Stratabound Sulfide Occurrences in the Paleozoic of the Yauli Dome, Central Peru

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1 Introduction

The Yauli domal structure is located in the Western Cordillera of the Peruvian Andes (76 °W, 11°40′S) at 4000–5300 m altitude. Among several inliers to the W of the coherent Paleozoic belt in the Eastern Cordillera (Fig. 1) it is the largest (covering an area of 10×30 km), best studied, and most distinguished for its economic potential.

A core of Lower to Middle Paleozoic weakly metamorphosed formations (Excelsior Group) is overlain discordantly by Upper Paleozoic volcanics and volcaniclastics (Mitu Group) surrounded by discordant Lower Mesozoic (Pucará Group) and younger sediments with minor volcanics and volcaniclastics. Plutonic to subvolcanic activity had taken place during all these periods, to which at least in the Tertiary extensive mineralized vein sytems in the Morococha and San Cristobal mining districts can be related (Fig. 2).

These Paleozoic and Mesozoic formations, as well as the Tertiary structures, are the metallotects for the mineral content of each epoch; summaries of these formations are given in Kobe (1982a) and Rivera and Kobe (1983a, b). This account, however, is restricted to the somewhat unique stratabound sulfide occurrences in the metamorphic Paleozoic formations (see also Kobe 1982b, 1984, 1986), while the figures illustrate their pertinent features from the regional to the microscope scale.

2 Geology of the Excelsior Group Formations

The metamorphic Paleozoic is exposed over an area of 6×20 km, updomed in essentially two subparallel anticlines. While the western Chumpe anticline extends continuously over 17 km, the eastern Ultimatum anticline is divided into two portions (N and S) by a cover of Upper Paleozoic volcanics in the center of the dome (Fig. 2).

The Excelsior Group consists predominantly of dark gray phyllites with occasional thin sandy (quartzitic) beds. Whitish, highly fossiliferous limestones (marble) intercalations are concentrated particularly in the Ultimatum anticline and have been macrofolded into the two outstanding hills Morro Blanco in the N and Cerro Yuraccgaga in the S, besides the partly disjointed occurrences at Trapiche. Fairly abundant basic volcanics (lavas and breccias) to volcaniclastics (tuffs) are

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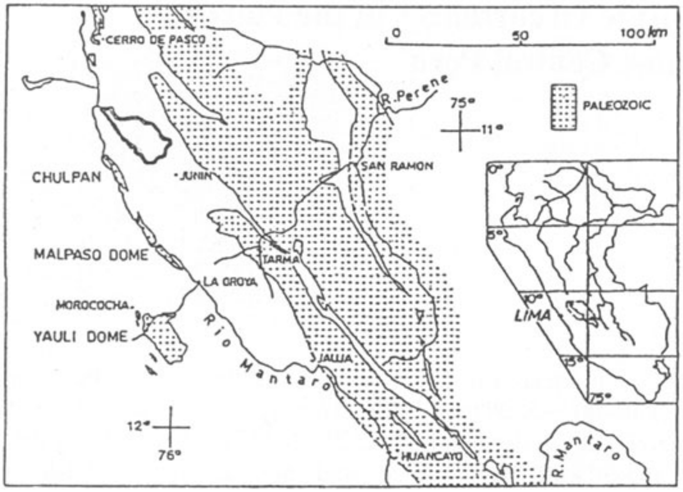

Fig. 1. Distribution of Paleozoic in Central Peru and location of the Yauli Dome. (After Mégard 1979)

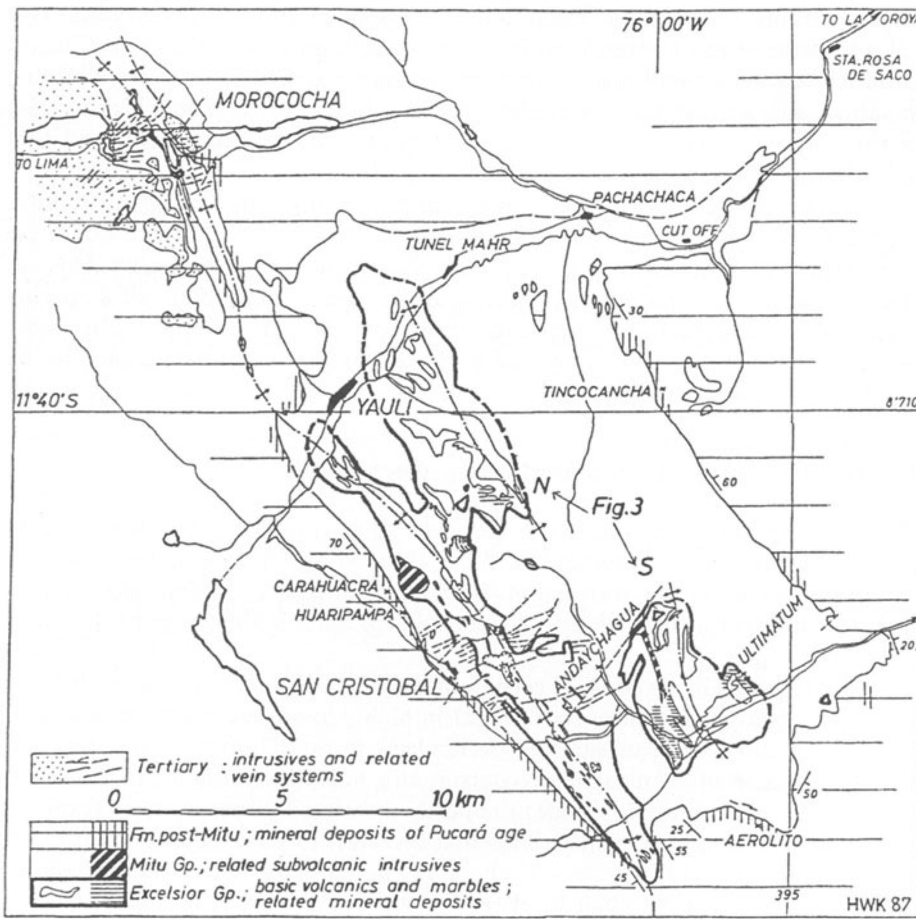

Fig. 2. General geology of the Yauli Dome

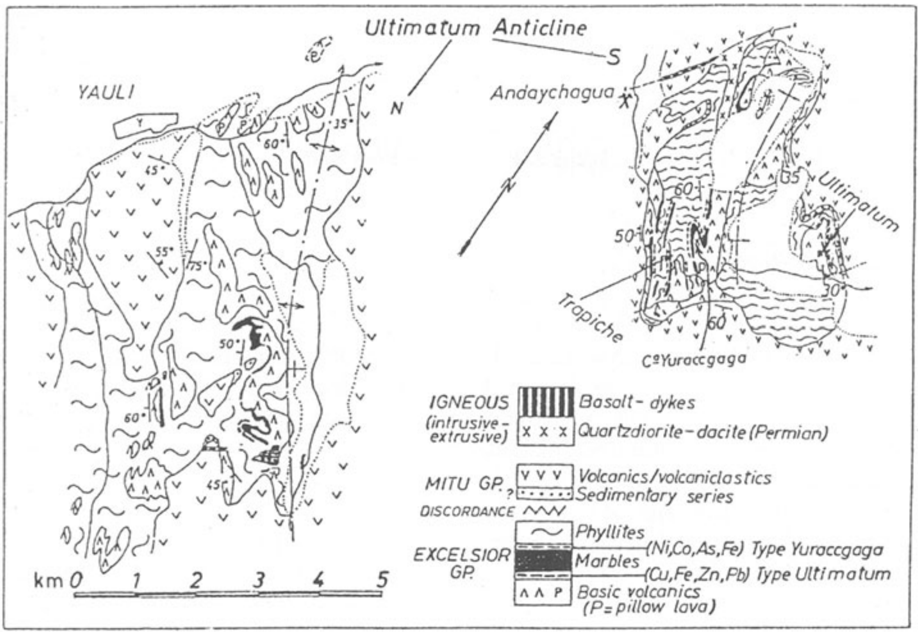

Fig. 3. Geology and stratabound mineral deposits in the Lower-Middle Paleozoic of the Ultimatum anticline

transformed into greenschists, but pillow lavas can still be recognized in various places (Fig. 3).

Stratabound sulfide concentrations accompany basic volcanic/limestone complexes predominantly in the Ultimatum anticline, but they are not entirely absent in the originally small and tectonically dismembered occurrences in the S of the Chumpe anticline. Folding at all scales has affected the whole formation and a superposition of Paleozoic (more northerly) and Andine (more NW) trends can be observed, especially in the larger limestone accumulations. A thorough structural analysis of the region, however, is still to be done.

3 Stratabound Sulfide Deposits

Two types of stratabound sulfide deposits can be distinguished by their metal content, mineralogy, fabric differences and associated rock formations (the position of the two types in the legend to Fig. 3 does not mean that they occur necessarily in that stratigraphic order):

Ultimatum Type

Metals – Fe, Cu, As, Zn, Pb, Ag

Minerals – pyrite, pyrrhotite, chalcopyrite, arsenopyrite, sphalerite (marmatite), galena, hematite, leucoxene, siderite, dolomite, quartz

Fabric – predominantly massive, also cementing breccias and disseminated sulfides
Associated rock formations:
hanging wall – phyllites
footwall – basic volcanics (partly host rock), minor limestone and volcaniclastic/limestone mixtures

Yuraccgaga-Trapiche Type

Metals – Ni, Co, As, Fe, Cu, Zn, Sb
Minerals – pyrite, violarite, millerite, gersdorffite, sphalerite, chalcopyrite, tučekite, leucoxene, hematite, chlorite, sericite, calcite, Mn-Fe carbonate, muscovite, quartz and chalcedony
Fabric – disseminated sulfides
Associated rock formations:
hanging wall – phyllites
footwall – (also host rock) marble, but bulk of sulfides occurs among an intimate mixture of fossiliferous limestone with basic tuffaceous and siliceous exhalative matter, now mainly chlorite, leucoxene, quartz/chalcedony and less often hematite.

3.1 Ultimatum Type

This paragenetic type is represented at only one locality, around the Ultimatum Mine (Fig. 2, 3) in the SE of the district. Unfortunately, little information is available from the mine (now inoperative) itself, but the overall setting (Fig. 4) shows that there is a close space-time relation between the basic volcanics and the associated, partly inherent (W portion), partly overlying (E portion) stratabound sulfide concentrations. Differentiation of the sulfides (and/or metals) is striking: in the W, pyrrhotite-chalcopyrite-(pyrite) occur as massive beds, accompanied by disseminations and veinlets, while in the E, pyrrhotite (with advanced transformation into the "intermediate mineral") is accompanied by pyrite, marmatite, galena, and siderite in massive beds and as breccia matrix, and in the lowermost adit, marcasite-pyrite rather than pyrrhotite forms the main sulfide body.

The zonation of the metals from the central Cu-Fe to the lateral Fe-Zn-Pb suggests a high-level submarine hydrothermal system in relation with the basic volcanics (mainly vesicular lavas, volcanic breccias, and minor tuffs), which only here are seen associated with a hydrothermally altered subvolcanic intrusive of gabbrodioritic composition. Large plagioclase laths (with clay alteration) are a major component, with titaniferous pyroxenes (in advanced alteration into half-opaque matter – leucoxene), chlorite, dendritic ilmenite, carbonate, and chalcedonic quartz. The fabric shows intense deformation and fragmentation of the component minerals, probably due to the eruptive conditions of emplacement. All these characteristics suggest a volcanic exhalative environment of formation for this deposit.

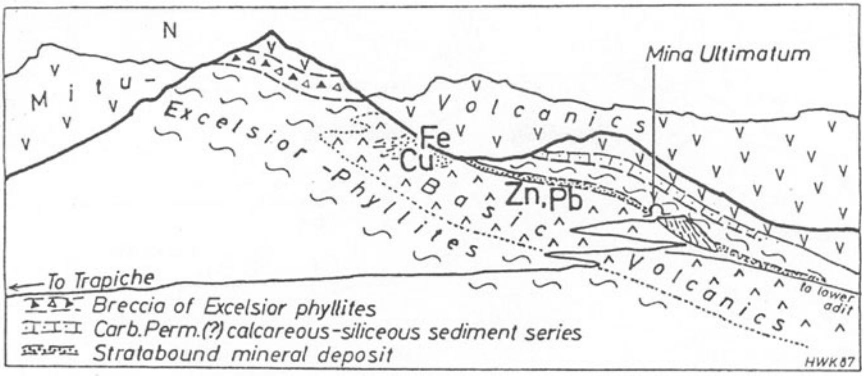

Fig. 4. View of the stratabound Fe-Cu-Zn-Pb mineral deposit (Ultimatum type)

3.2 Yuraccgaga-Trapiche Type

The paragenetic type is quite abundant in the two portions of the Lower Paleozoic exposed in the Ultimatum anticline (and even within a small occurrence in the southernmost part of the Chumpe anticline) (Figs. 2, 3). Stratabound sulfide enrichments are fairly strictly related to the complexes of substantial volumes of volcanics/volcaniclastics and limestones, where one component is very minor or absent, no mineral deposit has formed.

The association at outcrop scale is illustrated with Fig. 5 (two views of the macrofolds of Cerro Yuraccgaga) and partly microfolded in a cross-section at Trapiche (Fig. 6). The thickness of the sulfide-bearing portion of the limestone may vary from 0 or a few cm through an average of 2 m to locally over 10 m. The sequence basic volcanics/volcaniclastics-limestone-stratabound sulfides-phyllites is maintained in each occurrence and is taken to be the actual stratigraphic sequence (Fig. 7).

The host rock to the sulfides is a highly fossiliferous limestone (crinoids, corals etc.) which varies in composition. The bulk weathering colour of this quite pure limestone, away from the sulfide concentrations is white (zone 5), but turns to brown (zone 4) and black (zone 3) due to a change of composition of the constituent carbonate (higher Fe in 4, higher Mn in 3), and there is an increasing admixture of volcanogenic (tuffaceous/exhalative) material including the sulfides towards the top (the fine-grained fresh rock here taking a light gray-greenish color). Shrinkage cracks through this top portion stand out by their white infilling of calcite and quartz. The contact to the dark gray phyllites (without sulfides) is sharp.

The irregularly layered intimate mixture of limestones with volcanogenic/exhalative material and the fine dissemination of sulfides at hand-specimen scale is illustrated in Fig. 8:

Siliceous titaniferous volcanic fragments causing geopetal deformation of the sediment layering (4) represent the coarsest volcaniclastic material, while enrichments of chlorite (several varieties) often with quartz and titaniferous mat-

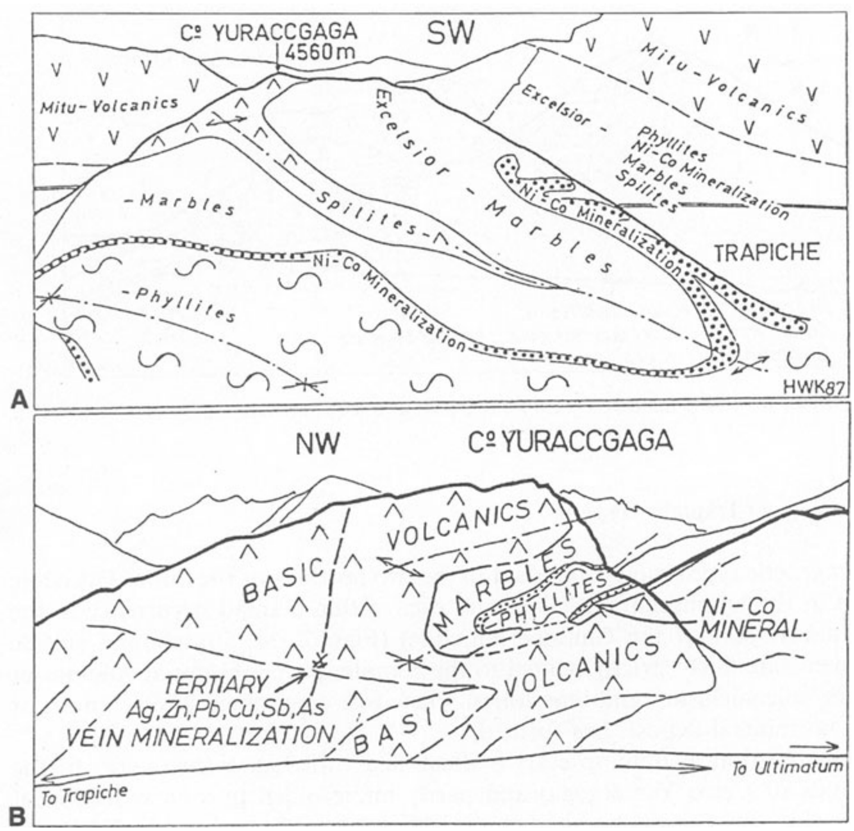

Fig. 5A, B. Views of the stratabound Ni-Co mineral deposits (Yuraccgaga-Trapiche type)

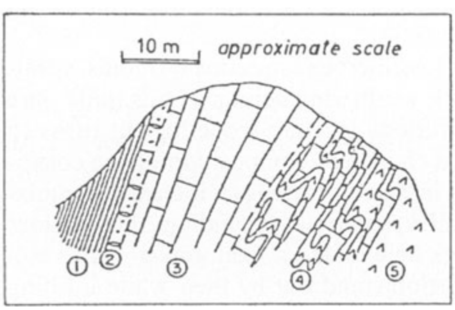

Fig. 6. Section through the marble outcrop 1 km N of Trapiche (coord. 8'700'100/391'300) (bedding 160/70 SW): *1* Phyllites (dark gray); *2* sulfide-bearing bed (1 m); *3* marbles (white); *4* mixed series of marble with intercalations of green volcanics, folded; *5* volcanics (dark green)

ter (leucoxene) (1, 3) are derived from the finer tuffaceous depositions. Quite well-defined microlayered schlieren of chalcedonic silica with fine hematite and leucoxene (5) are interpreted as intercalated exhalative material (cf. Fig. 4 in Kobe 1982b).

There is no apparent preference for sulfides to be concentrated in one or the other of these host rocks. Sulfides are irregular intercalations in a mixed matrix

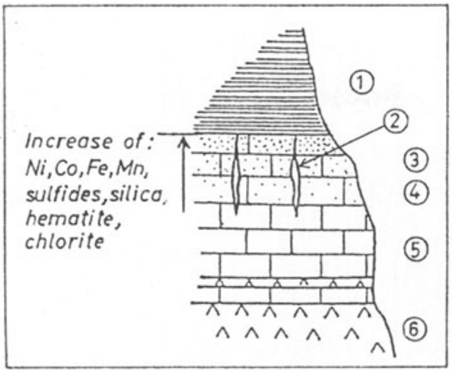

Fig. 7. Schematic section through stratabound Ni-Co mineral deposit (Yuraccgaga-Trapiche type): *1* Phyllites (dark gray); *2* shrinkage fractures; 3–5 marbles: *3* fine-grained black; *4* medium-grained, brown; *5* coarse-grained, white; *6* basic volcanics/volcaniclastics (dark green)

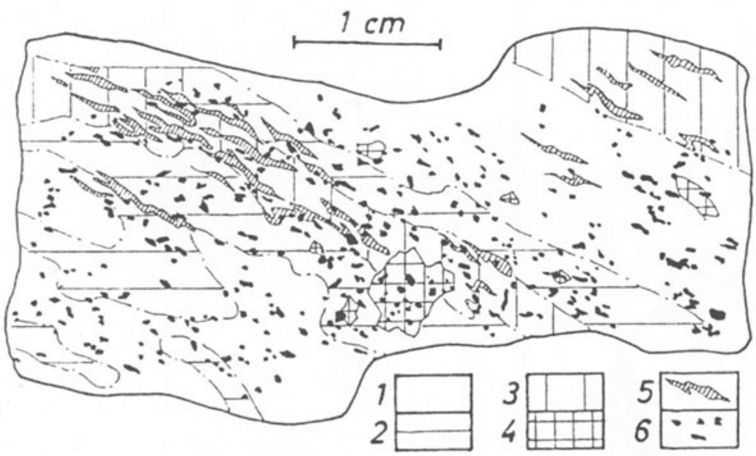

Fig. 8. Polished face of sulfide-rich tuffaceous sediment: *1* Mainly chlorite-(quartz) aggregate; *2* predominance of carbonate (including fossil fragments); *3* titaniferous chlorite-quartz aggregate; *4* volcanic fragments; *5* titaniferous-siliceous schlieren; *6* sulfide aggregates

(Fig. 9D), but at microscope scale larger aggregates are often associated with coarse carbonate and muscovite among the volcanogenic matter (compare Figs. 6, 7, 8 in Kobe 1982b and Figs. 4, 6 in Kobe 1984). Other examples showing typical intergrowths are illustrated in Fig. 9A, B, C:

The following characteristics of the *sulfide minerals* can be specified:

1. *Pyrite* – in irregular patches, appears corroded and porous among violarite; frequently intergrown myrmekitically with chalcopyrite.

2. *Gersdorffite* – has strong tendencies towards idiomorphism, is often zoned, occasionally with chalcopyrite inclusions. Its composition varies widely, which is reflected in two electron-microprobe analyses of adjacent grains (see Fig. 6C in Kobe 1984), calculated to $Ni_7(Co,Fe)As_4S_6$ and $Co_5(Ni,Fe)_3As_4S_6$ respectively (Kobe 1982b, Table 1).

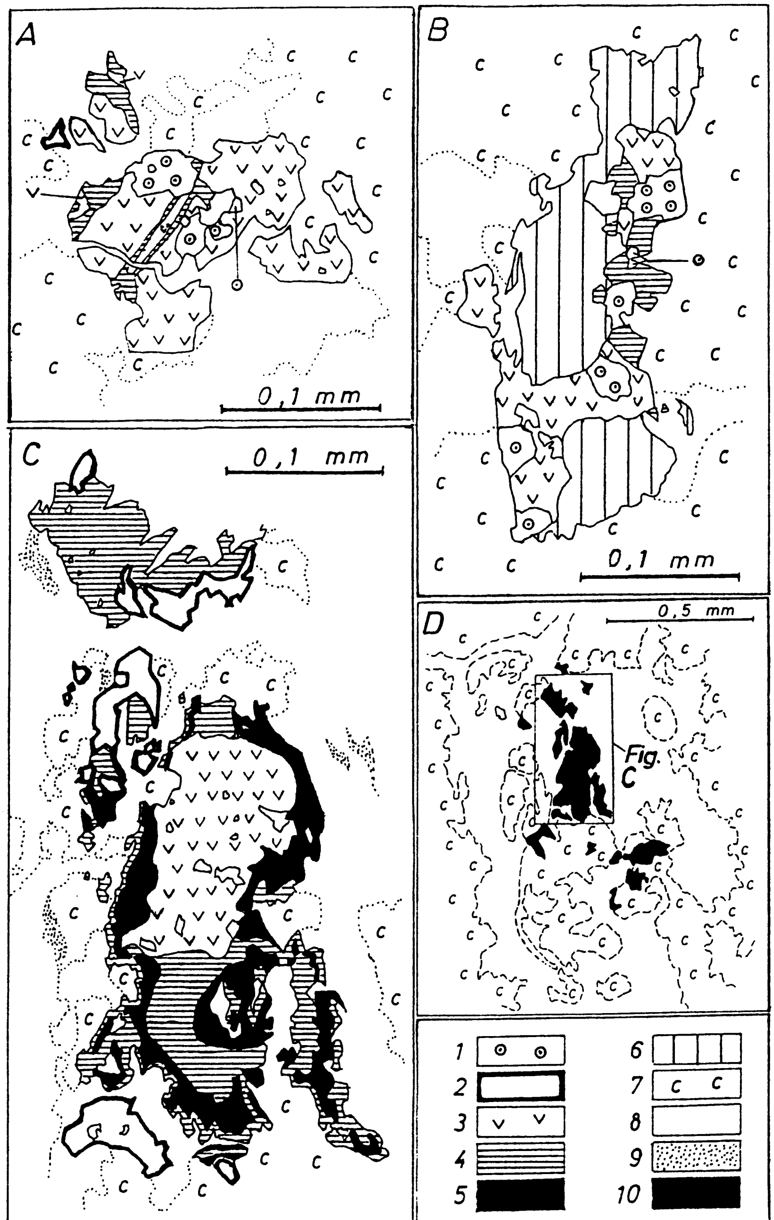

Fig. 9. A–D. Polished section, typical sulfide distribution in gangue: *1* Pyrite; *2* gersdorffite; *3* violarite; *4* millerite; *5* tučekite; *6* sphalerite; *7* carbonate; *8* chlorite-quartz mixtures; *9* Ti-phase (leucoxene); *10* (in Fig. **D** only) sulfides

3. *Violarite* – $(Ni,Co,Fe)_3S_4$, appears to be a relatively early formation, because it is seen traversed by millerite veins (fracture fillings?), its most common associate with irregular contacts.

4. *Millerite* – NiS, the most abundant sulfide (with violarite), usually coarser-grained, is often dove-tailed with surrounding coarse carbonate (see, e.g., Fig. 8, middle frame, in Kobe 1982b).

5. *Tučekite* – approximately $(Ni,Fe)_9Sb_2S_8$ is a rare, and the only Sb-bearing phase present. It rims partially both violarite and/or millerite (Figs. 7b and 8, Kobe 1982b and Fig. 6F in Kobe 1984) but may itself be surrounded by millerite (Fig. 9C). Although investigations other than electron-microprobe analyses could not be made due to the rarity of this sulfide phase, composition, fabric, and optical properties compare reasonably well with those reported by Just and Feather (1978) (see Kobe 1984).

6. *Sphalerite* – with very fine chalcopyrite inclusions, is irregularly distributed, often associated with coarse muscovite, more rarely with other sulfides.

7. *Chalcopyrite* – in addition to the mentioned intergrowths with other sulfides, it occurs as small specks disseminated and clustered among the silicate/carbonate mixtures.

The *nonsulfide minerals* may be roughly characterized as follows:

1. *Carbonate* – (a) may be fine-grained admixture to the chloritic-siliceous complexes, or (b) occur in radiating, spheroidal aggregates, or (c) coarse-grained in association with the sulfides and/or muscovite. Systematic analytical work has not yet been done, but it appears possible that at least biochemical precipitates – organic remain, mostly of (b) –, probable metamorphic recrystallizates (c), and a primary zonation according to Fig. 7 could be distinguished.

2. *Chlorite/silica* – again, no work on these mixtures has as yet been done.

3. *Muscovite* – practically always present with the coarse carbonate-sulfide aggregates, interpreted as metamorphic recrystallizates from sericite (decomposition product of former plagioclase).

4. *Titaniferous matter* (leucoxene) – may occur (a) as pseudomorphs in distinct crystal shapes (showing lamellar networks akin to those derived from alteration of titanomagnetite), or coarser intergrowths of rutile(?)/quartz, or (b) more commonly finely interlayered among silica (sometimes associated with fine hematite blades, both also observed as coarser prismatic crystals/blades in a fine volcaniclastic rock without sulfides) and displaying a very fluidal fabric, that may express primary sedimentary features and/or their metamorphic modifications (Kobe 1982, Figs. 5A, B, 6, and 7).

5. An *unkown*, fine-grained isometric mineral (possibly a silicate) is disseminated throughout most of the sulfide-bearing rock (Kobe 1982, Figs. 5A, B), even as inclusions in the sulfides, and appears to be an early metamorphic formation.

4 Conclusions

The stratabound character of the sulfide concentrations in both types of deposit from the regional to the microscopic scale and their association with submarine basic volcanics/volcaniclastics and fossiliferous (reef) limestones within an argillaceous sedimentary sequence indicates a syngenetic formation. The volcanic influence is manifest most directly in the proximal volcanic-exhalative setting of Ultimatum, while for the Yuraccgaga-Trapiche type deposits a more distal chemical/biochemical precipitation is envisaged. The pre-Permian greenschist-grade metamorphism has affected these deposits only slightly (mainly by recrystallization in situ).

The stratabound concentration of Ni-Co sulfides described above is unique in that it is not repeated in otherwise similar environments in the other, more recently investigated Paleozoic inlier, the Malpaso Dome (Fig. 1) (see Kobe 1986), while the Ni-Co deposits in the Eastern Belt are reported to be of vein-type, related dissemination and replacement, thus epigenetic to their Paleozoic host rocks (Kobe 1982b).

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