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Abstract

The Cuale mining district, situated in the Cordillera Madre del Sur, ~30 km southeast of Puerto Vallarta, Mexico, comprises a number of small, polymetallic Pb, Zn, Cu, volcanogenic massive sulfide deposits (VMS), and vein and stockwork-hosted deposits with low-sulfidation epithermal characteristics. Massive sulfide mineralization contains high Ag ± Au grades when compared to similar deposits in western Mexico. The massive sulfide bodies are hosted by an interbedded rhyolitic volcanic and volcaniclastic succession, herein termed the Cuale volcanic sequence. Regionally, the Cuale volcanic sequence is part of the Zihuatanejo subterrane belonging to the Guerrero terrane, which is interpreted to be a complex Mesozoic accreted arc terrane hosting the majority of VMS deposits in Mexico.

The rocks of the Cuale volcanic sequence are not metamorphosed and are only weakly deformed but exhibit intense chlorite, sericite, and quartz hydrothermal alteration. Three stratigraphic units are identified within the Cuale volcanic sequence: (1) a more than 400-m-thick footwall unit of quartz and plagioclase phyric rhyolite flows, related hyaloclastites, and subordinate heterolithic volcaniclastic breccias; (2) an ore horizon characterized by sedimentary rocks ranging from volcaniclastic conglomerates to black shales, as well as aphyric to quartz and plagioclase phyric rhyolite; and (3) late intrusions composed of quartz and plagioclase phyric rhyolite and subordinate andesitic dikes intruding all units. The sedimentary rocks of the ore horizon are intercalated with rhyolite tuff horizons, some of which exhibit welding or accretionary lapilli that are interpreted as evidence for shallow submarine or subaerial deposition.

The rhyolites of the Cuale volcanic sequence are calc-alkaline with only limited compositional variations. However, the trace element signatures reveal a weak trend from the footwall rhyolites, which are characterized by low Zr/Y (1–1.9) and low chondrite normalized La/Yb ratios (9 of 11 samples between 1.24 and 3.3), to slightly higher values in the ore horizon and late intrusive phase (Zr/Y = 1.6–7.6 and chondrite normalized La/Yb ratios between 2.25 and 15). This compositional evolution can be explained by slightly decreasing degrees of partial melting related to a transition from amphibole-free assemblages for the footwall to amphibole-bearing assemblages in the residue for the ore horizon and intrusive rhyolites. This interpretation is supported by the observed volcanic stratigraphy and indicates increasing pressure at the site of melt generation as the volcanic edifice was built.

Zircons from five samples of the Cuale volcanic sequence have been dated by the U-Pb method, using isotope dilution thermal ionization mass spectrometry (ID-TIMS). Although some samples show evidence of a minor inherited Pb component, an age range of 157.2 ± 0.5 to 154.0 ± 0.9 Ma has been established. Cuale represents the oldest dated VMS camp in western Mexico as other VMS districts of western Mexico are between 151.3 and 138 Ma.

Two styles of mineralization are recognized: volcanogenic massive sulfide mineralization (VMS) and late low-sulfidation epithermal vein and stockwork mineralization characterized by high Au (1.89 ppm) and Zn (2.35%) but low Cu (0.2%) contents. The VMS mineralization is contained in more than 15 small orebodies, which exhibit a range of mineralization styles. Orebodies interpreted as proximal are characterized by stockwork vein networks with high Au and Cu contents, underlying massive pyrite bodies, which grade laterally and vertically into sphalerite- and galena-rich massive sulfide ore. Stockwork mineralization is locally hosted by aphyric rhyolite. More distal orebodies, rich in Pb, Zn, and Ag, are hosted by black shale and locally exhibit laminated or brecciated sedimentary textures in the galena-sphalerite-pyrite ore. The sedimentary textures observed in some massive sulfide orebodies suggest that the sulfide has been transported and deposited in anoxic basins adjacent to the rhyolite domes. Some of the more significant orebodies show evidence of both distal sedimentary ore textures and proximal features indicated by intense quartz-sericite-pyrite alteration in the immediate footwall.
Introduction

Recent discoveries of large and/or precious metal-rich (bimodal)-volcanogenic massive sulfide deposits (VMS) in accreted arc terranes of Jurassic to Cretaceous age, such as the 83-Mt San Nicolas deposit in Mexico (Fig. 1; Johnson et al. 1999, 2000; Danielson, 2000) and the gold-rich Eskay Creek deposit in British Columbia, Canada (Roth et al., 1999), have increased exploration interest in areas of similar geologic setting along the North American Cordillera. The Guerrero terrane, composing much of west-central Mexico, is of interest as it is interpreted as a Jurassic to Cretaceous accreted arc terrane (Campa and Coney, 1983; Centeno-García et al., 1993; Dickinson and Lawton, 2001) and has a long history of mining and exploration for VMS deposits. The known deposits range from large to small in size (Fig. 1; Miranda-Gasca, 2000). From a historical perspective, the Cuale district is one of the more significant VMS districts of the Americas. Mining operations were initiated in the Prieta orebody by the Spanish in 1805 to extract silver-rich ore zones (averaging 500 g/t) and exploration for VMS deposits. The known deposits in western Mexico (Figs. 1, 2) and ~4 km southwest of the small town of Cuale, So far, only 2.5 million metric tons (Mt) of ore averaging 0.83 ppm Au, 103 ppm Ag, 1.03 percent Pb, 3.22 percent Zn, and 0.23 percent Cu have been produced from more than 18 small but high-grade orebodies. All but the Chivas de Abajo deposit (Fig. 3) had been discovered and high graded prior to 1919 (Berrocal and Querol, 1991; Hall and Gomez-Torres, 2000a). The silver-rich nature of the ore (drill intercepts of up to 9630 g/t Ag) was the major driving force for mining in the 19th century, whereas Pb, Zn, Cu, Ag, and Au were the main commodities produced in the 1980s by Zimapán S.A de C. V., which bulk mined orebodies where high-grade silver ore was extracted previously. Mining in the district ceased in 1989, once the easily accessible reserves were mined out; however, the area is currently being explored.

Despite the long history of mining and exploration at Cuale, only limited scientific research has been carried out. Macomber (1962) produced a detailed geologic map and established a stratigraphic succession. This work was done before the current genetic models for VMS deposits were accepted (e.g., Hutchinson, 1965). In 1986, the Japan International Cooperation Agency and Metal Mining Agency of Japan, in conjunction with the Consejo de Recursos Minerales de Mexico, conducted a multidisciplinary study of VMS deposits of western Jalisco state (JICA-MMAJ, 1986), which included reconnaissance-scale geologic mapping. Additional geologic mapping of the immediate Cuale district was carried out by Zimapán geologists during the exploration activities of the late 1970s to early 1980s. Diamond drilling in the district was initiated in the late 1950s by Eagle Picher S.A. de C.V. with Zimapán S.A. de C.V. completing approximately 500 (generally short), diamond drill holes between 1978 and 1989. Unfortunately, much of the drill core is lost or inaccessible and reliable drill log records are scarce.

FIG. 1. Map of the Guerrero terrane of western Mexico, showing the distribution of various exposures and the subterrane divisions of Centeno-García et al. (2003), modified from Mortensen et al. (2008). The Arteaga Complex (Centeno-García et al., 1993) and the Las Ollas Complex (Talavera-Mendoza, 2000), both part of the Zihuatanejo subterrane, are indicated. Black stars show volcanogenic massive sulfide (VMS) deposits and prospects hosted by the Guerrero terrane (see text and Mortensen et al., 2008, for further discussion). The gray shaded area in the inset map indicates the inferred extent of the Guerrero terrane. Abbreviations: SMO = Sierra Madre Occidental, SMS = Sierra Madre del Sur mountain belts.

FIG. 2. Geologic map of the Cuale region. Only limited regional geologic information is available and has been taken from 1:100,000 scale maps of the Instituto Nacional de Geografía e Informática (INEGI) Mexico and maps from the report of the Japan International Cooperation Agency-Metal Mining Agency of Japan (JICA-MMA, 1986).
Fig. 3. Lithologic map of the Cuale mining district (this study). The traces of the cross sections (Fig. 4) are indicated. The approximate extents of the ore zones, projected to the surface are indicated. Coordinates are given as Universal Transverse Mercator (UTM) zone 13, North American Datum 83 (NAD83).
District-scale geologic mapping at Cuale is challenging, as the volcanic rocks display only limited compositional vari-
tions (see below), are altered and deeply weathered, and the
terrain is steep and vegetated. Despite these limitations, the
Cuale district is well suited to the study of the volcanologic
setting at the time of ore formation, since it represents a con-
tinental margin VMS district that has not undergone meta-
morphism or significant later deformation, and the steep ter-
rain permits geologic mapping in three dimensions.

The main aim of this study is to improve the geologic un-
derstanding of the district and establish constraints on the
volcanologic setting at the time of mineralization. This paper
presents the results of new district-scale mapping (Figs. 3, 4),
including areas only accessible using technical climbing
equipment, supplemented by whole-rock geochemistry, and
U-Pb geochronology.

Tectonostratigraphic Framework: The Guerrero Terrane

The subdivision of Mexico into tectonostratigraphic terr-
rane was laid out by Campa and Coney (1983), subsequently
discussed and refined by Centeno-Garcia et al. (1993, 2003),
Dickinson and Lawton (2001), Keppie (2004), and Centeno-
Garcia (2005). The Guerrero terrane constitutes much of
west-central Mexico (Fig. 1) and, physiographically, includes
parts of the Sierra Madre Occidental and Sierra Madre del
Sur mountain belts. It is a composite arc terrane, divided into
five subterranes (Fig. 1) on the basis of differences in base-
ment geology, stratigraphy, style, and intensity of deformation
(Campa and Coney, 1983; Centeno-García et al., 1993, 2003;
Centeno-García, 2005). We follow the subterrene definitions
proposed by Centeno-García et al. (2003) and, for simplicity,
hereafter use the term Guerrero terrane when referring to
the Guerrero Composite terrane.

The complex arc-back arc system of the Guerrero terrane
was accreted to the North American continent late in the
Early Cretaceous (Dickinson and Lawton, 2001) and hosts
the majority of the VMS occurrences in Mexico (Miranda-
Gasca, 2000; Mortensen et al., 2008; Fig. 1). Among the
most significant are the 31-Mt Campo Morado district
(Oliver et al., 2000, 2001), the 4.3-Mt Tizapa deposit (Parga

![Fig. 4. Geologic cross sections based on the lithologic map of the Cuale mining district and limited drill core informa-
tion. The approximate extents of the ore zones are projected onto the cross-section plane. Traces of the cross sections are in-
dicated in Figure 3.](image-url)
and Rodriguez, 1991), and the 3-Mt Rey de Plata deposit (Miranda-Gasca et al., 2001). All of these are located in the southern Guerrero terrane (Fig. 1) and hosted by metamorphosed bimodal calc-alkaline volcanic rocks of Upper Jurassic to Lower Cretaceous age. The 83-Mt San Nicolas deposit in the eastern Guerrero terrane (Johnson et al., 1999, 2000) is the largest known VMS deposit of Mexico and is hosted by a bimodal sequence of tholeiitic volcanic and volcanioclastic rocks. Massive sulfide deposits of the western Guerrero terrane are smaller and include the ~6-Mt barite-rich Zn-Ag deposit of La Minita, near Colima (De la Campa, 1991), and the Cuale deposits, as well as the small Bramador and Amalteo districts 10 to 12 km to the south and southeast of Cuale (Figs. 1, 2).

The Guerrero terrane is composed of mostly submarine volcanic and volcanioclastic rocks of Jurassic and Cretaceous age, interbedded with shallow marine limestones, and siliciclastic sedimentary rocks. These rocks were deposited unconformably on a Permian(?)-Triassic to Early Jurassic basement of deformed deep marine siliciclastic sequences (e.g., Campa and Coney, 1983; Centeno-García et al., 1993, 2003).

Large volumes of calc-alkaline magmas intruded the Guerrero terrane after accretion to the continent in the Late Cretaceous to Eocene (Schaaf et al., 1995), whereas Tertiary to recent volcanic rocks emplaced in the continental arcs of the Sierra Madre Occidental and Sierra Madre del Sur, as well as the Trans-Mexican volcanic belt, cover the Mesozoic and Cenozoic rocks. Massive sulfide deposits of the western Guerrero terrane are smaller and include the ~6-Mt barite-rich Zn-Ag deposit of La Minita, near Colima (De la Campa, 1991), and the Cuale deposits, as well as the small Bramador and Amalteo districts 10 to 12 km to the south and southeast of Cuale (Figs. 1, 2).

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Terrane subdivisions

Five subterranes have been indentified by Centeno-García et al. (2003; Fig. 1).

The Teloloapan subterrane, host to the Campo Morado, Tizapa, and Rey de Plata VMS districts, occupies the southeastern part of the Guerrero terrane, which consists mostly of shallow submarine, Lower Cretaceous basaltic to andesitic lavas with subordinate limestone intercalations. The basement is unknown. These rocks are strongly deformed and metamorphosed to lower greenschist facies assemblages. The Teloloapan subterrane was thrusted eastward over Lower to Upper Cretaceous platform carbonates deposited on the adjacent Mixteco terrane.

The Arcelia subterrane borders the Teloloapan subterrane to the northwest and is an intensely deformed sliver of basalt and ultramafic rocks intercalated with black shale and chert, to which an Upper Cretaceous age is assigned (Ramírez et al., 1991). No significant VMS mineralization has been reported from this subterrane.

The Zihuatanejo subterrane is the largest subterrane, occupying much of the central Mexican Pacific coastal region. It consists of Upper Jurassic to Cretaceous shallow marine limestones and marine to subaerial basaltic to rhyolitic volcanic rocks, overlying a Triassic basement, which locally is intruded by Jurassic granitoids. Some of the best studied parts of the Guerrero terrane lay in this subterrane. It is discussed in more detail below, as it hosts the Cuale district and, in its eastern extensions, the large San Nicolas deposit.

The Geology of the Zihuatanejo Subterrane

The Zihuatanejo subterrane occupies the Pacific coastal portion of Mexico from Puerto Vallarta to Zihuatanejo and extends several hundred kilometers inland (Fig. 1). According to Centeno-García et al. (2003), it includes the Huetamo subterrane, which was considered a separate tectonostratigraphic domain by previous workers (e.g., Centeno-García et al., 1993).

The Zihuatanejo subterrane has been studied in most detail some 300 km southeast of Cuale, near the city of Zihuatanejo (e.g., Centeno-García et al., 1993; Freydier et al., 1997; Mendoza and Suastegui, 2000; Talavera-Mendoza, 2000). The stratigraphy defined by these workers is characterized by a late Paleozoic and Triassic basement, consisting of weakly metamorphosed, strongly deformed terrigenous clastic sedimentary rocks with minor basalts (Arteaga Complex: Centeno-García et al., 1993; Fig. 1). These basement rocks are intruded by calc-alkaline, I-type granitoid rocks to which a Late Jurassic age of ~160 Ma has been assigned (Tumbiscatío and Macías intrusions: Centeno-García et al., 2003; Petróleos Mexicanos (PEMEX) unpub. company reports). The Arteaga Complex is overlain by the weakly deformed Upper Jurassic to Lower Cretaceous Zihuatanejo sequence of Mendoza and Suastegui (2000), consisting of arc-related volcanic and volcanioclastic rocks, ranging from andesitic to rhyolitic in composition. An Early Cretaceous subduction-related mélangé, spatially associated with the largely undeformed Zihuatanejo sequence, is recognized as the Las Ollas complex (Talavera-Mendoza, 2000; Fig. 1). The Early Cretaceous volcanic and volcanioclastic sequences are capped by Albian reefal limestones and red beds (Mendoza and Suastegui, 2000).

The geology and stratigraphy of the Cuale area (Figs. 2, 3) have been loosely correlated with the above stratigraphy on the basis of overall stratigraphic similarities (e.g., Hall and Gomez-Torres, 2000a); however, our new observations (see below) lead to a significant refinement of this regional comparison.

Geologic Setting of the Cuale District

The oldest unit at Cuale comprises pelitic schists, intercalated with chloritic and sericitic schists and meta-arces and crops out to the west of the Cuale mining district (Figs. 2, 3). This package is gently folded and metamorphosed to subgreenschist...
Stratigraphy of the Cuale Volcanic Sequence

Due to the intense weathering (particularly on ridges) and locally strong hydrothermal alteration, distinguishing minor textural differences among the felsic rocks of the Cuale volcanic sequence is difficult. However, the coherent rhyolite sequence (Fig. 2) is assigned to the Cretaceous Puerto Vallarta sequence (Fig. 2). It is assigned to the Cretaceous to lower Tertiary (JICA-MMA, 1986). The volcanic rocks of the Cuale mining district, herein termed the Cuale volcanic sequence, are part of this stratigraphic succession. However, the results of this study cast doubt on the age constraints and compositional variations reported by JICA-MMA (1986).

We interpret the Cuale volcanic sequence to be almost entirely composed of Late Jurassic rhyolite and rhyolitic volcaniclastic sedimentary rocks with an overall thickness exceeding 800 m. Cretaceous and Tertiary volcanic rocks have not been recognized in the Cuale mining district.

The youngest rock unit found in the study area is massive and unaltered granodiorite that has intruded the Cuale volcanic sequence (Fig. 2). It is assigned to the Cretaceous Puerto Vallarta batholith, which, in the vicinity of the Cuale district, exhibits weak peraluminous characteristics (Schaaf et al., 1995).

Stratigraphy of the Cuale Volcanic Sequence

The largely undeformed and unmetamorphosed volcanic and associated volcaniclastic rocks that overlie the pelitic schists of the basement have been subdivided into several stratigraphic units based on reconnaissance-scale geologic mapping (Japan International Cooperation Agency and Metal Mining Agency of Japan (JICA-MMA: 1986)). Volcanic rocks in the region ranging from basalt to dacite were reported and assigned to the Lower Cretaceous to lower Tertiary (JICA-MMA, 1986). The volcanic rocks of the Cuale mining district, herein termed the Cuale volcanic sequence, are part of this stratigraphic succession. However, the results of this study cast doubt on the age constraints and compositional variations reported by JICA-MMA (1986).

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Stratigraphic map (Fig. 5) and schematic stratigraphic column (Fig. 6).

The stratigraphy of the Cuale volcanic sequence has been subdivided, in relationship to the massive sulfide mineralization and alteration, into a footwall, ore horizon, and late intrusive phase, and is described below. The stratigraphic units described herein have been deposited in an environment with significant relief, and individual lithologic horizons are generally of limited lateral extent.

Footwall

The footwall stratigraphy exceeds 400 m in thickness and is dominated by quartz and feldspar phryic rhyolite flows and cryptodomes, commonly enveloped by large volumes of monomictic, commonly matrix-supported, volcanic breccias interpreted as carpaccio or flow breccias and hyaloclastites (Fig. 7). Its outcrop extent includes the topographically low-lying areas to the south and southeast of Naricero and much of the western and northwestern flank of Cerro Caracol (Fig. 5). The rhyolite flows rarely are massive but normally exhibit flow banding, spherulitic devitrification, amygdalae, and lithophysae (Fig. 7). They contain 5 to 8 vol percent slightly embayed quartz phenocrysts that are up to 3 mm in diameter and, where not obliterated by alteration, similar amounts of euhedral feldspars. The outcrop extent and accessibility does not permit detailed mapping of lateral variations in individual flows and their geometric relationships to the brecciated rocks nor does it allow identification of individual extrusive centers.

Coarse, polymeric volcaniclastic breccias (Fig. 7) to finer grained conglomerates are interbedded with the volcanic rocks of the sequence. Clasts are all derived from the Cuale rhyolitic sequence but may be from flows as well as from previously deposited volcaniclastic rocks. The coarse polymeric volcaniclastic breccia deposits are commonly matrix supported, with angular clasts of up to 30 cm in diameter, and are generally not graded nor welded (Fig. 7). Thus, the footwall sequence is thought to have been extruded subaerially and, at least partly, in an explosive manner (hyaloclastites). Parts of the volcanic rocks have been reworked into volcaniclastic breccias and conglomerate horizons.

The overall stratigraphy of the footwall is dominated by proximal volcanic deposits, such as quartz-feldspar phryic rhyolite flows, monomictic volcanic breccias (hyaloclastites), and unstratified, coarse polymeric volcaniclastic breccias, interpreted as debris-flow deposits. Stratified volcaniclastic sedimentary rocks are relatively subordinate, and fine-grained silt and mudstone are absent.

Ore horizon

Quartz and feldspar phryic to aphyric rhyolite forms massive bodies with no internal structure and units with flow banding, spheneuliths developed in banded arrays, and rare horizons or lenses of hyaloclastite. This series of textures and structures is interpreted as representing flow and/or dome complexes using the criteria of McPhie et al. (1993).

These flow and/or dome complexes crop out in the Cerro Caracol and Coloradita area, whereas the central portion of the district (Figs. 3–5) is dominated by volcaniclastic sedimentary rocks ranging from conglomerate to sandstones, interbedded with rhyolitic tuffs and lenses of black argillite. The general absence of fine-grained sedimentary rocks at Cerro Caracol and Coloradita, combined with the relatively abundant rhyolite flows, suggests that these areas may represent paleotopographic highs bounding central sedimentary basins. Syndepositional tectonic activity at the western boundary of these central basins is inferred from soft-sediment deformation, such as east- southeast-vergent shunt folding and locally reworked shale to siltsone deposits (Fig. 8A). At one location (coord. UTM zone 13: 488.004/2252.992), a coarse breccia with rhyolite boulders exceeding 1 m in diameter was deposited directly over shale and siltstone, which themselves overlie massive quartz-feldspar phryic rhyolite similar to the boulders (Fig. 5B). Presumably, the breccia breccia represents mass wasting related to syndepositional normal faulting.
Fig. 5. Stratigraphic map of the Cuale mining district, based on the lithologic map of Figure 3. Locations mentioned in the text are given. Coordinates are given as UTM zone 13, NAD83.

Fig. 6. Schematic stratigraphic column for the Cuale volcanic sequence, as interpreted from mapping carried out in this study (see Figs. 3–5). Mineralization events are indicated in their respective time-stratigraphic position.
The rhyolites of the ore horizon differ from those of the footwall sequence in that some flows contain only minor (<5%) and small (<1 mm) quartz phenocrysts. These aphyric rhyolites are intercalated with quartz and feldspar phyric rhyolites similar to those in the footwall. The ore horizon is characterized by relatively abundant fine grained sedimentary rocks interbedded with rhyolitic tuffs and volcanioclastic conglomerates, whereas rhyolite flows and hyaloclastic breccias are volumetrically subordinate compared to the footwall. In contrast to the footwall sequence, the tuffaceous rocks of the ore horizon include welded horizons (Fig. 8C) and, immediately below Mina Jesús María (Fig. 3), tuffaceous strata containing accretionary lapilli (Fig. 8D). Although welded rocks may also be deposited at considerable water depth (e.g., Koke-laar and Busby, 1992), the presence of both welding and accretionary lapilli (e.g., Brown et al., 2002) is taken as an indication of shallow water depths at the time of deposition.

The late intrusive phase

The footwall and ore horizon sequences are intruded by dikes, sills, and small hypabyssal bodies of quartz and feldspar phyric rhyolites. In contrast to the flows of the footwall and ore horizon, the intrusive rhyolites are more massive and lack spherulitic devitrification textures, lithophysae, and amygdules, although flow banding is common in some dikes and near the summit of Cerro Cantón. The intrusive rhyolites are slightly less intensely altered compared to the footwall and ore horizon sequence. Moderate quartz-sericite ± pyrite ± chlorite alteration dominates and chloritized mafic phenocrysts (most likely biotite pseudomorphs) are preserved locally. Columnar jointing in some dikes indicates intrusion into cold wall rock (Fig. 9). The dikes have a variable but predominantly northwesterly strike. This late phase of rhyolitic magmatism probably consists of several discrete intrusive pulses but cannot be subdivided further due to the limited petrographic variability.

The latest phase of magmatism of the Cuale volcanic sequence is represented by four subvertical, west-northwest–striking andesitic dikes cutting the intrusive rhyolites (Figs. 3, 5). The andesites are fine grained and have a plagioclase-plagioclase-pilzotaxitic texture in a fine-grained matrix, which is weakly altered to chlorite-rich assemblages. Their age is uncertain but bracketed by the intrusive rhyolite (Late Jurassic; see below) and the granodiorite of the Puerto Vallarta batholith (Late Cretaceous).

Geochronology

A total of five samples of rhyolitic flows, tuffs, and high-level intrusions, distributed over the entire Cuale volcanic sequence, were dated using conventional U-Pb zircon isotope dilution thermal ionization mass spectrometry (ID-TIMS) at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) facility at the University of British Columbia. Zircons were generally small and inclusion rich which, in some cases, resulted in relatively imprecise age determinations. The methodology for zircon grain selection, abrasion, dissolution, geochemical preparation, and mass spectrometry are described by Mortensen et al. (1995). All zircon fractions were air abraded (Krogh, 1982) prior to dissolution to minimize the effects of postcrystallization Pb loss. Procedural blanks for Pb and U were 2 and 1 pg, respectively. Analytical data are listed in Table 1 and are shown on conventional U-Pb concordia plots in Figure 10. Errors attached to individual analyses were calculated using the numerical error propagation method of Rodrick (1987). Decay constants used are those recommended by Steiger and Jäger (1977) and compositions for ini-
tial common Pb were taken from the model of Stacey and Kramer (1975). All errors are given at the 2σ level. Results for the five samples are discussed briefly below, sample locations are given within parentheses as coordinates UTM zone 13, NAD83.

Sample TB-368A (486.680/2253.326): This sample was a hyaloclastic, quartz and plagioclase phyric rhyolite from the footwall to the VMS bodies, north of Cerro Caracol. Zircon recovered from this sample comprised pale-brown, stubby, square prisms with abundant clear bubble- and rod-shaped inclusions. Four strongly abraded fractions were analyzed (Table 1). Two fractions (A and D, Fig. 10A) yielded overlapping concordant analyses with a total range of 206Pb/238U ages of 157.2 ± 0.5 Ma, which is considered to give the crystallization age of the sample. Two other fractions are slightly discordant with older 207Pb/206Pb ages. The data form a short array with a poorly defined calculated upper intercept age of ~1.62 Ga. The data are interpreted to indicate the presence of a minor inherited zircon component in the sample with an average age of ~1.62 Ga.

Fig. 8. Field photographs of typical outcrops from the ore horizon of the Cuale volcanic sequence. A and B show evidence for synvolcanic faulting. C and D show features indicating probable subaerial or shallow-water deposition of volcanic products. A. Siltstones and shale of the ore horizon featuring slump folding (Naricero, coord. 488.006/2252.379; hammer for scale, handle ~50 cm). B. Coarse boulder breccia (b) deposited directly on laminated siltstones (s). The inset shows detail of the contact relationship. Note the siltstone beds deformed due to the impact of the boulder (coord. 488.004/2252.992; hammer, ~50 cm, for scale). C. Welded rhyolite lapilli tuff. Approximate plane of welding is indicated by the dashed white line (coord. 487.330/2252.311). D. Accretionary lapilli from Jesús-Maria (coord. 489.335/2252.625, pencil for scale).

Fig. 9. Field photograph of a rhyolite dike (between white dashed lines) intruding massive outcrops of volcaniclastic deposits (coord. 486.493/2251.760, person for scale). The dike features columnar jointing perpendicular to the dike walls. Note also the color contrast between the intensely chlorite-pyrite-quartz altered wall rock and the only moderately quartz-sericite ± chlorite altered dike.
Sample TB-369A (488.569/2253.978): This sample was from an aphyric rhyolite flow from the footwall of the La Prieta fault, collected in the Coloradita open pit, at approximately the ore horizon in this part of the Cuale district. Zircons were pale-pink stubby prisms with morphologies similar to those in the previous sample. Four abraded fractions were analyzed, and the results also indicate the presence of a minor older inherited zircon component (Table 1, Fig. 10B). The best estimate for the crystallization age of the sample is given by fraction A with a 206Pb/238U age of 154.0 ± 0.9 Ma. The other three fractions are either imprecise due to the presence of high levels of common Pb (from abundant inclusions) or fall slightly to the right of concordia, indicating the presence of inherited zircon.

Sample TB-368A (487.699/2252.037): This sample was from a vesicular, quartz and feldspar phryic rhyolite flow from the immediate footwall of the San Nicolas deposit. The flow belongs to the lowermost ore horizon. Only a small amount of relatively fine grained zircon was recovered. Five fractions of lightly abraded zircon were analyzed (Table 1, Fig. 10C-D). A more substantial amount of inherited zircon was recovered. Two fractions (D and E) give overlapping concordant analyses with a total range of 206Pb/238U ages of 152.5 ± 1.5 Ma. This volcanic unit is intruded by a quartz-plagioclase phryic rhyolite dike, which yields a slightly older crystallization age (sample TB241b; see discussion below). The data are interpreted to indicate that these two fractions have experienced postcrystallization Pb-loss effects that were not completely removed by the light abrasion. The 152.5 ± 1.5 Ma age does provide a minimum crystallization age for the sample. The other three fractions contain older inherited zircon components, and a calculated upper intercept age of 1.59 Ga gives the average age of the inherited component.

Sample TB-241B (488.122/2253.341): This sample was from a quartz-plagioclase phryic rhyolite dike that intrudes the rhyolite flow (sample TB389A) in the immediate footwall of the San Nicolas deposit. Zircons from the sample form colorless elongate prisms. Four strongly abraded fractions were analyzed (Table 1, Fig. 10E). All yielded concordant analyses with a total range of 206Pb/238U ages of 155.9 ± 1.6 Ma, which is inconsistent with the other age determinations discussed above and the significance of inherited component.

Sample TB-241F (488.122/2253.341): This sample was from a quartz-plagioclase phryic rhyolite dike that intrudes the rhyolite flow (sample TB389A) in the immediate footwall of the San Nicolas deposit. Zircons from the sample form colorless elongate prisms. Four strongly abraded fractions were analyzed (Table 1, Fig. 10E). All yielded concordant analyses with a total range of 206Pb/238U ages of 155.9 ± 1.6 Ma, which is considered to give the crystallization age of the sample.

Sample TB-57C (485.527/2254.049): This sample is from a quartz and feldspar phryic crystal tuff from the hanging wall of the La Prieta fault taken in the Coloradita open pit. Three strongly abraded fractions were analyzed (Table 1, Fig. 10F) and yielded concordant analyses with a total range of 206Pb/238U ages of 159.2 ± 2.2 Ma. This is inconsistent with the other age determinations discussed above and the significance of

---

**Table 1. U-Pb Analytical Data**

<table>
<thead>
<tr>
<th>Sample/description</th>
<th>Wt (mg)</th>
<th>U (ppm)</th>
<th>Pb (ppm)</th>
<th>Total common Pb (%)</th>
<th>206Pb/238U (meas.)</th>
<th>207Pb/235U (meas.)</th>
<th>207Pb/206Pb (meas.)</th>
<th>206Pb/238U age (Ma; ± 2σ)</th>
<th>208Pb/206Pb age (Ma; ± 2σ)</th>
<th>207Pb/206Pb age (Ma; ± 2σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample TB-369A</td>
<td>A: N2, 104-134</td>
<td>0.008</td>
<td>1278</td>
<td>32.0</td>
<td>3090</td>
<td>5</td>
<td>11.0</td>
<td>0.02465(0.13)</td>
<td>0.1672(0.25)</td>
<td>0.04921(0.19)</td>
</tr>
<tr>
<td>Sample TB-369A</td>
<td>B: N2, 104-134</td>
<td>0.014</td>
<td>1381</td>
<td>34.8</td>
<td>2365</td>
<td>12</td>
<td>11.5</td>
<td>0.02472(0.11)</td>
<td>0.1680(0.21)</td>
<td>0.04931(0.14)</td>
</tr>
<tr>
<td>Sample TB-369A</td>
<td>C: N2, 104-134</td>
<td>0.007</td>
<td>697</td>
<td>17.8</td>
<td>2224</td>
<td>3</td>
<td>12.2</td>
<td>0.02453(0.16)</td>
<td>0.1703(0.36)</td>
<td>0.049571(0.30)</td>
</tr>
<tr>
<td>Sample TB-369A</td>
<td>D: N2, 104-134</td>
<td>0.008</td>
<td>1506</td>
<td>38.0</td>
<td>4233</td>
<td>4</td>
<td>11.7</td>
<td>0.02465(0.16)</td>
<td>0.1675(0.26)</td>
<td>0.04930(0.21)</td>
</tr>
</tbody>
</table>
the results is not certain. Fraction C falls slightly to the right of concordia, indicating the presence of a minor older inherited zircon component, and the other two fractions are too imprecise to evaluate whether a minor inherited component was also present in these analyses. In view of the stratigraphic position of this sample in the hanging wall of the ore and the relatively robust crystallization ages that we have obtained from stratigraphically lower units, we tentatively conclude that all three zircon fractions contained minor inherited zircon components or represent reworked zircons. An unequivocal crystallization age, therefore, cannot be assigned to the sample from our data.
Characteristics of the Sulfide Deposits at Cuale

Eleven orebodies, ranging from 20,000 to 783,000 metric tons (t) of polymetallic ore (Table 2) along with a number of smaller occurrences were in production in the 1980s (Hall and Gomez-Torres, 2000a). Most of this ore is mined out and the following descriptions are summarized from Berrocal and Querol (1991) and Hall and Gomez-Torres (2000a). The style of mineralization and the relative abundance of the metals vary significantly between the orebodies.

The Naricero, Socorredora, La Prieta-Rubí, San Nicolas, and Refugio deposits (Table 2), which were the source of about half of the mined ore in the district, are hosted by or spatially associated with black argillites. The massive sulfide ore, compared to the other deposits of the district, is characterized by high average silver grades up to several hundreds of parts per million. The silver is contained within fine-grained galena and sphalerite that is locally brecciated (e.g., Naricero) or laminated (e.g., Socorredora). As the Pb-Ag–rich orebodies locally exhibit sedimentary textures (lamination) we interpret them to be in a distal setting, possibly transported into anoxic basins adjacent to proximal sulfide mounds.

The Coloradita, Chivos de Arriba, and Chivos de Abajo deposits are considered to be proximal to hydrothermal upflow zones. These deposits contain up to 3 g/t Au and 0.4 to 1.5 percent Cu but are relatively low in Ag and Pb compared to the more distal deposits. The precious and base metals are partly hosted by pyrite- and chalcopyrite-rich stockwork zones that are hydrothermally altered. The stockwork zones are in turn overlain by massive sulfide bodies (mostly pyrite with chalcopyrite that grade laterally and vertically into sphalerite- and galena-rich zones). Host rock for the Coloradita deposit is aphyric rhyolite.

Minas de Oro/Grandeza consists of stockwork mineralization and gold grades of 1.9 ppm, but only 0.2 wt percent Cu, which distinguishes it from other gold-rich orebodies of the district where Cu is more abundant. The described ore mineralogy at Minas de Oro/Grandeza (Macías and Solís, 1985) is essentially sphalerite, pyrite, and lesser amounts of galena and freibergite [(Ag,Fe)12(Sb,As)4S13], whereas gangue is essentially sphalerite, pyrite, and lesser amounts of galena and freibergite [(Ag,Fe)12(Sb,As)4S13], whereas gangue is mainly composed of quartz and calcite. Limited fluid inclusion data on liquid-rich inclusions in quartz and sphalerite (Macías and Solís, 1985) support the interpretation of Minas de Oro/Grandeza being similar to low-sulfidation epithermal deposits (i.e., homogenization temperatures between 220° and 265°C, salinities around 5 wt % NaCl equiv, together with the estimated average density of 0.86 g/cm³) and having formed at 400- to 700-m depth below surface.

An approximately 4-m-wide quartz vein with epithermal textural characteristics (open-space filling and local colloform texture) is present on the summit of Cerro Descumbridora. This vein was mined historically (no grade and tonnage data available) and crops out northwest of and along strike from the stockwork mineralization at Minas de Oro/Grandeza. Both the vein and the stockwork mineralization postdate the main VMS deposits of Cuale since they are hosted by the post-VMS intrusive rhyolite. Further evidence for a late mineralization event with epithermal characteristics comes from quartz-carbonate ± adularia vein material found in the float of the northwestern ridge of Cerro Cantón, as well as from stream-sediment geochemistry near Santa Rita (a small prospect ~3 km north of Cerro Cantón, outside the study area and not shown in Fig. 2) where anomalous arsenic and mercury concentrations have been reported (International Croesus Ventures Corp. unpub. reports).

Hydrothermal Alteration

Moderate to intense hydrothermal alteration is ubiquitous and affects all rocks of the Cuale volcanic sequence. The footwall alteration associated with the deposits considered proximal is characterized by intense quartz-sericite-pyrite alteration, laterally grading into more chlorite-rich assemblages. However, the alteration in the footwall of Socorredora and Naricero also exhibits moderate to intense quartz-sericite-pyrite alteration, which indicates that part of the ore of these deposits may have been contributed by a low-temperature hydrothermal fluid and not all mineralization is the result of transport and redeposition in anoxic basins. The black argillite which host part of the ore is locally slightly carbonaceous or cut by calcite veins, but it is unclear whether or not this carbonate is related to hydrothermal alteration.

The late intrusive rhyolites are affected by less intense alteration (Fig. 9). The rocks are moderately silicified with

<table>
<thead>
<tr>
<th>Mine</th>
<th>Metric tons</th>
<th>Au (g/t)</th>
<th>Ag (g/t)</th>
<th>Pb (%)</th>
<th>Zn (%)</th>
<th>Cu (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naricero</td>
<td>782,544</td>
<td>0.34</td>
<td>157</td>
<td>1.05</td>
<td>2.85</td>
<td>0.06</td>
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<tr>
<td>Mina de Oro/Grandeza</td>
<td>756,661</td>
<td>1.89</td>
<td>22</td>
<td>1.41</td>
<td>2.35</td>
<td>0.2</td>
</tr>
<tr>
<td>Socorredora</td>
<td>200,492</td>
<td>0.13</td>
<td>187</td>
<td>1.89</td>
<td>6.93</td>
<td>0.16</td>
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<tr>
<td>Coloradita</td>
<td>170,035</td>
<td>0.66</td>
<td>85</td>
<td>1.99</td>
<td>6.51</td>
<td>0.37</td>
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<tr>
<td>Las Talpas</td>
<td>141,425</td>
<td>0.34</td>
<td>24</td>
<td>0.65</td>
<td>1.94</td>
<td>0.24</td>
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<tr>
<td>La Prieta-Rubí</td>
<td>113,335</td>
<td>0.73</td>
<td>226</td>
<td>3.8</td>
<td>9.24</td>
<td>0.32</td>
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<tr>
<td>Chivos de Abajo</td>
<td>85,771</td>
<td>1.08</td>
<td>179</td>
<td>1.48</td>
<td>4.71</td>
<td>1.54</td>
</tr>
<tr>
<td>San Nicolas</td>
<td>79,965</td>
<td>0.19</td>
<td>121</td>
<td>1.57</td>
<td>3.18</td>
<td>0.13</td>
</tr>
<tr>
<td>Jesús María</td>
<td>46,751</td>
<td>0.06</td>
<td>109</td>
<td>1.85</td>
<td>3.31</td>
<td>0.09</td>
</tr>
<tr>
<td>Refugio</td>
<td>34,569</td>
<td>0.14</td>
<td>156</td>
<td>0.89</td>
<td>1.95</td>
<td>0.1</td>
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<tr>
<td>Chivos de Arriba</td>
<td>23,588</td>
<td>2.79</td>
<td>70</td>
<td>0.85</td>
<td>2.18</td>
<td>0.74</td>
</tr>
<tr>
<td>Eight other small deposits</td>
<td>39,199</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2,474,355</td>
<td>0.83</td>
<td>103</td>
<td>1.03</td>
<td>3.22</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Table 2. The Ore Deposits of the Cuale District


modest amounts of sericite. Disseminated pyrite is absent or much less abundant than in the lower parts of the stratigraphy. Ferromagnesian minerals (most likely biotite) are preserved as chloritized relics only in the rhyolites of the late intrusive phase.

**Structural Evolution of the Cuale District**

The major control on the erosional landforms at Cuale is the type and degree of alteration rather than fault traces, and air-photo interpretation is therefore of limited use for structural interpretations. The following is a summary based on limited mapping.

Synvolcanic faulting (D$_2$) and subsequent erosion is evidenced by coarse volcaniclastic rocks commonly found on the southern and eastern flanks of Cerro Caracol. Slump folds (Fig. 8A) and boulders deposited directly on fine-grained sediment (Fig. 8B) may be taken as further evidence for deformation during the deposition of the Cuale volcanic sequence. Five out of six measurements of fold axis in slump folds within fine-grained sedimentary rocks plunge at shallow angles to the north or south, an orientation consistent with slumping induced by steepening relief due to displacements along north-south–striking normal faults. Synvolcanic structures have not been observed directly, but two roughly north–south–striking cleavage zones have been recognized at San Nicolas and 200 m northwest of Jesús-Maria. These zones may represent zones of structural weaknesses that controlled fluid flow.

The late andesite dikes and many rhyolite dikes cutting all the previous units within the volcanic pile have an east-west to southeast-northwest strike direction (Fig. 3). This predominant dike orientation, together with the inferred north-south–striking structures described above, is consistent with emplacement of the rhyolite in tension fractures associated with sinistral transtensional rifting along north-south– to north-northwest– south-southeast–striking faults. From this interpretation of the Upper Jurassic tectonic environment, Cuale is in agreement with the Upper Jurassic subduction geometry suggested by Dickinson and Lawton (2001) as well as the parallel Upper Jurassic sinistral transtensional arc that has been documented for northwestern Mexico (Busby et al., 2005).

A northeast-dipping district-scale fault, the Paso Caracol fault (Fig. 3), has been inferred from limited outcrop exposure at Paso Caracol as well as from map interpretation along strike to the northwest and southeast. Although no unequivocal kinematic indicators have been recognized, we interpret the offset to be reverse (D$_2$) since smaller scale northwest–southwest–striking reverse faults have been observed throughout the district. Bedding planes of fine-grained sedimentary units of the ore horizon, where not affected by synsedimentary slump folding, have dips varying from 0° to 35° at variable strikes. It is thus unclear whether contractional deformation resulted in gentle folding in the district or whether the variation in bedding plane dips may be attributed solely to the intrusion of the late rhyolite. D$_2$ deformation predates the later La Prieta fault as the latter appears to terminate at a structure parallel to the Paso Caracol fault north-east of Socorredora (Figs. 3, 5).

Late normal faults are important as they locally separate the Cuale volcanic sequence from older units, but normal faults with offsets of typically less than 30 m are observed throughout the district. However, in the case of the La Prieta fault (Figs. 3, 5) a minimum normal offset of 200 m has been inferred from drill log records. The fault crops out in the Colorado open pit as a ~30-m-thick fault zone filled with gouge and brecciated rocks. The La Prieta fault dips ~45° to the north-northwest and steepens at depth (Macomber, 1962). A normal offset is further suggested by parallel smaller scale fractures in the vicinity of the fault trace which have a demonstrably normal offset. The massive sulfide mineralization at La Prieta, Colorado, Chivos de Arriba, and Chivos de Abajo terminates at the La Prieta fault and thus predates normal slip on the fault.

**Whole-Rock Geochemistry**

Fifty samples of rhyolite from the Cuale volcanic sequence have been analyzed for major and trace elements using inductively coupled plasma atomic emission spectroscopy (ICP-AES) for major elements and inductively coupled plasma mass spectrometry (ICP-MS) for trace elements. Lithium metaborate fusion was applied to ensure complete dissolution of the lithophile elements. The rocks were submitted as a single batch and analyzed using standard exploration grade analytical packages at ALS-Chemex laboratories in North Vancouver, British Columbia, Canada. The complete data set is available as a digital supplement to this paper at <http://www.geoscienceworld.org> or, for members and subscribers, on the SEG website, <http://www.segweb.org>.

All analyzed samples have experienced considerable hydrothermal alteration, precluding the use of mobile elements for tectonic discrimination purposes. Thus, major elements were used only to characterize the alteration by means of alteration indices. The Cuale samples, taken over a vertical range of 800 m from throughout the map area shown in Figure 3 (see digital data supplement for sample coordinates), have been plotted in the alteration box plot of Large et al. (2001; Fig. 11). Most samples of rhyolite from the footwall and ore horizon fall within the range typical for intense chlorite-pyrite ± sericite alteration. In contrast, the samples of intrusive rhyolite occupy a range from unaltered to sericitized to altered rhyolite but do not extend as far into the chloritoid-pyrite–altered field as the stratigraphically lower units. The late mafic dikes all plot within or close to the field for the least altered andesite. Thus, the intensity of alteration clearly distinguishes between the footwall and ore horizon versus the late, post-VMS mineralization intrusive rhyolites.

With the exception of three late-stage andesite dikes, all rocks have rhyolitic compositions when using the Zr/TiO$_2$ versus Nb/Y diagram of Winchester and Floyd (1977; Fig. 12A). The Y versus Nb diagram of Pearce et al. (1984; Fig. 12B) shows the Cuale samples straddling the triple point between “volcanic arc,” ”ocean ridge,” and ”anomalous ridge” fields. The Cuale volcanic rocks plot within a very narrow compositional range consistent with a rifted-arc environment, but these widely used diagrams fail to discriminate between the stratigraphic units of the district. Incompatible trace elements such as Zr, Y, and REE show sufficient variation to discriminate between the stratigraphic units of the district. The chondrite normalized (La/Yb)$_n$ versus Yb$_n$ tectonic discrimination diagram of Hart
et al. (2004; Fig. 13A), originally proposed by Lesher et al. (1986), shows that the Cuale volcanic rocks straddle FI and FII fields, indicating calc-alkaline compositions (Fig. 13A). The footwall rhyolites, with two exceptions, plot at relatively low (La/Yb)n values, whereas the rhyolite of the ore horizon and late intrusive rhyolite have somewhat higher ratios. A similar relationship can be observed when using the La versus Yb discrimination diagram proposed by Barrett and MacLean (1999; Fig. 13B); the footwall rhyolites generally occupy a field transitional between calc-alkaline and tholeiitic rocks, whereas the rhyolite of the ore horizon and late intrusive rhyolite have overlapping but generally more calc-alkaline compositions (Fig. 13B).

The footwall rhyolites have low Zr contents (56–109 ppm), whereas Zr ranges from 58.5 to 195 ppm in the rhyolite of the ore horizon and hanging-wall rhyolite (Fig. 13C). Late andesite dikes have the highest Zr concentrations (176–230 ppm) within the Cuale volcanic sequence. Titanium concentrations in the footwall rhyolite are low (0.05–0.08 wt % TiO₂) and are lower than in the stratigraphically higher rhyolites (0.03–0.2 wt % TiO₂). The andesite dikes contain from 1.31 to 1.84 wt percent TiO₂.

Discussion

Stratigraphy

The footwall sequence is characterized by large volumes of rhyolite flows and hyaloclastite deposits with subordinate volcaniclastic sedimentary rocks, all of which are interpreted to have been deposited in a subaqueous setting. The ore horizon, in contrast, is dominated by volcaniclastic sedimentary rocks ranging from conglomerates to sandstones with intercalated tuffs. Black shale to siltstone horizons within this sequence are the main host for Pb-Zn-Ag-rich massive sulfide mineralization. Rhyolite flows and domes, commonly aphyric to weakly quartz-phyric, crop out at Coloradita and at Cerro Caracol and are separated by the central domain of fine-grained volcaniclastic sedimentary rocks (Figs. 3, 14). The distribution of volcanic and volcanic-sedimentary rocks suggests that Coloradita and Cerro Caracol may have represented topographic highs bordering a central sedimentary basin (Fig. 14). A general decrease in water depth during the evolution of the Cuale volcanic sequence is indicated by some of the tuff layers within the ore horizon that have welded or accretionary lapilli. Tuffites, locally welded, are common on
the southern flanks of Cerro Cantón and lie in the hanging wall of the La Prieta fault, but at a topographic level of <200 m above the mineralization at Coloradita. These tuffites therefore correspond to the higher portions of the ore horizon stratigraphy and suggest that the area may have become emergent during the waning stages of volcanic activity.

No significant input of continent-derived siliciclastic sediment is apparent within the Cuale volcano-sedimentary sequence, indicating a position that was isolated from major continental sediment sources in the Late Jurassic. However, a minor older inherited zircon component is present in several of the rhyolite samples (TB-368A, Tb-369A, TB-389A, TB-57C), indicating that older rock units, or sediments derived from them, are present in the subsurface. A continental sediment influx, if present, may also have been obscured by rapid eruption rates for the Cuale volcanic sequence, an interpretation which is in agreement with the U-Pb age determinations.

The lack of carbonate sedimentary rocks that would normally be expected in a shallow marine setting may be interpreted as further indication for such a rapid eruptive cycle represented in the footwall and at the ore horizon.

**Whole-rock geochemistry**

The Cuale rhyolite sequence is remarkably homogeneous in chemistry. Apart from the late andesitic dikes, which may not be directly related to the rhyolites as indicated by their higher Zr concentrations, only subtle geochemical variation over a vertical stratigraphic interval of more than 800 m is observed. Similar to the gold-rich Eskay Creek deposit (Barrett and Sherlock, 1996), Ti and Zr concentrations in the rhyolite are low at Cuale. However, Zr, Ti, and with LREE are slightly enriched in rhyolite at the ore horizon and in late intrusive rhyolite compared to the footwall. This small change is interpreted as an evolution from transitional tholeiitic to...
FIG. 14. Schematic E-W cross section through the Cuale district in the Late Jurassic. The volcanic sequence evolves from a submarine to a Late Jurassic, partly subaerial setting. Stage 1 (footwall) is characterized by subaqueous eruption of rhyolite flows, cryptodomes, and hyaloclastites. Stage 2 (ore horizon) is characterized by emplacement of rhyolite domes and proximal pyroclastic and hyaloclastic rocks near Cerro Caracol and Coloradita. Some of the volcanism was subaerial at this time. A central basinal domain is characterized by reworked volcanioclastic facies and black shales. Massive sulfide mineralization occurs as sulfide mound and underlying stockwork mineralization associated with aphyric rhyolite domes, as well as in the central basinal domain, associated with black shale. Stage 3 (late intrusive phase) is characterized by emplacement of shallow intrusions, dikes, and domes of quartz-feldspar phryic rhyolite. Stockwork and vein mineralization with epithermal characteristics cuts the late intrusive rhyolite unit.
calc-alkaline to calc-alkaline compositions. The overall geochemical compositions are consistent with an intra-oceanic island-arc setting (Barrett and MacLean, 1999) or a pericontinental arc setting, the latter interpretation being favored because of the presence of an inherited Pb component in the zircon U-Pb data.

Low Zr/Y and (La/Yb)_n ratios have been related to large degrees of melting and high zircon saturation temperatures, indicative of high magma temperatures (Watson and Harrison, 1983; Barrie, 1995) or, alternatively, melting at low pressures (Hart et al., 2004). Mineralization in other Panerozoic massive sulfide districts has been shown to be associated with high-temperature rhyolites which have undergone little assimilation and fractional crystallization (Lentz, 1998; Piercey et al., 2001).

In these cases, the high zircon saturation temperatures (Barrie, 1995; Piercey et al., 2001) typically distinguish VMS-bearing felsic sequences from barren rhyolites. In the Cuale volcanic sequence a slight overall increase of Zr/Y and (La/Yb)_n in the ore horizon and late intrusive rhyolites, compared to the footwall rhyolite, is observed. This evolution may indicate slightly decreasing magma temperatures. However, the observed trace element patterns may also be the effect of lower degrees of melting related to changes in the residual mineralogy from plagioclase + clinopyroxene- to hornblende + clinopyroxene-bearing assemblages (e.g., Hart et al., 2004), which would be indicative for increasing pressure at the site of magma generation. The pressure increase is in agreement with the observed stratigraphy, which indicates a buildup of a volcanic edifice that becomes emergent in the late stages; therefore, we interpret the data as reflecting variations in the degree of melting and increasing pressure at the site of melting rather than changing magma temperatures. VMS ore was emplaced immediately following this weak geochemical transition, whereas the late mineralization with low-sulfidation epithermal characteristics is associated with more typical calc-alkaline rocks.

The late andesite dikes have relatively high Zr concentrations, which indicate a different magma source and may indicate more involvement of continental crust or higher degrees of partial melting. These dikes clearly postdate the rhyolite sequence and may have been emplaced during accretion of the Guerrero terrane to the North America craton. While small changes in magma chemistry commonly coincide with VMS mineralization (e.g., Barrett and MacLean, 1999), the transition from a deep to shallow marine setting, along with the late epithermal mineralization observed at Cuale is unusual. VMS mineralization in most deposits of similar settings (e.g., Kuroko: Ohmoto, 1983, 1996; Kutcho Creek: Barrett et al., 1996; see also Lentz, 1998) occurred during extensional tectonic events and is commonly overlain by deep marine sedimentary sequences. However, a shallow marine ore-forming environment also has been postulated for Eskay Creek (Barrett and Sherlock, 1996) and may be an important factor that led to the silver-rich mineralization at Cuale. The unusual evolution of Cuale indicates that the mineralization was not emplaced in a typical evolving back-arc environment but rather suggests a setting in an epicontinental transtensional volcanic area undergoing riftting simultaneous to uplift. It is likely that the epithermal mineral potential of Cuale and surrounding areas has been underappreciated (e.g., Sillitoe and Hedenquist, 2003).

Regional context of the Cuale stratigraphy and VMS mineralization in the Guerrero terrane

Previous studies loosely correlated the Cuale volcanic sequence with the Early Cretaceous volcanic sequences in the southern Zihuatanejo subterrane (JICA-MMA, 1986). However, rhyolites from Cuale are now known to be Late Jurassic and are only slightly younger than the Tumbiscatío and Macías granitoid intrusions of the southern Zihuatanejo subterrane. These granitoids may represent part of the same arc as the Cuale rhyolites, which predates the Lower Cretaceous arc previously recognized. The Late Jurassic arc, judging from limited inherited Pb in the dated zircons, may have been underlain by vestiges of continental crust. Early Cretaceous rocks similar to those of the southern Zihuatanejo subterrane have not been recognized in the immediate Cuale area but are likely to be present regionally around Cuale (JICA-MMA, 1986).

Volcanogenic massive sulfide mineralization in the Guerrero terrane is generally hosted by latest Jurassic to Early Cretaceous arc and back-arc sequences (Mortensen et al., 2003, 2008). Cuale is an exception because it formed in the Late Jurassic, ~5 to 16 m.y. before the other VMS districts of the Guerrero terrane (Mortensen et al., 2003, 2008). Thus, the new data on Cuale not only extend the previously established age range for VMS mineralization but also provide important constraints on the tectonic evolution of western Mexico.

Conclusions

The Cuale mining district contains silver-rich VMS mineralization emplaced in a shallow marine setting, as well as late Au-Zn (Pb, Ag) stockwork mineralization with low-sulfidation epithermal characteristics. The ore deposits are all hosted by rhyolitic rocks (Cuale volcanic sequence) with transitional tholeiitic to calc-alkaline to calc-alkaline affinities. High field strength element contents of the rhyolites at Cuale are consistent with those observed in rhyolites associated with other Panerozoic VMS districts. Increasing La/Yb and Zr/Y ratios during eruption of the Cuale volcanic sequence are thought to be the result of a change in residual mineralogy from amphibole-free to amphibole-bearing assemblages as pressure at the melting site increased. This is in agreement with the observed stratigraphy which indicates buildup of a more than 800-m-thick volcanic edifice that became emergent in the late stages.

The age of the Cuale volcanic sequence is 157 ± 0.5 to 154.0 ± 0.9 Ma, which corresponds to the Upper Jurassic. Cuale, thus, represents the oldest known VMS deposit of the Guerrero terrane. Based on geologic mapping, whole-rock geochemistry, geochronology (inherited Pb in zircons), and regional comparisons we propose that the Cuale district was emplaced in a transtensional pericontinental arc environment.
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