MAGMATIC CONSTRAINTS UPON THE EVOLUTION OF THE BOLIVIAN ANDES SINCE LATE OLIGOCENE TIMES

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RESUMEN : Se presenta una síntesis de la distribución espacial y temporal de las rocas igneas (ácidas peraluminosas, alcalinas, shoshoníticas / peralcalinas) de tras-arco del Altiplano y de la Cordillera Oriental de Bolivia y se discuten las relaciones entre este magmatismo y los diferentes episodios de estructuración orogénica de los Andes Bolivianos.

KEY WORDS : Bolivia, Oligocene, Neogene, Magmatism, Arc, Back-arc

INTRODUCTION

In addition to their peculiar tectonic and morphological features, the central Andes of southern Peru, Bolivia and northwesternmost Argentina (i.e. the "Bolivian Orocline") display quite specific Oligocene to Present magmatic and metallogenic (the tin province) features when compared with adjacent segments of the Andes. We present a synthesis of available data relevant to the distribution in time and space of the different types of back-arc magmatic rocks in the Altiplano and Cordillera Oriental of Bolivia and discuss the relationships between this back-arc magmatism and the orogenic evolution of the Bolivian Andes.

THE DIFFERENT MAGMATIC EPISODES

In the Altiplano and Cordillera Oriental of Bolivia, East of the Oligocene to Present subduction -related volcanic arc of the Central Volcanic Zone of the Andes, three types of magmatic rocks are known since late Oligocene times : (1) acidic, often peraluminous, effusive and intrusive rocks; (2) alkaline volcanic rocks; and (3) shoshonitic and ultrapotassic volcanic and subvolcanic rocks. Available radiochronological data show that this back-arc magmatic activity is distributed into discrete episodes, each one displaying a specific position within the orocline.

Felsic magmatism

Four pulses of felsic, more or less peraluminous, magmatism have been documented within the Altiplano and the Cordillera Oriental of Bolivia and southern Peru.

1) The first one, with ages between 28 and 23.5 Ma, defines a belt restricted to the northern NW-trending branch of the Cordillera Oriental in southern Peru (data and references in Clark et al., 1990) and Bolivia. In Bolivia, the most conspicuous features of this belt are the granodioritic to granitic, metaluminous to slightly peraluminous massifs of the Cordillera Real southeast of La Paz (Illimani, Quimsa Cruz, Santa Vera Cruz - Evernden et al., 1977; McBride et al., 1983) and metaluminous stocks (Kumurana, Coriviri, San Pablo-Morococala - Evernden et al., 1977; Grant el al., 1979; Schneider and Halls, 1985) of the Potosi-Morococala area. This episode is characterized by a northwestward increasing peraluminosity and increasing initial Sr isotopic ratios (0.707 to 0.719) of the magmas.

2) A second episode (22 to 19 Ma) is documented only in the southeastern part of NW-trending branch of the Cordillera Oriental of Bolivia from Santa Vera Cruz to Kari Kari (Potosi). The

most striking features of this episode are subvolcanic stocks and extrusive rocks (Llallagua, Colquechaca, Tinquipaya,, ...) and the Kari Kari caldera (peraluminous, garnet and cordierite-bearing high-K andesite to high-K rhyolite with initial Sr isotopic ratio at 0.7105 - e.g. Francis et al., 1981; Schneider, 1985) and associated effusive rocks (Agua Dulce and Mondragon volcanics).

3) After a period of apparent magmatic quiescence, the belt corresponding to the third episode (17 to 13 Ma) has a greater longitudinal extension and is shifted towards the West with respect to the first two belts. It is documented in the Altiplano and Cordillera Oriental of southern Peru (see Clark et al., 1990). In the Altiplano and the western part of the Cordillera Oriental of northern Bolivia many small extrusive and shallow intrusive, mainly dacitic, bodies belong to this episode (Evernden et al., 1977; Grant et al., 1979; McBride et al., 1983; Redwood and Macintyre, 1989). In the Potosi area, the Cerro Rico, and the Cebadillas extrusive (slightly peraluminous dacites, with initial Sr isotopic ratio in the range 0.707-0.712 - Schneider, 1985) belong to this episode. This third belt extends southwards down to the Bolivia-Argentina border [volcanic centers of Tasna, Chocaya, Chorolque, Tatasi (Grant et al., 1978), San Vicente, Bonete and Morokho (Fornari et al., 1991, this volume)].

4) The fourth episode (10.5 and 2 Ma, main activity between 8,5 and 5 Ma) is the most important in volume. The main feature of this episode is the emission of enormous quantities of peraluminous quartz-latitic to rhyolitic ignimbrites with some resurgent domes in three centers within the Cordillera Oriental: Macusani (see Clark et al., 1990) in southern Peru, Morococala (Koeppen et al., 1987; Lavenu et al., 1989; Ericksen et al., 1990) and Los Frailes (Schneider, 1985; Schneider and Halls, 1985) in Bolivia. In Los Frailes the compositions and isotopic ratios of these tuffs are quite similar to those of the previous Cebadillas episode. In this area post-meseta domes of Pliocene age (4-2 Ma) are known. The partly eroded and undated stratovolcanoes (Cuzco, Cosuña, ...) immediatly to the south of Los Frailes would belong to this last Pliocene pulse. This episode also comprises various stocks and volcanic complexes in the Cordillera Oriental of southern Peru (see Clark et al., 1990), and in both the northern (Redwood and Macintyre, 1989) and southern (Orstom, unpub. data) Altiplano of Bolivia.

Alkaline volcanism

One of the more peculiar feature of the Bolivian Altiplano is the presence of a voluminous alkaline volcanism of late Oligocene - early Miocene age (28-21 Ma). This episode gathers various previously described volcanic formations, the kinship of which has been recognized only recently (see Jimenez et al., this volume; Soler et al., this volume.).

In the northern and central Altiplano of Bolivia, this volcanism — Abaroa Fm. towards the NW (Lavenu et al., 1989; Jimenez et al, 1993 and this volume), Tambo Tambillo lavas towards the SE (Evernden et al., 1977; Soler et al., this volume and unpub. data), and unnamed equivalents in the intermediate Andamarca-Corque region — define a NNW-trending, 400 km long, *en échelon* belt, which is quite oblique with respect to the mid-Miocene to modern calc-alkaline arc. In its northwesternmost part this belt is presently partly covered by the subduction-related arc, while southeastwards it is well apart from the arc. This belt seems to have a northern prolongation in the Altiplano of southern Peru where the presence of monzogabbros, and trachytic to phonolitic flows has been documented (Ayaviri area - ages between 28 and 23 Ma, Bonhomme et al., 1985).

In the southern Altiplano outcrops of alkaline volcanism [e.g. Julaca Fm., Rondal Fm. (Kussmaul et al., 1975; Fornari et al., 1991, this volume), Tupiza volcanics (Hérail et al., 1992, this volume) are less continuous and are mostly known along documented N-S and SW-NE trending strike-slip faults (Sempere et al., 1988, 1990a; Hérail et al., 1992, this volume).

Shoshonitic and ultrapotassic volcanism

Four short-lived episodes of shoshonitic / ultrapotassic volcanism have been documented along the Bolivian Orocline since late Oligocene times.

The first one (28-24 Ma) is mostly known in the Cordillera Oriental of southeastern Peru (Moromoroni, Crucero basin) (data and references in Clark et al., 1990). In the Cordillera Real southeast of La Paz some lamprophyric dykes of the Illimani massif and surrounding area (27.3 Ma - McBride et al., 1983) belong to this episode.

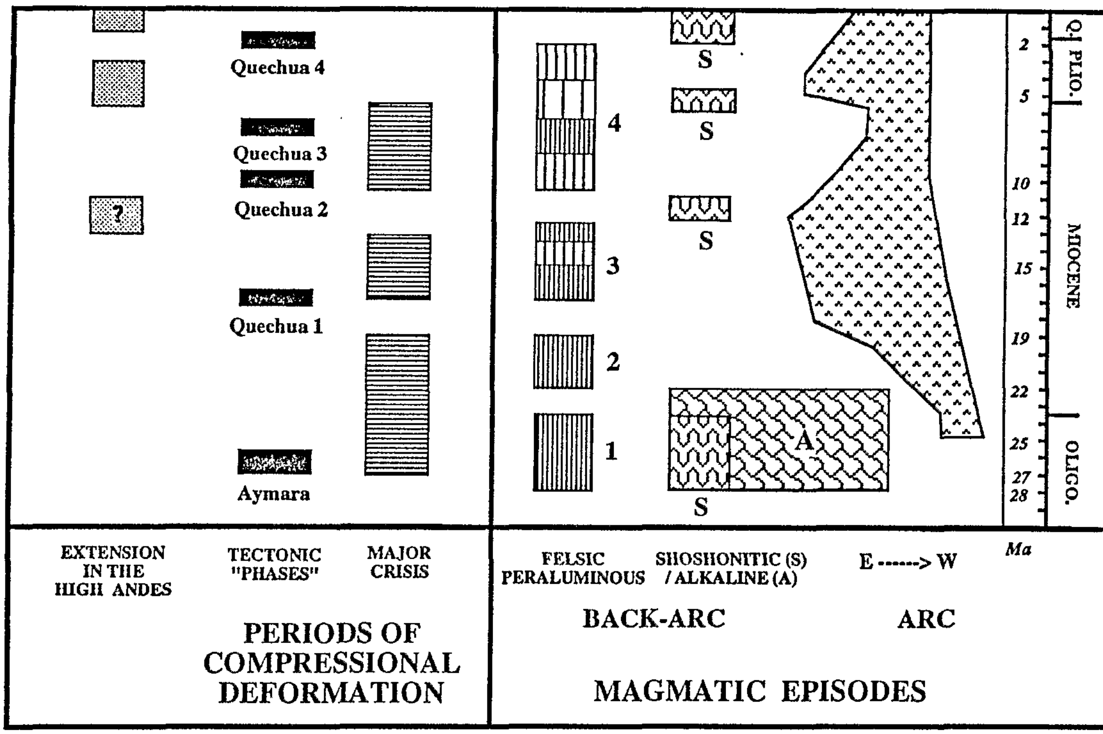
A second short-lived episode of shoshonitic volcanism (13-11 Ma) has been documented in Bolivia (Redwood and Macintyre, 1989; Soler et al., 1992a; Hérail et al., in press) within the Huarina Thrust and Fold Belt (Sempere et al., 1988, 1990a) at the transition Cordillera Oriental-northern Altiplano.

A third episode of shoshonitic volcanism of Pliocene age has been reported by Lefèvre (1979) in the Altiplano of southeasternmost Peru. This episode has not been documented so far in the Bolivian Altiplano.

A fourth episode of shoshonitic volcanism, Quaternary in age (less than 1 Ma), has been documented in the central Altiplano of Bolivia (Davidson et al., 1991; Carlier et al., 1992; Soler et al., 1992, 1993 and in prep.). It was already well known in southeastern Peru and northwesternmost Argentina.

The first episode of shoshonitic volcanism is coeval with the first episode of felsic magmatism to the northern NW-trending branch of the Cordillera Oriental, while the subsequent episodes of shoshonites seem to have occurred (although some overlapping may be observed) in periods during which no peraluminous, felsic magmatism is documented.

Magmatic episodes and tectonics in the Bolivian Andes since Late Oligocene times



RELATIONS WITH THE TECTONIC EVOLUTION AND THE GEODYNAMIC SETTING

The long-lived episodes of felsic, more or less peraluminous magmatism seem to be coeval with long periods of compressional deformation (e.g. Sempere et al., 1988, 1990ab; Sempere, 1991; Gubbels et al., 1993; Hérail et al., 1993) which would include some climax of deformation corresponding to the so-called (and challenged; see Sempere, 1991) compressional phases or events (e.g. Lavenu, 1986; Sébrier and Soler, 1991).

The mid-Miocene to Quaternary short-lived episodes of shoshonitic/ultrapotassic volcanism seem be restricted to the periods during which extensional or trans-tensional conditions prevailed in the high Andes (Lavenu, 1986; Sébrier and Soler, 1991; Carlier et al., 1992b; Soler et al., 1992b, in prep.).

The shoshonites and the peraluminous rocks are restricted to the segment of the Andes and the time span in which a lithospheric scale underthrusting of the Brazilian shield beneath the Andes is documented. We consider (Carlier et al., 1992ab; Soler et al., 1992b, in prep.) that the source of the shoshohitic volcanism of the Central Andes is the subcontinental lithospheric mantle in which the low percentage of melting which produces primary peralkaline magmas is triggered by the "continental subduction" of the Brazilian Shield under the Andes. These magmas undergo complex processes of contamination (by difusion, partial melting of the country rocks and mingling, ...) in the lower and middle crust. They reach the surface only when extensional or trans-tensional conditions prevail. During the long-lived periods of compressionnal structuration no shoshonitic volcanism is observed and the peralkaline and shoshonitic magmas evolve through magmatic differentiation and crustal contamination towards felsic (mostly dacitic), often peraluminous, magmas, the crustal origin of which (following the standard viewpoint) should be challenged. In this view, neither the shoshonitic volcanism nor the felsic, peraluminous magmatism are directly linked to the subduction of the Nazca plate under the South American continent.

This absence of direct relation with the subduction process is very clear for the late Oligocene - early Miocene period during which the documented alkaline "belt" is located between the western calc-alkaline arc and the eastern belt of felsic and shoshonitic/peralkaline magmatism. The beginning of this alkaline episode (and of episodes 1 of felsic magmatism and shoshonitic volcanism) corresponds to a period (30-25 Ma) during which no subduction-related calc-alkaline arc is documented — probably because the rate of convergence between the Nazca plate and South America was very low (e.g. Soler, 1991) —, and to the onset of orogenic deformation in the eastern part of the Altiplano, the Cordillera Oriental and Subandean zone of Bolivia (Sempere et al., 1990ab; Sempere, 1991). Although still poorly understood, this very primitive alkaline magmatism would be derived from the subcontinental lithospheric mantle in trans-tensional conditions.

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