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A GIS-based isotope map of the Central Andes (13°S-28°S) and implications for ore formation

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INTRODUCTION

Georeferenced geochemical information on c. 1500 samples, including 819 Pb-isotope analysis were used to construct GIS-based (under ArcView, ESRI) maps for isotopes and trace elements of igneous, sedimentary, and metamoprhic rocks as well as samples from ore deposits. The maps cover an area of 840,000 km^2 of southern Peru, western Bolivia, northern Chile and northwestern Argentina between latitudes 13°S-28°S and longitudes 66°W-75°W. The database comprises new and existing data from the Göttingen Andes Project, BRGM GIS Andes Project (see http://gisandes.brgm.fr/) and selected published data on igneous rocks and ore deposits. These GIS-maps integrate in separate layers the geological, structural, metallogenic, and geophysical datasets. We focus on what Pb isotopes tell us in this context about the influence of basement rocks and tectonic settings on the metal sources of ore deposits in order to understand regional and temporal controls on ore formation.

THE CENTRAL ANDEAN GEOCHEMICAL INFORMATION SYSTEM (CA-GIS)

CA-GIS contain numerous data-layers which can be subdivided into the following categories:

Geology: a geological synthesis at 1:2,000,000 scale and the distribution of Jurassic-Cretaceous-Paleogene intrusions and Neogene volcanic rocks and eruptive centers.
Geochemistry: a database with 1500 whole rock analysis (major elements, trace elements, Sr-Nd-Pb isotopes) covering an age range from the Jurassic to the Present.
Metallogeny: Pb isotope data on 120 Andean ore deposits combined with metadata on locations, main metallogenic features of the mining district and provinces.
Geography and Topography: a DCW ® geographic base; three digital elevation models with a structural analysis.
Geophysic: gravimetry (Bouguer anomalies) and a gravity model for the Nazca Plate.
The "*ArcView Spatial Analysis*" is a tool to document and understand spatial relationships between data. The method applied is IDW (inverse distance weighted) and aims to interpolate points (e.g. ^{206}Pb/^{204}Pb-isotope ratios) and creates surfaces from point samples (e.g. Pb-isotope zones). For our mapping we use 12 points (nearest neighbors) within 12 km radial distance.
The interest of this study focuses onto the Central Volcanic Zone (CVZ) because of an abundance of data, which include many igneous rocks. These have been previously shown to provide an image of the isotopic composition of the Andean basement and thus can be used to map out crustal domains (Macfarlane et al., 1990; Wörner et al., 1992; Aitcheson et al., 1995, Loewy et al. 2004). This is because the crustal component has a particularly strong impact on Pb-isotope ratios of the erupted lavas through the process of assimilation, in addition to its effect on Sr-Nd, and O-isotopic composition, (Tilton and Barreiro, 1980; Davidson et al., 1991; Aicheson et al., 1995). Sulfides in epithermal ore deposits have been shown to develop as the crust is thickened and the focus of igneous activity shifts regionally (Kay et al., 1999). Interpolation of Pb-isotopes at a regional scale requires a wide distribution and full coverage of point samples and also a knowledge of the spatial and temporal distribution of the igneous rocks and ore deposits along and across of the Central Volcanic Zone. The samples used in the interpolation are from: Frontal arc: Holocene Active volcanoes (0 - 0.3 Ma), Pleistocene Extinct volcanoes (0.8 – 3 Ma), Mio-Pliocene centers (3 – 15 Ma), Miocene Syn-uplift volcanics (15 – 25 Ma), Eocene-Oligocene Pre-uplift volcanics (> 25 Ma), Miocene to Recent local ignimbrites (0 – 15 Ma), Miocene Regional Ignimbrites (15 – 25 Ma). Back arc: Holocene volcanoes (> 0.7 Ma), Miocene-Pliocene volcanics (3 – 15), Oligocene volcanics (28 – 30 Ma), Mio-Pliocene Ignimbrites (1 -6 Ma), Oligocene Intrusions (28 – 30 Ma). Margin and Intraplate

rocks: Cretaceous-Paleocene intrusions (33 – 90 Ma), Jurassic intrusions (100 – 190 Ma). Basement: Proterozoic (2000 - ~960 Ma), Paleozoic (~530 - ~250 Ma). Ore deposits: Meso-Cenozoic mineral deposits (~230 – 0 Ma).

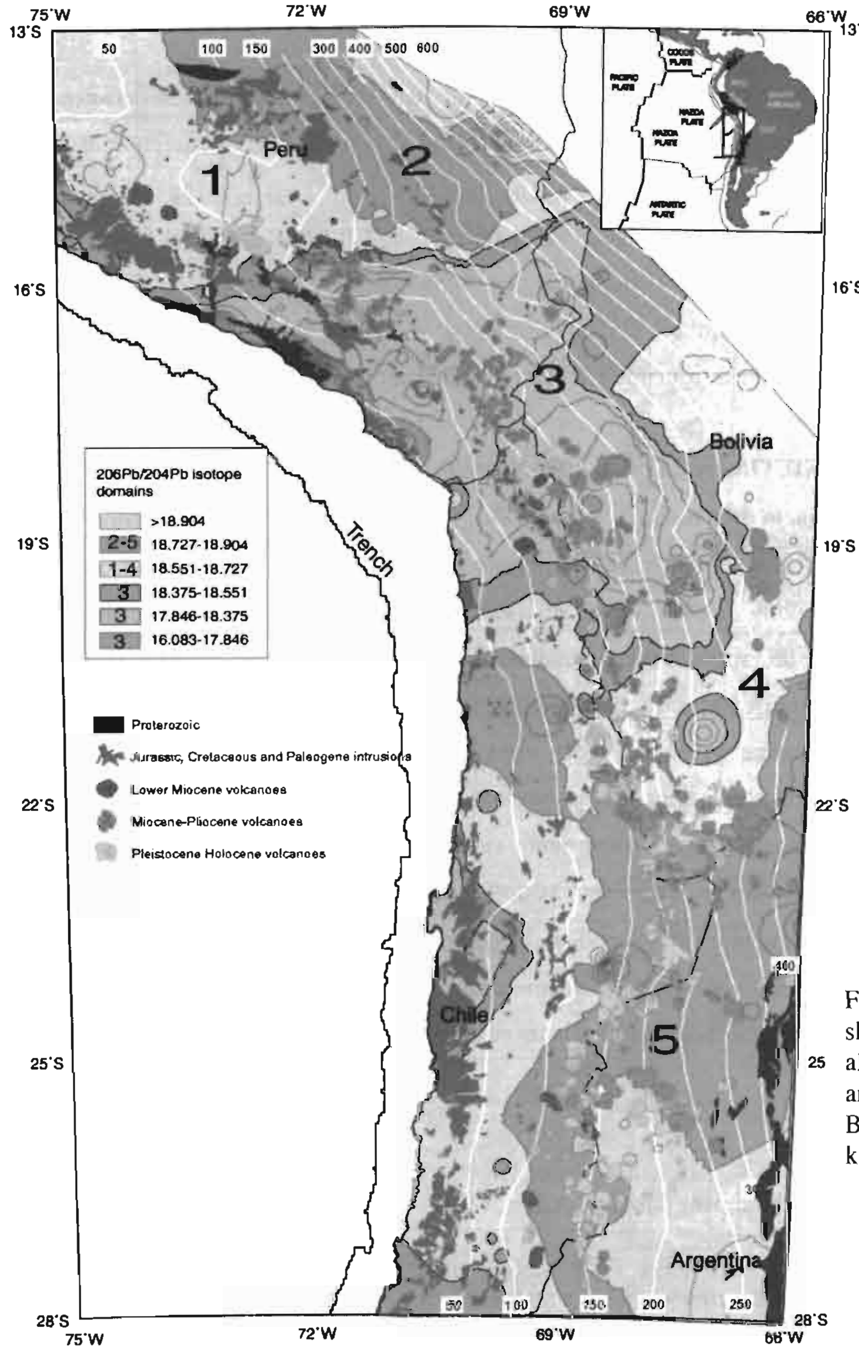

Fig. 1: $^{206}Pb/^{204}Pb$ isotope map showing the different domains along the Central Volcanic Zone and contours to the Wadati-Benioff zone with depths in kilometers.

Based on the compiled data set, extended with more than 815 of own unpublished data from volcanic rocks of the Central Andes, we present a series of maps showing the isotopic and geochemical zoning of crustal rocks in the Andes with respect to geology, structure and ore deposits. As an example, we present here a map that shows the distribution of $^{206}Pb/^{204}Pb$ ratios on a regional scale (Fig. 1). This map delineates rather exactly the boundaries of crustal domains, which have geochemical and metallogenic significance along and across of the Central Volcanic Zone (see Table 1). This kind of Pb-isotopic map may help exploration and can also be used as a tool during prospect evaluation if it can be shown that the composition and structure of the basement has a control on ore forming processes.

RELATIONS BETWEEN STRUCTURES AND ISOTOPE DOMAINS

The isotopic domain boundaries reflect the positions and character of real geologic boundaries between the different crustal blocks and these follow large-scale structural trends. The abrupt boundary between domains 1 and 3 coincides with the West-East Chuquibamba fault zone. The transition to the East between domains 1- 2 and 3-4 could be a major fault apparently parallel to the Andahuayllas-Anta–Copacabana-Coniri fault system. The transition zone to the west between domains 5 and 4 and the abrupt boundary between domains 3 and 4 coincides with West fissure fault system in northern Chile. Positions of minor Pb domains also coincide with small faults. Transitional domains exist because domains 1-2-4-5 are more radiogenic than domain 3.

RELATIONS BETWEEN TYPE AND TIMING OF ORE DEPOSITS AND CRUSTAL DOMAINS

Jurassic and Cretaceous Cu-Ag deposits in domain 3 have low $^{206}Pb/^{204}Pb$ from 17.0 to 18.5. Paleogene Cu-Au-Ag deposits in domains 2 and 5 have higher $^{206}Pb/^{204}Pb$. Miocene and Pliocene Au-Ag-Cu deposits of the volcanic arc (domains 1+4) have slightly higher $^{206}Pb/^{204}Pb$ (Tab. 1). Mio-Pliocene auriferous epithermal deposits on radiogenic basement (Paleozoic rocks) have even higher $^{206}Pb/^{204}Pb$ in domains 2-4 and 5. In domain 3 between Jurassic margin type deposits with oceanic-like Pb ratios and Cretaceous intra-arc type deposits have interacted with crustal Pb ratios. Pb isotope ratios of Miocene and Pliocene from domains 1-2-4-5 are higher than for Cretaceous deposits because they have a greater percentage of crustal Pb than the older deposits. Pb isotopes of Neogene deposits are age-independent and are interpreted to reflect directly different Pb basement from thickened continental crust (up to 70 km). Important Miocene Au-Ag deposits (e.g. Orcopampa, Shila, Coipa, Refugio, Escondida) in domain 1-4 and 5 developed as the crust thickened over a shallowing subduction zone (Fig. 1, Kay et al., 1999). Sr - Nd isotope values of igneous rocks have a similar pattern between Jurassic margin magmas and Cretaceous intra-arc rocks because they were emplaced on a thinner continental crust.

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Tab.1: $^{206}Pb/^{204}Pb$ domains and their metallogenic significance. (Ep=Epithermal, EpHs=Epithermal high sulphidation, EpLs=Epithermal low sulphidation, V=vein, P=Porphyry, BrP=Breccia pipe, ?=Unspecified).

Domain	$^{206}Pb/^{204}Pb$	Main Commodity	Type	Mineral deposit name
1	18.551 - 18.727	> Au	EpHs	Paracota
			EpLs	Ares, San Miguel
			V	Cristo Rey, Los Incas, San Luis
			?	Caraveli, Barrero
		> Ag	EpLs	Arcata, Shila, Cailloma, Orcopampa
			Ep	Chapi, Paola
			V	Jarhuarazo
		< Cu	V	Otoca
			?	Tereniso, Tuyumina
2	18.727 - 18.904	> Cu	Skarn	Tintaya, Coroccohuayco, Ferrobamba
			?	Huinchos, Morosayhuas
		< Au	Skarn	Katanga
			V	Manco Capac, Winicocha
3	17.846 - 18.199	> Cu	V	Rosales, Rosa Maria, Norvill
			EpLs	Cacachara
			P, Ep	Cuajone, Copajuyo-Vita
			BrP	Cerro Verde, Toquepala
			?	Antacori
		≤ Ag	EpHs	Choquelimpe, Guadalupe
			EpLs	Todos Santos, San Antonio de Esquilache
			Ep	Wara Wara, Golden Hill
			V	Santa Barbara
5	18.727 - 18.904	> Cu	Skarn	Lagarto
			Ep	Babilonia, Laguna Verde
			P	Mocha, Collahuasi, El Abra
			?	Inka Viejo
		≤ Au	V	Paiquina, Farillón, Pabellon, Incahuasi
			Ep	Victoria, Chinchilla, Escondida
			P	Agua Rica
		< Ag	Ep	Cerro Gordo, Tres Quebradas
			P-EpLs	Diablillos-Antofalla
4	18.551 - 18.727	> Au	V	Copacabana, Suma Pacha, Iroco, Sakanhuaya, La Isleña
			EpLs	Kori Kollo, La Joya
			Ep	El Mestizo, Aguas Calientes, El Peñon
			P	Manto Ruso, La Pepa, Refugio, Marte
		≥ Ag	Ep	Guacazul, Esperanza
			EpLs-EpHs-P	Faride-La Coipa-Ubina and Animas