1982. Ages and Structures of the Basic and Ultrabasic Complexes of the Pacific Coast between 3-Degrees-N and 12-Degrees-N (Colombia, Panama and Costa-Rica). Bulletin de La Société Géologique de France, 24, 545-554.

Buchs, D.M., 2008. Late Cretaceous to Eocene geology of the South Central American fore-arc area (southern Costa Rica and western Panama): Initiation and evolution of an intra-oceanic convergent margin. Doctoral Thesis. Switzerland, Université de Lausanne, 230pp.

Buchs, D.M., Baumgartner, P.O., Baumgartner-Mora, C., Bandini, A., Jackett, S-J., Diserens, M-O., Stucki, J., 2009. Seamount accretion and melange formation of the Osa Peninsula (southern Costa Rica): Eocene–Miocene mass wasting and tectonic processes along the Middle American Trench. In: James, K., Lorente, M.A., Pindell, J. (eds.). The geology and evolution of the region between North and South America. Geological Society of London, Special Publications, 411-456.

Buchs, D.M., Arculus, R.J., Baumgartner, P.O., Baumgartner-Mora, C., Ulianov, A., 2010. Late Cretaceous Arc Development on the SW margin of the Caribbean Plate: Insights from the Golfito (Costa Rica) and Azuero (Panama) Complexes. Geochemistry, Geophysics, Geosystems, 11(7), 35pp.

Coates, A.G., Collins, L.S., Aubry, M.-P., Berggren, W.A., 2004. The Geology of the Darien, Panama, and the late Miocene-Pliocene collision of the Panama arc with northwestern South America. Geological Society of America Bulletin, 116, 1327-1344.

Coates, A.G., Jackson, J.B.C., Collins, L.S., Cronin, T.M., Dowsett, H.J., Bybell, L.M., Jung, P., Obando, J.A., 1992. Closure of the Isthmus of Panama: The near-shore marine record of Costa Rica and western Panama. Geological Society of America Bulletin, 104, 814-828.

Corral, I., 2008. El dipòsit d'Au-Cu de "La Pava" (Península d'Azuero, Panamà): caracterització geològica i mineralògica. Master of Science. Universitat Autònoma de Barcelona, 31pp.

de Boer, J.Z., Drummond, M.S., Bordelon, M.J., Defant, M.J., Bellon, H., Maury, R.C., 1995. Cenozoic magmatic phases of the Costa Rican island arc (Cordillera de Talamanca). Geological Society of America, 295, 35-55.

Del Giudice, D., Recchi, G., 1969. Geología del área del Proyecto Minero de Azuero. Informe técnico preparado para el gobierno de la República de Panamá por las Naciones Unidas. Panamá City (Panamá), Gobierno de la República de Panamá, 48pp.

Denyer, P., Alvarado, G.E., 2007. Mapa Geológico de Costa Rica 1:400.000. Librería Francesa S.A.

Dirección General de Recursos Minerales, 1976. Panama Geologic Map (Mapa geológico de la República de Panamá), scale 1:250.000. Panama City, Panama.

Di Marco, G., Baumgartner, P.O., Channell, J.E.T., 1995. Late Cretaceous-early Tertiary paleomagnetic data and a revised tectonostratigraphic subdivision of Costa Rica and western Panama. Geological Society of America, 295, 1-27.

Duque-Caro, H., 1990. Neogene stratigraphy, paleoceanography and paleobiogeography in Northwest South America and the evolution of the Panama Seaway. Palaeogeography, Palaeoclimatology, Palaeoecology, 77, 203-234.

Escalante, G., 1990. The geology of southern Central America and western Colombia In: Dengo, G., Case, J.E. (eds.). The Caribbean Region. Boulder, Colorado, Geological Society of America, The Geology of North America, H, 201-230.

Ferencic, A., 1970. Porphyry copper mineralization in Panama. Mineralium Deposita, 5, 383-389.

Ferencic, A., 1971. Metallogenic provinces and epochs in southern Central America. Mineralium Deposita, 6, 77-88.

Fisher, D.M., Gardner, T.W., Marshall, J.S., Sak, P.B., Protti, M., 1998. Effect of subducting sea-floor roughness on fore-arc kinematics, Pacific coast, Costa Rica. Geology, 26, 467-470.

Gardner, T., Marshall, J., Merritts, D., Bee, B., Burgette, R., Burton, E., Cooke, J., Kehrwald, N., Protti, M., Fisher, D., Sak, P., 2001. Holocene fore-arc block rotation in response to seamount subduction, southeastern Peninsula de Nicoya, Costa Rica. Geology, 29, 151-154.

Giggenbach, W.F., 1992. Magma degassing and mineral deposition in hydrothermal systems along convergent plate boundaries. Economic Geology, 87, 1927-1944.

Goossens, P.J., Rose, W.I.J., Flores, D., 1977. Geochemistry of tholeiites of the Basic Igneous Complex of northwestern South America. Geological Society of America Bulletin, 88, 1711-1720.

Hannington, M.D., 1997. The Porphyry-Epithermal-VMS Transition: Lessons from the Iskut River Area, British Columbia, and Modern Island Arcs. Society of Economic Geology Newsletter, 29, 12-13.

Harmon, R.S., 2005. Geological development of Panama. Water Science and Technology Library, 52, 45-62.

Hauff, F., Hoernle, K., van den Bogaard, P., Alvarado, G., Garbe-Schoenberg, D., 2000. Age and geochemistry of basaltic complexes in western Costa Rica; contributions to the geotectonic evolution of Central America. Geochemistry Geophysics Geosystems, 1(5), 41pp.

Hedenquist, J.W., 1987. Mineralization associated with volcanic-related hydrothermal systems in the Circum-Pacific basin. Transactions of the Circum-Pacific Energy and Mineral Resources Conference, 4, 513-524.

Hedenquist, J.W., Lowenstern, J.B., 1994. The role of magmas in the formation of hydrothermal ore deposits. Nature, 370, 519-527.

Herzig, P.M., Hannington, M.D., Arribas, A.Jr., 1998. Sulfur isotopic composition of hydrothermal precipitates from the Lau back-arc: implications for magmatic contributions to seafloor hydrothermal system. Mineralium Deposita, 33, 226-237.

Hoernle, K., Hauff, F., 2007. Oceanic Igneous Complexes. Central America, geology, resources and hazards, 1, 523-548.

Hoernle, K., Hauff, F., van den Bogaard, P., 2004. 70 m.y. history (139-69 Ma) for the Caribbean large igneous province. Geology, 32, 697-700.

Hoernle, K., van den Bogaard, P., Werner, R., Lissinna, B., Hauff, F., Alvarado, G., Garbe-Schonberg, D., 2002. Missing history (16-71 Ma) of the Galapagos hotspot: Implications for the tectonic and biological evolution of the Americas. Geology, 30, 795-798.

Horlacher, C.F., Lehmann, J.H., 1993. Regional Geology, Geochemistry and Exploration potential of the central Cerro Quema concession, Panama. Unpublished report, 36pp.

Irvine, T.N., Baragar, W.R.A., 1971. A guide to the chemical classification of the common volcanic rocks. Canadian Journal of Earth Sciences, Revue Canadienne des Sciences de la Terre, 8, 523-548.

Kellogg, J.N., Vega, V., Stallings, T.C., Aiken, C.L.V., 1995. Tectonic development of Panama, Costa Rica, and the Colombian Andes; constraints from Global Positioning System geodetic studies and gravity. Geological Society of America, 295 (Special Paper), 75-90.

Kerr, A.C., Marriner, G.F., Tarney, J., Nivia, A., Saunders, A.D., Thirlwall, M.F., Sinton, C.W., 1997. Cretaceous basaltic terranes in western Colombia: Elemental, chronological and Sr-Nd isotopic constraints on petrogenesis. Journal of Petrology, 38, 677-702.

Kesler, S.E., Campbell, I.H., Smith, C.N., Hall, C.M., Allen, C.M., 2005. Age of the Pueblo Viejo Gold-Silver Deposit and its significance to models for High-Sulfidation Epithermal Mineralization. Economic Geology, 100, 253-272.

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, Dominican Republic. Economic Geology, 76, 1096-1117.

Kesler, S.E., Sutter, J.F., Issigonis, M.J., Jones, L.M., Walker, R.L., 1977. Evolution of porphyry copper mineralization in an oceanic island arc; Panama. Economic Geology, 72, 1142-1153.

Kolarsky, R.A., Mann, P., Monechi, S., Meyerhoff-Hull, D., Pessagno, E.A., 1995. Stratigraphic development of southwestern Panama as determined from integration of marine seismic data and onshore geology. Geological Society of America Special Paper, 295, 159-200.

Kolarsky, R.A., Mann, P., 1995. Structure and neotectonics of an oblique-subduction margin, southwestern Panama. Geological Society of America Special Paper, 295, 131-157.

Krawinkel, H., Wozazek, S., Krawinkel, J., Hellmann, W., 1999. Heavy-mineral analysis and clinopyroxene geochemistry applied to provenance analysis of lithic sandstones from the Azuero-Soná Complex (NW Panama). Sedimentary Geology, 124, 149-168.

Krawinkel, J., and Seyfried, H., 1994. Struktur und Kinematik im Fore-arc der suedlichen zentralamerikanischen Landbruecke. Bonn, Terra Nostra, 2(94), 47-48.

Le Maitre, R.W., Bateman, P., Dudek, A., Keller, J., Lemeyre, J., Le Bas, M.J., Sabine, P.A., Schmid, R., Sorensen, H., Streckeisen, A., Wooley, A.R., Zanettin, B., 1989. A classification of igneous rocks and glossary of terms. Oxford, Blackwell Scientific, 193pp.

Leach, T.M., 1992. Petrological Evaluation of the High Sulphidation Systems in the La Pava and Cerro Quema Prospect Areas, Panama, for Cyprus Gold Company. Unpublished report, 55pp.

Lissinna, B., Hoernle, K., van den Bogaard, P., 2002. Northern migration of arc volcanism in western Panama: evidence for subduction erosion? Eos Transactions, American Geophysical Union, 83, 1463-1464.

Lissinna, B., 2005. A profile through the Central American Landbridge in western Panama: 115 Ma Interplay between the Galápagos Hotspot and the Central American Subduction Zone. Doctoral Thesis. Germany, Christian-Albrechts-Universität zu Kiel, 102pp.

Lissinna, B., Hoernle, F., Hauff, P., van den Bogaard, P., Sadofsky, S., 2006. The Panamanian island arc and Galápagos hotspot: A case study for the long-term evolution of arc/hotspot interaction. Geophysical Research Abstracts, 8, 05106.

Mann, P., Kolarsky, R.A., 1995. East Panama deformed belt; structure, age, and neotectonic significance. Geological Society of AAmerica, 295 (Special Paper), 111-130.

Mann, P., Corrigan, J., 1990. Model for late Neogene deformation in Panama. Geology, 18, 558-562.

Marshall, J.S., Idleman, B.D., Gardner, T.W., Fisher, D.M., 2003. Landscape evolution within a retreating volcanic arc, Costa Rica, Central America. Geology, 31(5), 419-422.

Maury, R.C., Defant, M.J., Bellon, H., De Boer, J.Z., Stewart, R.H., Coten, J., 1995. Early Tertiary arc volcanic from eastern Panama. Geological Society of America, 295 (Special Paper), 30-34.

Metti, A., Recchi, G., 1976. Geología de la Península de Sona e Isla de Coiba. Boletín de Geología Publicación Especial, 541-553.

Metti, A., Recchi, G., Esquivel, D., 1972. Mapa geológico Sona-Isla de Coiba: scale 1:250.000. Ministerio de Comercio e Industrias, Panama City (Republica de Panamá).

Nelson, C.E., 1995. Porphyry copper deposits of southern Central America. Arizona Geological Society Digest, 20, 553-565.

Nelson, C.E., 2000. Volcanic domes and gold mineralization in the Pueblo Viejo District, Dominican Republic. Mineralium Deposita, 35, 511-525.

Nelson, C.E., 2007. Metallic mineral resources. In: Bundschuh, J., Alvarado, G.E. (eds.). Central America. Geology, Resources and Hazards. The Netherlands, Taylor & Francis, 32 (Chapter), 885-915.

Nelson, C.E., Nietzen, F., 2000. Metalogenia del oro y cobre en América Central. Revista Geológica de América Central, 23, 25-41.

Paulick, H., Vanko, D.A., Yeats, C.J., 2004. Drill core-based facies reconstruction of a deep-marine felsic volcano hosting an active hydrothermal system (Pau Ridge, Papua New Guinea, ODP Leg 193). Journal of Volcanology and Geothermal Research, 130, 31-50.

Pindell, J., Kennan, L., 2009. Tectonic evolution of the Gulf of Mexico, Caribbean and northern South America in the mantle reference frame: an update. In: James, K., Lorente, M.A., Pindell, J. (eds.). The geology and evolution of the region between North and South America. Geological Society of London, 328 (Special Publications), 1-55.

Recchi, G., Miranda, R., 1977. Calizas de los Planes-Guaniquito (Tonosí). Unpublished report, Panama City, Dirección General de Recursos Minerales, 27pp.

Révillon, S., Hallot, E., Arndt, N.T., Chauvel, C., Duncan, R.A., 2000. A complex history for the Caribbean plateau: Petrology, geochemistry and geochronology of the Beata Ridge, South Hispaniola. Journal of Geology, 108, 641-661.

Rye, R.O., 1993. The evolution of magmatic fluids in the epithermal environment; the stable isotope perspective. Economic Geology, 88, 733-752.

Sak, P.B., Fisher, D.M., Gardner, T.W., 2004. Effects of subducting seafloor roughness on upper plate vertical tectonism: Osa Peninsula, Costa Rica. Tectonics, 23, 16pp.

Sillitoe, R.H., 1989. Gold deposits in western Pacific island arcs; the magmatic connection. Economic Geology Monographs, 6, 274-291.

Sillitoe, R.H., 1995. Exploration of porphyry copper lithocaps. Publication Series – Australasian. Institute of Mining and Metallurgy, 9(95), 527-532.

Sillitoe, R.H., Hannington, M.D., Thompson, J.F.H., 1996. High sulfidation deposits in the volcanogenic massive sulfide environment. Economic Geology, 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 mode of formation beneath barren limestone cover. Economic Geology, 101, 1427-1435.

Silver, E.A., Reed, D.L., Tagudin, J.E., Heil, D.J., 1990. Implications of the North and South Panama thrust belts for the origin of the Panama Orocline. Tectonics, 9, 261-281.

Sinton, C.W., Duncan, R.A., Denyer, P., 1997. Nicoya Peninsula, Costa Rica; a single suite of Caribbean oceanic plateau magmas. Journal of Geophysical Research, 102(B7), 15, 507-15, 520.

Sinton, C.W., Duncan, R.A., Storey, M., Lewis, J., Estrada, J.J., 1998. An oceanic flood basalt province within the Caribbean Plate. Earth and Planetary Science Letters, 155, 221-235.

Sun, S.S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts; implications for mantle composition and processes. Geological Society, 42 (Special Publications), 313-345.

Taboada, A., Rivera, L.A., Fuenzalida, A., Cisternas, A., Philip, H., Bijwaard, H., Olaya, J., Rivera, C., 2000. Geodynamics of the Northern Andes; subductions and intracontinental deformation (Colombia). Tectonics, 19, 787-813.

Torrey, C., Keenan, J., 1994. Cerro Quema Project, Panama, Prospecting in tropical and arid terrains. Toronto, Ontario, Canada, Unpublished report, 23pp.

Trenkamp, R., Kellogg, J.N., Freymueller, J.T., Mora, H.P., 2002. Wide plate margin deformation, southern Central America and northwestern South America, CASA GPS observations. Journal of South American Earth Sciences, 15, 157-171.

Tournon, J., Triboulet, C., Azéma, J., 1989. Amphibolites from Panama: anticlockwise P-T paths from a Preuper Cretaceous metamorphic basement in Istmian Central America. Journal of Metamorphic Geology, 7, 539-546.

Weyl, R., 1980. Geology of Central America. Berlin, Gebrueder Borntraeger, 2nd edition, 371pp.

White, N.C., 1991. High sulfidation epithermal gold deposits; characteristics and a model for their origin: Chishitsu Chosajo Hokoku. Report-Geological Survey of Japan, 9-20.

Wegner, W., Wörner, G., Harmon, R.S., Jicha, B.R., 2011. Magmatic history and evolution of the Central American Land Bridge in Panama since Cretaceous times. Geological Society of America Bulletin, 123, 703-724.

Wörner, G., Harmon, R.S., Wegner, W., 2009. Geochemical evolution of igneous rocks and changing magma sources during the formation and closure of the Central American land bridge of Panama: Backbone of the Americas: Shallow Subduction, Plateau Uplift, and Ridge Terrane Collision. Geological Society of America Memoir, 204, 183-196.

Wörner, G., Harmon, R.S., Hartmann, G., Simon, K., 2005. Igneous Geology and Geochemistry of the Upper Río Chagres Basin. In: Singh, V.P., Harmon, R.S. (eds.). The Río Chagres, Panama: A Multidisciplinary Profile of a Tropical Watershed. Springer, 65-81.

Wörner, G., Harmon, R.S., Wegner, W., Singer, G., 2006. Linking America's backbone: Geological development and basement rocks of central Panama. Mendoza (Argentina), 2-7 April 2006, Geological Society of America Conference "Backbone of the Americas", Boulder (Colorado), Geological Society of America, Abstrstracts with Programs, 60.

Manuscript received November 2010;
revision accepted July 2011;
published Online July 2011.