ERUPTIVE PROCESSES, MINERALIZATION AND ISOTOPIC EVOLUTION OF THE LOS FRAILES KARIKARI REGION, BOLIVIA

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RESUMEN

El campo volcánico del Karikari Los Frailes está ubicado en la Cordillera Oriental de Bolivia, trasarco de los Andes Centrales. En este campo volcánico se ubica una parte importante de los yacimientos polimetálicos de Sn-Ag de Bolivia, configurando una franja metalogénica de características y posición geotectónica únicas, cuyo emplazamiento se produjo durante un episodio extensivo, ocurrido entre la Deflección de Arica y el Escudo Brasileño.

Las dataciones K-Ar y por trazas de fisión demuestran que las primeras etapas del magmatismo se produjeron hace 25 Ma, con intrusiones granodioríticas pequeñas y una menor actividad volcánica, desarrollada hasta alrededor de los 20 Ma. Desde esta edad, la actividad aumentó considerablemente y, alrededor de 10 Ma, hubo un gran aumento en la producción de magma, lo que habría formado la meseta Los Frailes. La mineralización en este sector está fuertemente relacionada con los episodios magmáticos producidos entre los 20 y 15 Ma, época en la cual se formaron los depósitos de Karikari y Cerro Rico. En consecuencia, como los yacimientos de estaño se formaron antes del Mioceno tardío y antes de que se produjera la segmentación de la Placa de Nazca y sus nuevas condiciones de subducción tuvieran lugar, no se le puede atribuir ninguna influencia a estas condiciones de subducción en la distribución de los yacimientos de estaño.

El principal centro eruptivo en este sector es la caldera resurgente de Karikari, que tuvo una subsidencia asimétrica, seguida por la eyección de magmas a lo largo de esta zona deprimida.

Las vetas y la mineralización diseminada de los yacimientos polimetálicos ocurrieron asociadas a tres períodos diferentes de la evolución de la caldera. La mineralización está ubicada a lo largo de la zona de falla que controla el margen occidental de la caldera, donde, a su vez, se emplazó el domo portador de Sn-Ag de Cerro Rico. Otros depósitos se ubican también en zonas apicales y laterales del domo resurgente.

El carácter peraluminoso y la evidencia petrológica, tal como la presencia de granate-biotita y gros.-an.-sill.-qz., indican que una probable fuente de origen de los magmas estuvo entre la parte superior de las facies anfibolíticas y la inferior de las granulíticas, dentro de la corteza continental.

Geoquímicamente, los magmas karikari fueron generados en una cámara magmática zonada. La composición de las rocas va desde andesitas a toscanitas con alto contenido en potasio. Las razones iniciales de Sr revelan valores entre 0,707 y 0,716, lo que es típico de una evolución cortical, con la posible adición de componentes derivados del manto. Las evidencias aportadas por los análisis de Nd/Sm muestran la presencia de componentes más antiguos en los magmas de karikari. Los isótopos Pb, por su parte, caracterizan una fuerte naturaleza cortical del magma, incluso para el origen de la mineralización; sin embargo, se muestran, a su vez, diferentes grados de mezcla de Pb primitivo con Pb recirculado. A pesar de que los elementos HFS muestan una influencia del manto, las similitudes químicas entre el Sn y los elementos HFS podrían usarse como evidencias de la interacción entre el Sn y estos elementos concentrados en un manto enriquecido en álcalis en un ambiente intracontinental. De este modo, el estaño fue, ciertamente, concentrado en la corteza, durante los primeros ciclos magmáticos y quedó disponible para ser incluido en las sucesivas etapas magmáticas, que incluyen procesos anatécticos.

En las etapas finales de la evolución magmática, los fluidos residuales, ricos en boro y cloro, fueron los principales responsables de la depositación de los compuestos metálicos. Estos compuestos depositaron los metales en las vetas y en forma diseminada, en los stocks volcánicos y domos, durante las etapas de confinamiento. En estos yacimientos, las asociaciones paragenéticas están divididas en tres fases de mineralización, dentro de las cuales, la tercera es la portadora de las sulfosales de Pb-Ag-Sb, que son las de mayor significado económico.

Palabras claves: Metalogénesis, Estaño, Caldera Karikari, Meseta Los Frailes, Bolivia Suroeste.

Key words: Metallogenesis, Tin, Karikari caldera, Los Frailes plateau, Southwest Bolivia.

REGIONAL AND STRUCTURAL GEOLOGY

The Los Frailes Karikari Volcanic Field is located within the Eastern Cordillera of Bolivia forming a dominant part of the back-arc of the Central Andes (Fig. 1). This field was mainly developed during the Miocene event of the Andean orogeny. It is the largest composite eruptive sequence in the Eastern Cordillera, covering about 8,500 km^2 at altitudes between 4000-5200 m. It hosts important metal deposits, which constitute a major part of the southern subvolcanic section of the Bolivian Tin Belt (Fig. 2).

The volcanic products are to a dominant part acid to intermediate ashflow tuffs, while acid-andesitic lava flows are only locally developed. Source regions for these large volumes of ashflow tuff material are several eruptive centres of different dimensions such as the Karikari Caldera (20-15 km) or unknown huge structures such as Villacollo, Livicucho or Condor Nasa. Local domes and stocks dissected or covered by these eruptive events, host a great variety of economically important Sn-Ag-polymetallic ore deposits.

This important metallogenic belt occupies a unique geotectonic position within the Central Andes, whose emplacement was controlled by an extensional zone in the region of the Brazilian Shield behind the Arica deflection. Such a zone of dilatancy was necessary to allow the emplacement of a large magmatic mass, which now forms the most important back-arc belt of the Andes. Its high level emplacement was especially favoured by the reactivation of deep-reaching, early-formed lineaments.

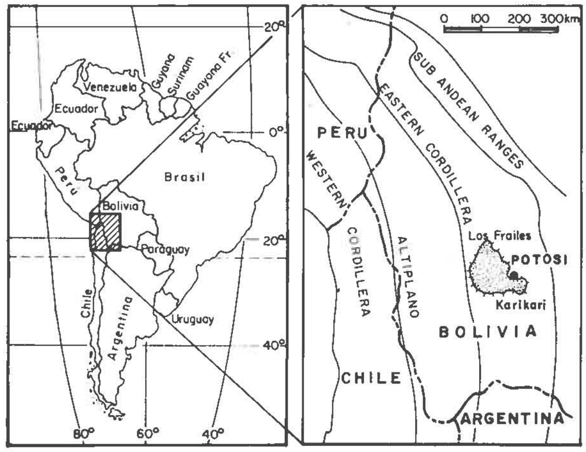

FIG. 1. Location map of the Eastern Cordillera, Bolivia.

GEOCHRONOLOGY

Results of K-Ar (biotite, alunite) and fission track (zircon) dating demonstrates that magmatic activity began about 25 Ma ago, with smaller granodioritic (Kumurana granidiorite) and granitic (Azanaques granite) intrusions associated to minor volcanic activity. At about 20 Ma the eruptive activity increased markedly, adjacent to the slow uprise of a major magmatic mass. At about 10 Ma a strong increase in the rate of magma production led to the formation of the Frailes Meseta.

Thereafter the eruptive activity exhausted rapidly and the focus of magmatism shifted southwards into the Nuevo Mundo province.

Mineralization is essentially correlated to the episode between 25-12 Ma and reached a climax at about 20-15 Ma. This is the time interval when the Cerro Rico and the Karikari deposits were formed. Here the mineralization was dated directly, using alunite gangue and fission tracks of zircons from the altered horizons.

This is also the time span prior to the main Andean uplift and of major crustal thickening, causing the vast eruptive period which formed the Los Frailes Meseta. The main Los Frailes and Post-Frailes magmatic episodes ($<$8Ma) are related to the marked increase in spreading and magma production which thickened the crust and caused extensive eruptive volcanism. This eruptive stage marked the end of major ore-forming processes.

In this way the tin deposits were formed prior to the Late Miocene segmentation of the Nazca plate and thus the differences in conditions of subduction arising from this could have had no influence on the distribution and formation of the tin deposits.

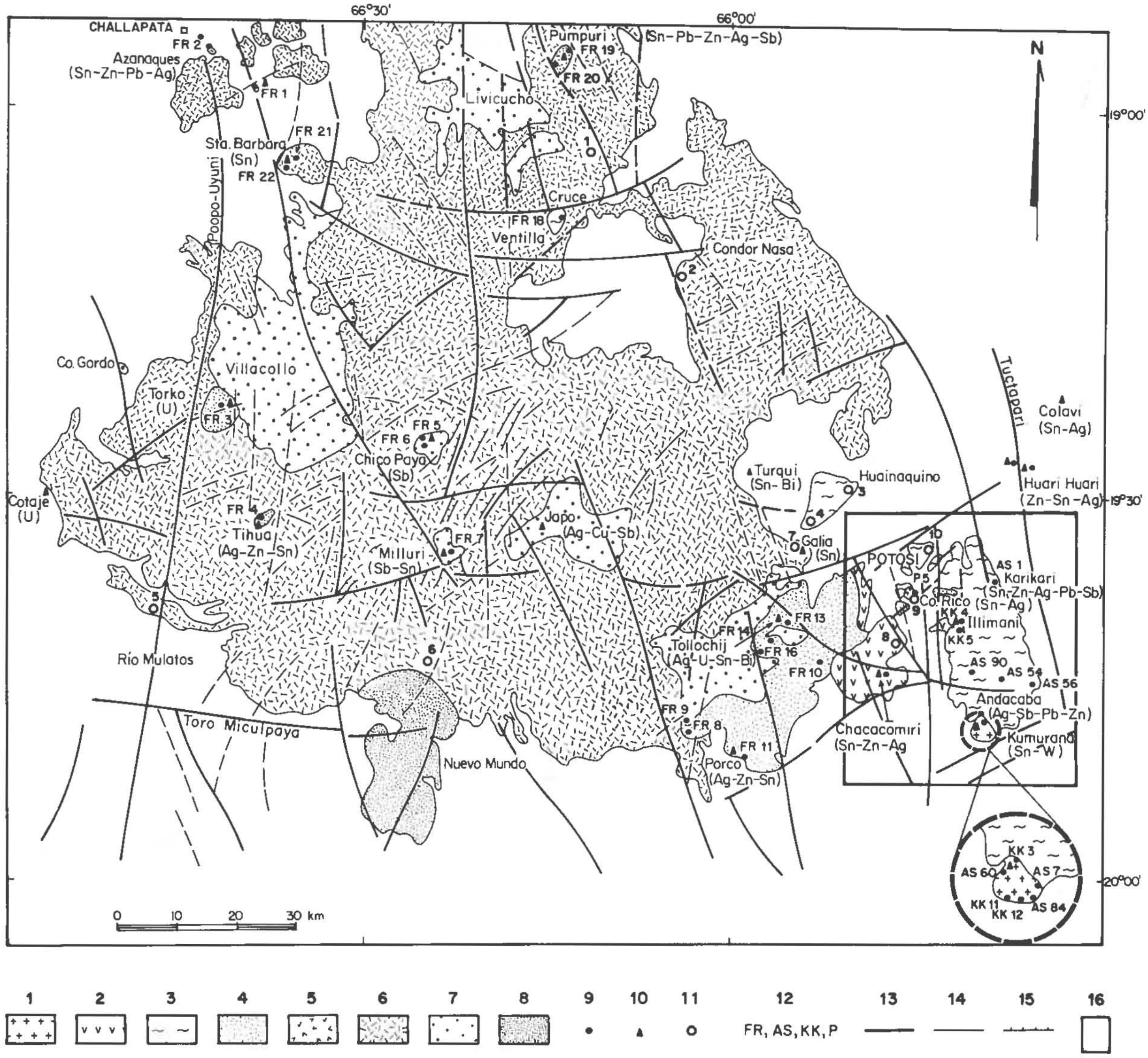

FIG. 2. The Los Frailes Karikari volcanic field. 1. Kumurana (~ 25 Ma); 2. Agua Dulce (~ 20 Ma); 3. Karikari (~ 20 Ma); 4. Cebadillas (11-16 Ma); 5. Cerro Rico dome (~ 12 Ma); 6. Los Frailes cover (~ 5-8 Ma); 7. Post-Los Frailes; 8. Nuevo Mundo; 9. Sample points; 10. Age data: literature; 11. Ore deposits + alteration zones; 12. K-Ar, fission track sample locality; 13. Major lineaments, faults; 14. Lineaments, faults; 15. Central graben faults; 16. Area of Fig. 3.

THE KARIKARI ERUPTIVE CENTRE

The dominant single eruptive centre in the volcanic field is the resurgent Karikari trap-door caldera (Francis *et al.*, 1981; Schneider, 1985). Such a caldera is characterized by asymmetrical subsidence of the roof, followed by magma ejection along this subsided zone of the caldera (Figs. 2, 3).

This eruption generated the crystal-rich, densely welded and fiamme-bearing Karikari ashflow tuff. Its entire volume of about 500 km^3 was ponded within the caldera depression.

This tuff was uplifted during resurgence and is now preserved as the Karikari Cordillera. Other eruptive products associated to the initial stages of eruption were instead stripped off by the high level

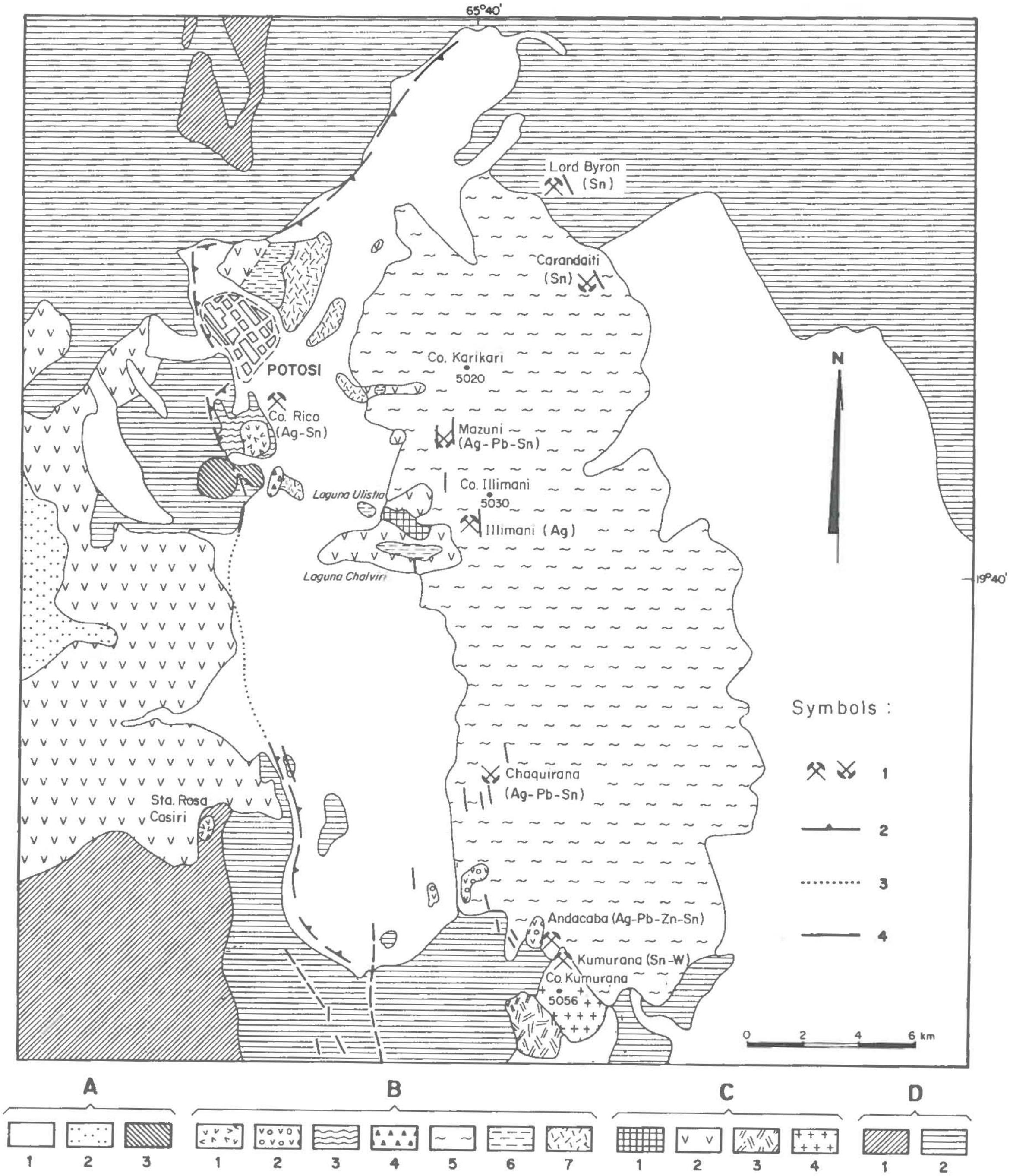

FIG. 3. The Geology of the Karikari Caldera. A. Los Frailes volcanic period (< 15 Ma) 1. Quaternary, alluvials; 2. Cebadillas ashflow tuffs, poorly welded, crystal poor; 3. Huackachi ashflow tuffs, poorly welded, crystal poor. B. Karikari volcanic period (~ 20 Ma) 1. Altered + mineralized domes, quartz-latite porphyry; 2. High-K andesite, crystal rich, porphyritic lava; 3. Caracoles, lacustrine tuffaceous lake sediments; 4. Pailaviri, caldera wall-breccia; 5. Karikari, garnet-bearing toscanitic ashflow tuff, densely welded, crystal rich. 6. Cantería, ashflow tuff, poorly welded, crystal poor; 7. Cantería, moat-breccia. C. Pre-Karikari period (> 20 Ma) 1. Ulistia, porphyritic eruptive; 2. Agua Dulce, ashflow tuff, poorly welded, included breccias; 3. Hornfels, contact metamorphic envelope; 4. Kumurana granodiorite. D. Basement 1. Cretaceous, calcareous sediments; 2. Undifferentiated Ordovicic-Silurian metasediments. Symbols: 1. Active, inactive mines (metal); 2. Topographic caldera wall; 3. Topographic caldera wall, covered by alluvials; 4. Faults.

of erosion. This situation complicates the geologic reconstruction of the centre, and for that reason many of the earlier workers claimed an intrusive origin of the rocks which now constitute the Karikari Cordillera.

This mineralized eruptive complex developed within a rectangular structural framework, which underwent stages of reactivation during magma resurgence and final uplift which was, at least, in the order of 600 m.

Tin-enriched tourmaline-bearing breccias indicate the volatile enriched nature of the uppermost fractions of its magma chamber at the ultimate stage. Different stages of erosion permit insight into various stages of its development.

Polymetallic (Sn-Ag-Pb-Sb-Bi-Zn-W-) mineralization, of vein and disseminated character, occurred in three distinct periods associated to the early and the later stages of caldera evolution. These are located along fault zones which control the western margin of the caldera, where the wellknown Cerro Rico Sn-Ag bearing dome was emplaced. Other deposits are located in apical and lateral zones of the resurgent dome, while an extensive geothermal system is still active along the eastern caldera margin, which is shown by the presence of three hotsprings.

PETROLOGY

The peraluminous character of the eruptive suite is shown by a distinct phenocryst mineralogy, consisting of alumina-rich phases like garnet, biotite, cordierite, pyroxene and also tourmaline.

The magmas of the adjacent Los Frailes sector are instead distinctly less peraluminous.

Petrological evidences (garnet-biotite geothermometry, gross.-an.-sill.-qtz. geobarometry) indicate a probable source region of these magmas in the upper amphibolite to lower granulite facies within the continental crust. It is further believed that underplating of this sector of the South American plate was necessary to initiate anatectic melting in the intracontinental environment. For this the mantle must be regarded as having a significant influence. Evidence for this is provided by the hybrid feature of the Kumurana granodiorite, which was emplaced during pre-caldera events at about 25 Ma and those of the high-K-andesites, which represent the least developed magmas of the Karikari centre, generated during the stage of magma resurgence.

The magmatic evolution of the Karikari magmas can be explained in terms of differentiation of mafic and peraluminous mineral phases such as garnet, pyroxene, biotite rather than by feldspar-dominated fractionation. This is concluded from results of trace, REE (rare earth elements) and microprobe phase analyses.

GEOCHEMISTRY

The Karikari magmas were generated from a zoned magma chamber which can be classified after Hildreth (1981) as a "monotone intermediate" ranging from 58-65 wt% SiO_2. The rocks range in composition from a high-K-andesite to high-K-toscanites. The term toscanite of Chappell and McKenzie (1972) was used in order to express the distinct K-enrichment of the rocks in the range of 63-69 wt% SiO_2. Their initial Sr ratios show evolutionary trends between 0.710-0.711, while the overall pattern within the volcanic field is developed between 0.707-0.716. This is typical for a dominantly crustal evolution but also involving possible mantle-derived components.

Evidence from Nd/Sm analyses (initials for garnet and plagioclase separates: -5.45-6.22) further show that the oldest components of the Karikari magmas were separated from the mantle in the Upper Paleozoic, thus coinciding with the early Hercynian orogenic cycles or even with Pre-Hercynian events. Though Sr+ Nd systematics indicate a transitional position on crust/mantle mixing lines.

Pb isotopes show instead the strong crustal nature of the magmas. The source of the ore metals in the various deposits is interpreted on the basis of Pb isotope analyses as being derived largely from upper crustal levels of which some were at least of Pre-Tertiary age, as shown by the various degrees of mixing between young and ancient Pb sources.

The influence of the mantle to the formation of the eruptives in the volcanic field is indicated in the overall increase in HFS elements (High Field Strength) and specially of Nb, Zr, Y across the volcanic field from west to east towards the intraplate environment. This seems to suggest an interaction of a HFS-element enriched mantle upon the genesis of these alkali-calcic magmas, with increasing distance away from the continental main magmatic arc, dominated by calc-alkali magmatism.

The chemical similarities between Sn and the HFS elements could be used as evidence in favour of interaction of Sn with these elements concentrated in an alkali enriched mantle within the intracontinental environment. These elements are largely carried in accessory phases such as rutile, zircon, sphene which are known to be more refractory and therefore more stable during the subduction process. The LIL elements (Large Ion-Lithophile) were instead mobilized during the initial melting subduction and characterize the development of the main magmatic arc, while the back-arc magmas are depleted in these elements.

The tin itself was certainly concentrated in the crust during the earlier magmatic cycles, and this tin would therefore be available for further involvement in any magmatic event including anatexis. Evidence for reworking of this type is provided by the results of the Pb-isotope data of the Tin Belt ores and magmas. Though inheritance of tin from multiple magmatic rejuvenation processes have been certainly an important factor of tin concentration apart from primary magmatic differentiation processes, although magmatic differentiation of these tin-bearing peraluminous magmas cannot be regarded as being an important factor of tin concentration in the eruptive environment.

HYDROTHERMAL EVOLUTION AND SULFIDE MINERALOGY

Boron and chlorine-rich residual fluids at the final stages of magmatic evolution were mainly responsible for metal complexing. These complexes deposited the ore metals in veins and disseminated subvolcanic stocks and domes during stages of confinement, though before or after the explosive eruptive event, where volatiles and the metal complexes were lost in disseminated form due to vigorous explosive eruption.

These deposits are either situated at the intersection of N-S and WSW-ENE trending lineaments, like the great Cerro Rico deposit, or along long trending N-S, NNW-SSE and NW-SE faults and lineaments like the essentially vein type deposits of the Karikari caldera. The paragenetic association of the ores and evidence from fluid inclusion studies show a typical hydrothermal zoning from high T °C and salinity assemblages to lower T °C and lower salinity conditions. Optical and microprobe phase analyses indicate a complex ore paragenesis where the earliest phases to form are cassiterite-wolframite and pyrite-arsenopyrite, found in the deepest levels at the Cerro Rico deposit and in the Kumurana mine. The second mineralizing stage is that of the stannite-arsenopyrite-pyrite-sulfosalt association at Cerro Rico. The third stage is the polymetallic paragenetic sequence which consists of iron sulfides, lead-zinc sulfides and principally Pb-Ag-Sb sulfosalts. These are the dominant carriers of silver and are of significant economic potential.

Detailed microprobe work revealed a progressive enrichment of Ag at the expense of Cu in tetrahedrites during stages of fractionation. The Pb-Ag-Sb sulfosalts show a trend from galena to semseyite to andorite s.s. to miargirite to pyrargirite and finally to argentite. These fractionation trends are typical for the complex silver-bearing sequences and must be regarded as an important consequente future exploration for these vertically zoned silver-tin systems within southern Bolivia.

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