ORE DEPOSITS, MAGMAS AND TECTONISM IN ECUADOR

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INTRODUCTION

Lead isotopes are a powerful tool to trace metal sources in mineral deposits because lead approximates the behavior of accompanying metals (e.g., Zn, Cu, Au, Ag) in most base-metal rich hydrothermal solutions (e.g., Tosdal et al., 1999) and is ubiquitous in common ore minerals and rocks. Various studies suggest that lead isotopes of igneous rocks of the Central Andes reflect the compositions of the subjacent basements (e.g., Davidson et al., 1992; Aitcheson et al., 1995). (Macfarlane et al., 1990) have shown that ore lead of magmatic-related deposits in the Central Andes is a mixture of mantle and crustal sources and reflects the existence of different geological provinces. The mantle Pb input consists of magmatic addition into the crust whereas the crust input consists of basement rock lead assimilated by magmas before being delivered to ore fluids, and, to a lesser extent, of basement rock lead leached by hydrothermal fluids.

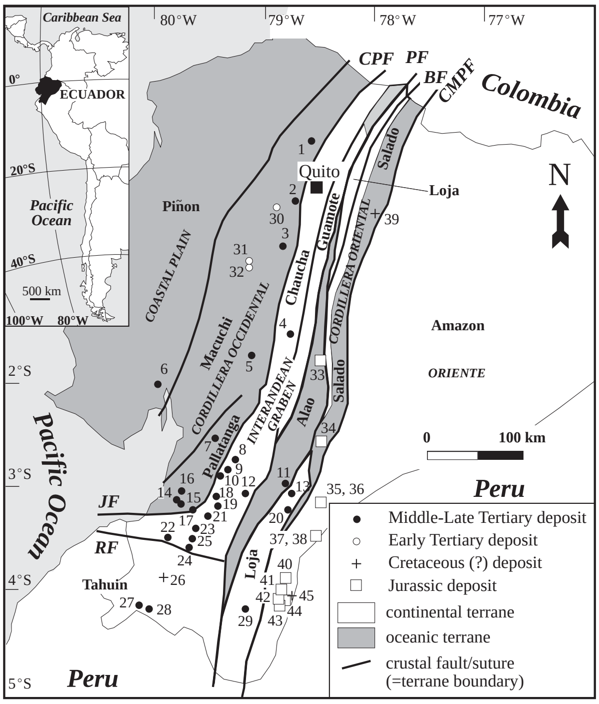

Figure 1. Geotectonic map of Ecuador.

In contrast to the Central Andes, the Ecuadorian crust is composed of terranes having both oceanic and continental affinity, accreted to the continent from the Jurassic to the Eocene (e.g., Feininger, 1987; Litherland et al., 1994). In this contribution we discuss 273 lead isotope data of ores as well as of metamorphic, intrusive, volcanic, and volcano-sedimentary rocks, ranging in age from Paleozoic to Miocene, in order to evaluate the possible metal sources for the mineral deposits of Ecuador (Chiaradia and Fontboté, 2001; Chiaradia and Fontboté, 2002; Chiaradia et al., 2004a). We also present strontium and lead isotope data combined with geochemical data of 27 Tertiary magmatic rocks (Chiaradia et al., 2004b). All investigated ore deposits are magmatic-related, and belong to skarn, porphyry, volcanic-hosted massive sulfide (VHMS), and epithermal mineralization types. The main economic metals are Au, Ag, and Cu with a limited number of occurrences having Pb and Zn in recoverable amounts.
Using the above data, we identify the sources of lead in the Jurassic to Miocene ore deposits as well as in the associated igneous rocks of Ecuador, test the multi-terrane model for the Ecuadorian crust, and explore the link between geochemistry of Tertiary magmatic rocks and mineralization. Our results indicate that lead isotope compositions of the Ecuadorian ore deposits and associated magmatic rocks

differ according to the terranes identified by Litherland et al. (1994) and encompass a range of isotopic compositions larger than that of provinces I and II of the Central Andes (Macfarlane et al., 1990). Also, numerous Tertiary magmatic-related deposits of the Ecuadorian Andes incorporate older basement rock lead most likely leached by hydrothermal fluids rather than assimilated by magmas. Tertiary deposits are preferentially associated with pre-9 Ma "normal" calc-alkaline magmatic rocks rather than with post-9 Ma adakitic magmatic rocks.

GEOLOGICAL SETTING

Ecuador consists of terranes having both continental (Chaucha, Tahuin, Loja terranes) and oceanic (Macuchi, Alao, Salado terranes) affinity, which were accreted to the Amazon craton from Late Jurassic to Eocene (Figure 1). Four main magmatic arcs were formed by the subduction of the Farallon/Nazca plate since the Jurassic: a Jurassic continental arc on the western margin of the Amazon craton, a Jurassic island arc (Alao terrane), an Early Tertiary island arc (Macuchi terrane), and a Middle-Late Tertiary continental arc encompassing the terranes of Macuchi, Chaucha, Tahuin, Loja and Alao after complete assembly of the Ecuadorian crust. Mineral deposits formed during these magmatic arc activities include porphyry-Cu and gold skarn deposits in association with the Jurassic continental arc, polymetallic volcanic-hosted massive sulfide deposits (VHMS) in association with the Jurassic island arc of Alao, Au-Cu-Zn VHMS deposits in association with the Early Tertiary island arc of Macuchi, and porphyry-Cu and precious metal epithermal deposits in association with the Middle-Late Tertiary continental arc magmatism on the newly assembled crust of Ecuador (Macuchi, Chaucha, Tahuin, Loja and Alao terranes).

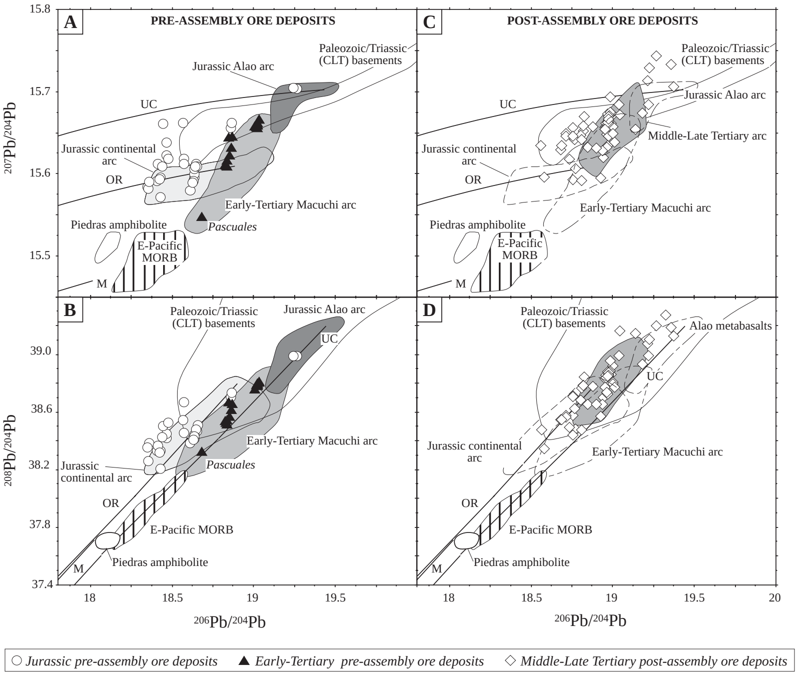

Figure 2. Lead isotope diagrams of ore minerals and rocks of Ecuador.

RESULTS AND DISCUSSION

Lead and strontium isotope compositions of the magmatic rocks of the four main arc events derive from mixing of various sources including mantle, variably enriched by pelagic sediments and/or by a HIMU (high $^{238}U/^{204}Pb$) component, and heterogeneous continental crust rocks.

Lead isotope compositions of the Ecuadorian ore deposits (Figure 2) display a broad range of values ($^{206}Pb/^{204}Pb$ = 18.3-19.3, $^{207}Pb/^{204}Pb$ = 15.54-15.74, $^{208}Pb/^{204}Pb$ = 38.2-39.2), which is as large as the range previously reported for all magmatic-related ore deposits of the Central Andean provinces I and II combined (MacFarlane et al., 1990). Ore deposits formed before complete assembly of the Ecuadorian crust through complete accretion of the several terranes (i.e., pre-Eocene) have lead isotope compositions overlapping those of the associated magmatic rocks, suggesting a largely magmatic origin for their lead (Figure 2). In contrast, post-assembly ore deposits (i.e., post-Eocene) have lead isotope compositions that only partly overlap those of the coeval magmatic rocks of the continental arc. In fact, several ore deposits have lead isotope compositions shifted towards those of the basement rocks that host them, suggesting that lead derives from a mixture of magmatic lead and basement rock lead leached probably by hydrothermal fluids (Figure 2).

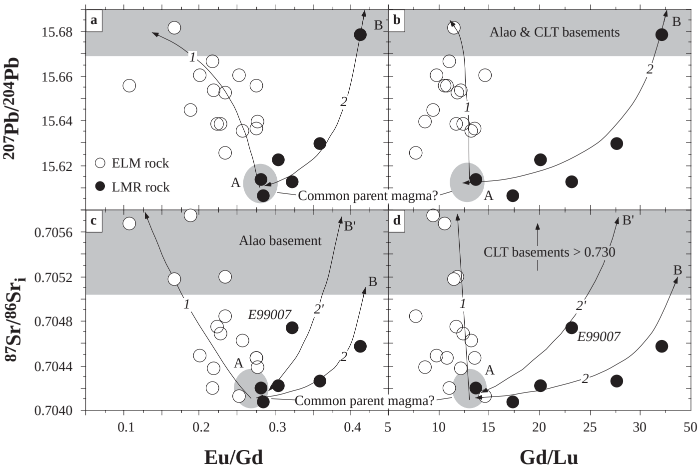

Figure 3. Sr and Pb isotopes vs. Eu/Gd and Gd/Lu ratios for Tertiary magmatic rocks of Ecuador.

Most of the economic ore deposits of Ecuador are porphyry-Cu and epithermal style gold deposits associated with Tertiary continental arc magmatism. Two groups of magmatic rocks of the Tertiary continental magmatic arc of Ecuador have been identified: Eocene to Late Miocene (~50-9 Ma, ELM) and Late Miocene to Recent (~8-0 Ma, LMR). The most primitive ELM and LMR rocks analyzed display similar trace element and isotopic signatures suggesting a common origin, most likely an enriched MORB-type mantle. In contrast, major and trace element geochemistry as well as radiogenic isotope systematics of the whole sets of ELM and LMR samples indicates strikingly different evolutions between ELM and LMR rocks (Figure 3). The ELM rocks have low Sr/Y, increasing Rb/Sr and decreasing Eu/Gd with SiO_2, suggesting an evolution through plagioclase-dominated fractional crystallization at shallow crustal levels (<20 km). The LMR rocks display features of adakite-type magmas (high Sr/Y, low Yb, low Rb/Sr) and increasing Eu/Gd and Gd/Lu ratios with SiO_2. The combination of strontium and lead isotopes with geochemical data suggest that the adakite-type geochemistry of LMR rocks, rather than by slab melting, can be explained by a model in which mantle-derived melts partially melt and assimilate residual garnet-bearing mafic lithologies at deeper levels than those of plagioclase stability (i.e., >20 km), and most likely at sub-crustal levels (>40-50 km) (Figure 3). The change in geochemical signatures of Tertiary magmatic rocks of Ecuador from the ELM- to the LMR-type chronologically coincides with the transition from a transpressional to a compressional regime occurred at ~9 Ma and attributed by other investigations to the onset of subduction of the aseismic Carnegie ridge (Figure 4). The major districts of porphyry-Cu and epithermal deposits of Ecuador (which have a small size, << 200 Mt, when compared to their Central Andean counterparts) are spatially and temporally associated with ELM magmatic rocks. No significant porphyry-Cu and epithermal deposits (except the epithermal high-sulfidation mineralization of Quimsacocha) appear to be associated with Late Miocene-Recent (LMR, ~9-0 Ma) magmatic rocks. The apparent "infertility" of LMR magmas seems to be at odds with the association of major porphyry-Cu/epithermal deposits of the Central Andes with magmatic rocks having adakite-type geochemical signatures similar to LMR rocks. The paucity of porphyry-Cu/epithermal deposits associated with LMR rocks might be only apparent and bound to exposure level, or real and bound, among other possibilities, to the evolution of magmatic chambers at great depths since ~9 Ma as a result of a prolonged compressional regime in the Ecuadorian crust. Circumstantial evidence supporting the latter scenario is provided by preliminary data on metal concentrations in whole rocks which seem to indicate a significant decrease of Cu with fractionation in post-9 Ma adakitic rocks, which is not observed in pre-9 Ma calc-alkaline rocks. This might suggest that Cu sequestration by phases crystallizing at depth (before magmas become fluid-saturated) in post-9 Ma adakitic rocks could play a role towards a low metallogenic potential of these rocks.

Ecuadorian ores have high $^{207}Pb/^{204}Pb$ values (>15.55: Figure 2) suggesting a dominant continental crust or pelagic sediment origin of the lead. However, we caution against concluding that chalcophile metals, for example Cu and Au, also have a continental crust origin. Indeed, the content of Cu of Middle-Late Tertiary porphyry-Cu and epithermal deposits seems to increase with increasing mantle lead contribution.

CONCLUSIONS

Ore deposits of Ecuador were formed in widely different geodynamic settings, including intraoceanic island arcs, a marginal basin, and continental arcs on the cratonic margin and on multiply accreted continental crust. Their isotopic signatures can be explained by mixing of different reservoirs involved in magma genesis and in magma-host rock interaction in each of these geodynamic contexts. The Pb isotope signatures of mineral deposits (and associated magmas) support the subdivision of the Ecuadorian crust into different terranes (e.g., Litherland et al., 1994).

Pre-assembly mineral deposits have isotopic compositions that coincide with those of the common lead of the magmatic rocks genetically associated with them and reflect the different geotectonic environments in which they were formed. VHMS deposits that formed in the Jurassic Alao (Guarumales, Las Pilas) and Early Tertiary Macuchi (La Plata, Macuchi) intraoceanic island arcs contain mixtures of >90 wt.% mantle and <10 wt.% pelagic sediment lead assimilated at the magma source in the mantle. Therefore, it is reasonable to assume that the majority of the chalcophile metals therein were mantle-derived. Lead (and presumably accompanying metals) of porphyry-Cu (El Pangui district) and skarn deposits (Nambija district) of the Jurassic continental arc derive from mixing of mantle (possibly but not necessarily enriched by pelagic sediments) and crustal basements, but more information on the petrology and geochemistry of the associated intrusions is needed to understand where and how such mixing occurred.

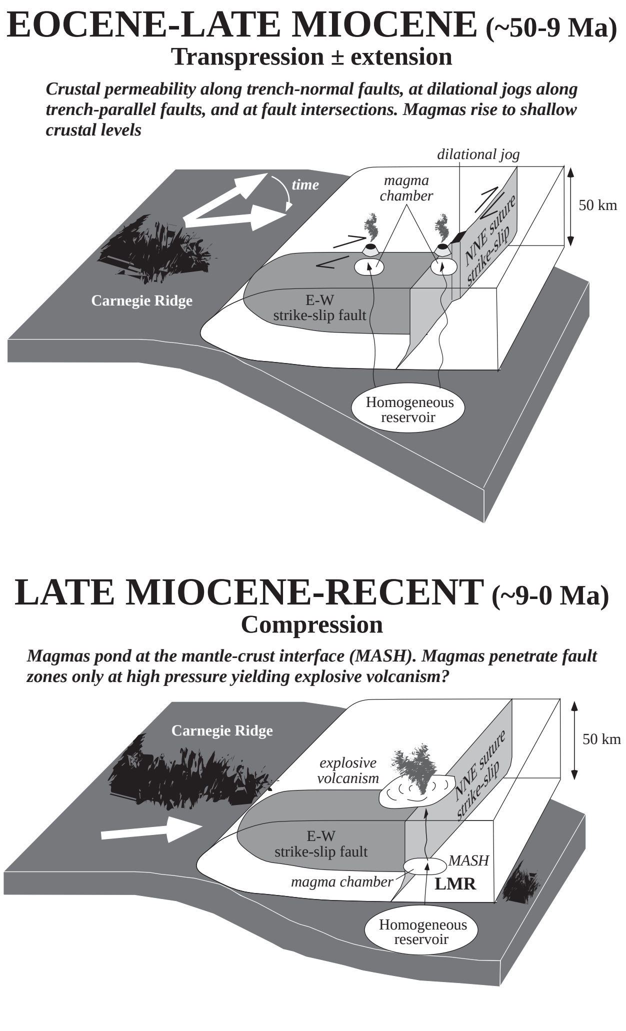

Figure 4. Geodynamic evolution of Ecuador and Tertiary magmatism.

Lead isotope compositions of post-assembly (Middle-Late Tertiary) deposits reflect a mixture of magmatic lead and lead leached from basement lithologies of the host terranes. Magmatic lead is related to the assimilation at shallow crustal levels of up to 19 wt.% crustal rocks by enriched mantle-derived magmas (Chiaradia and Fontboté, 2004b). Therefore, in post-assembly deposits the crustal component of lead was added to the mantle-derived component both at depth (pelagic sediments) and in the upper part of the crust (assimilation-fractional crystallization process). Despite the fact that the lead budget of the Middle-Late Tertiary deposits is largely dominated by crustal reservoirs (continental crust, pelagic sediments), we caution against concluding that other metals (especially Cu and Au) were also crustal, as the content of Cu of Middle-Late Tertiary porphyry-Cu and epithermal deposits seems to increase with increasing mantle lead contribution.

The large majority of Tertiary economic porphyry-Cu and epithermal deposits of Ecuador are spatially and chronologically associated with magmatic rocks of Eocene to Late Miocene age (ELM, ~50-9 Ma). The ELM magmatic rocks originated from mantle-derived calc-alkaline magmas that have evolved in parental chambers at shallow crustal levels (<20 km) through plagioclase-dominated fractionation. These magmas were emplaced at shallow crustal levels during a prolonged period of transpression ± extension in the Ecuadorian continental crust.

Only the ~5 Ma old Quimsacocha epithermal deposit has been recognized so far in association with Late Miocene to Recent (LMR) magmatic rocks. LMR rocks have adakite-type features that result not from slab-melting but from the evolution of mantle-derived magmas in parental chambers situated at subcrustal levels during a prolonged compressional phase initiated ~9 Ma ago. At these depths mantle-derived magmas assimilated residual garnet-bearing rocks (possibly underplated metabasalts of the Jurassic Alao arc) and evolved through plagioclase-free and amphibole fractionation (MASH-type processes). LMR magmatic rocks of Ecuador bear geochemical similarities with the magmatic rocks associated with large porphyry-Cu/epithermal deposits of the Central Andes and of other magmatic arcs (e.g., Philippines). However, in Ecuador, only one deposit (Quimsacocha) is associated with LMR-type magmatism. A possible explanation for the unfertility of LMR rocks is metal (Cu and Au) sequestration by mineral phases (e.g., pyrrhotite) crystallizing at depth before the magma reached fluid-saturation.

More work is needed to understand the real metallogenic potential of LMR rocks and to understand the petrogenesis of magmatic rocks of the various arcs of Ecuador. Our work on the Early Tertiary island arc of Macuchi (Chiaradia and Fontboté, 2001) and on the Middle-Late Tertiary continental arc (Chiaradia et al., 2004) indicates that combining multi-isotope with geochemical data of magmatic rocks can lead to a better evaluation of metal contributions to magmatic-related ore deposits. Such an approach has implications for exploration because mineral deposits of Ecuador result from the coincidence of specific magma evolution processes, geodynamic conditions (Chiaradia et al., 2004), and metal reservoirs (Chiaradia and Fontboté, 2001; Chiaradia et al., 2004a). Additionally, if the correlation between $^{207}Pb/^{204}Pb$ values and Cu content is confirmed by further data, high precision lead isotope analyses may be a useful exploration tool for Middle-Late Tertiary porphyry-Cu and epithermal deposits.

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