

# A Strata-Bound Ni-Co Arsenide/Sulphide Mineralization in the Paleozoic of the Yauli Dome, Central Peru

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## Abstract

The pre-Permian Paleozoic of the Yauli Dome in Central Peru contains a strata-bound finely disseminated Ni-Co arsenide/sulphide mineralization in a weakly metamorphosed series of interbedded slates/phyllites, fossiliferous marbles and basic volcanics and volcanoclastics. The intimate interlayering of these formations on both the macro- and micro-scales is taken to indicate a syngene origin for the mineralization, related to submarine deposition of lavas, tuffs and their hydrothermal exhalative derivatives among the seafloor sediments.

This is in stark contrast to other Ni-Co mineralization known from the Eastern Paleozoic Belt in Peru, attributed to either the plutonic ultrabasic or the hydrothermal granite environments.

## 1 Introduction and General Geology

The Yauli domal complex has a long history of mining activity, but as a structural unit, it was outlined as late as 1940 and 1943 by Harrison. Among the few existing local geological studies only those with relevance to the Paleozoic, i.e., Stone (1928), Kobe (1964), Rivera (1964) and Lyons (1968) have been consulted for the compilation of Fig. 1 (see also Fig. 9).

The Paleozoic, exposed along two major doming anticlines, consists of the Permian Mitu Group subvolcanic intrusives, volcanics and volcanoclastics, underlain discordantly by the pre-Permian Excelsior Group metamorphics which include basic subvolcanic intrusives, volcanics and volcanoclastics, abundant black slates to phyllites, rare quartzites, red cherts and argillites and fossiliferous marbles. The strata-bound Ni-Co mineralization is an integral part of the Excelsior Group. The Paleozoic Mitu and Excelsior Group basement is penetrated by Mesozoic and/or younger basic to acid intrusives (not distinguished on Fig. 1).

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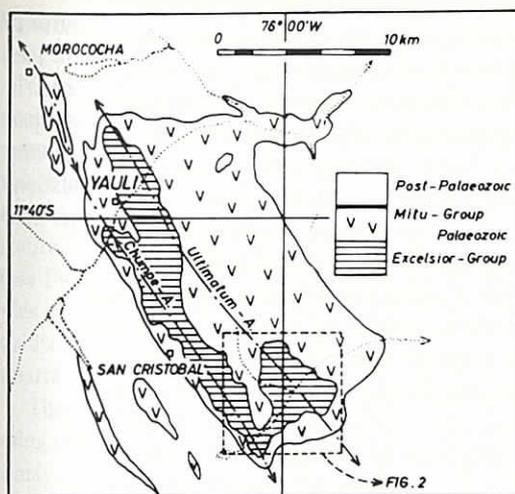


Fig. 1. Simplified geology and structure of Yauli Dome. (After available literature incl. documentation C. de P., Centromin and observations by Kobe 1978)

## 2 The Country Rocks

The predominant rock type in the Excelsior Group is a black to dark grey *slate to phyllite* occasionally with sandy layers and local *quartzites*. A pronounced schistosity, small-scale folding and boudinage in the quartzitic beds are widespread and pervasive. The intercalated bodies and thick beds of white to light-grey *limestones (marbles)* are strongly distorted and recrystallized but allow usually the recognition of abundant fossils, particularly crinoids. In the region SE of Andaychagua, the limestones are intimately intercalated on all scales (from the outcrop to the microscopic) with *red cherts* and *argillites* and greenish *volcanics* and *volcaniclastics*. This is the characteristic environment for the strata-bound Ni-Co mineralization.

The greater part of the green volcanics/volcaniclastics consists of crystal-lithic *tuffs* with a high content of chlorite, quartz, clear mica, semiopaque titaniferous material, carbonates and with or without disseminated opaques. The fine-layered "fluidal" texture is indicative of accumulation and movements of a fine-grained sediment. The fabric, mineralogy and the high carbonate content allow the interpretation as deposition of volcanic ash in the sea to become intimately mixed with the chemically and biochemically precipitated carbonate sediment. Strongly altered *lavas* with a mineral composition like the tuffs and additional relics of pyroxene and pseudomorphs after mafic constituents and plagioclase, can be interpreted as original andesitic/basaltic flows. Harrison (1940, 1943) recorded occasional pillow structures. The contact with limestones is similar as for the tuffs. A shallow *subvolcanic intrusion* similar in composition to the volcanics has been recognized near Mina Ultimatum. It is a gabbro-diorite with large plagioclase phenocrysts and dendritic ilmenite crystals that has suffered not only intensive movement indicated by the deformation, fracturing and brecciation of the plagioclase phenocrysts, but also a thorough deuteric alteration which affects to various degrees the primary mineral assemblage (now chlorites, micas, carbonates and chalcedonic quartz). The high content of titaniferous minerals, of carbonate, chlorite

and the other components in all the greenish derivatives of a basic igneous source in the region, as well as their interaction with the limestone, appears to support the idea of a common origin, although their field relations could not yet be ascertained. In addition, the grade of deformation and metamorphism of these rock types, comparable to that of the associated slates/phyllites is an indication for their contemporaneity and therefore pre-Permian age. In contrast, it appears obvious from the field relations that the stocks and dykes of gabbro/basalt, as well as those intrusives of more acid composition, are of post-Excelsior age (see Fig. 2).

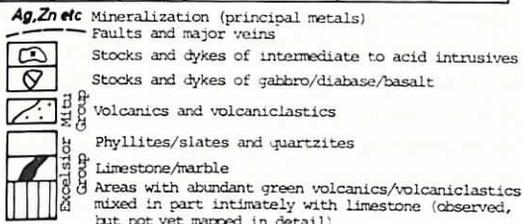
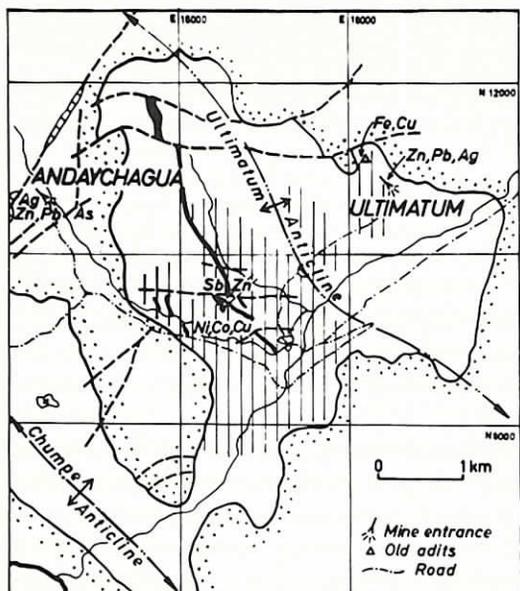


Fig. 2. General geology and mineral deposits in the southern part of Yauli Dome. (Traced from aerophotos by N. Rivera 1964, with modifications from field observations by Kobe)

### 3 The Mineralizations

Two types of mineralization occur in the Yauli Dome and must be distinguished by their difference in composition, age and mode of emplacement:

a) the *vein mineralization*, obviously related to the structural formation of the Yauli Dome (Kobe 1964; Rivera 1964), displays a zonation pattern around the Chumpee intrusive, demonstrated by the distribution of the metals in the veins, i.e.,

W(Sn) in the centre, followed by Cu, Zn, Pb and Ag and reaching As and Sb in the most distant regions (stibnite 2 1/2 km SE of Andaychagua).

b) the *strata-bound mineralization* is related to the basic volcanism, contemporaneous with the deposition of the Excelsior Group sediments. In the area of Mina Ultimatum, a Zn/Pb sulphide mineralization lies at the contact between underlying green volcanics and overlying Excelsior phyllites. This pyrrhotite-sphalerite-galena association is the possible lateral equivalent of the pyrrhotite-pyrite-chalcocopyrite mineralization strata-bound with the volcanics, 1/2 km NW of Mina Ultimatum (Kobe 1978) (see Fig. 2). A concentration of Ni, Co, Cu, As, Fe, Mn, intimately related to the complex of limestone intercalated with volcanics/volcaniclastics has been found in the immediate neighborhood of the vein mineralization of stibnite, sphalerite, calcite and quartz mentioned above (see Fig. 2), but the extent of it is not known.

The mineralized rock has a black manganese oxide coating (derived from the weathering of manganiferous calcite) but when cut is of greenish-grey colour, displaying the finely layered fabric seen in Fig. 3. Under the microscope this can be resolved into three associations of minerals:

- a) layers and flat lenses of chlorite, often with mosaic areas of quartz and fine reddish hematite flakes in subparallel layers (Fig. 4), accompanied by layers of semiopaque titaniferous matter, concentrated along the contacts with areas b) (see Fig. 7);
- b) irregular patches of carbonate, often with recognizable organic internal structure (fossil remains), as well as spherulitic aggregates of manganiferous calcite (see Fig. 6);
- c) the mineralization, disseminated or in discrete patches, elongated along the layering of the rock, though distorting occasionally the layered arrangement of the titaniferous mineral (see Fig. 5). The opaques are usually surrounded by coarse, clear calcite and muscovite blades (Fig. 8).

All this appears in a fine-grained texture of fluidal, contorted character, underlined by the distribution of fine, equidimensional grains of an apparently isotrope mineral, still elusive to determination attempts. It occurs as inclusions throughout all the other minerals (including the opaques) although least in the carbonate spherulites and is not present in the cross-cutting calcite veinlets. This indicates that the opaques cannot be a later addition to a preexisting metamorphosed sedimentary-volcanic rock complex. The mineralization has suffered the same fate as its host, i.e., been subjected to a pre-Permian metamorphic phase.

The *opaque minerals* are the Ni-Co compounds millerite (No. 1), violarite (No. 2), gersdorffite (Nos. 3 and 4), mineral No. 5 (in decreasing abundance) as well as pyrite, chalcocopyrite (No. 6) and sphalerite (No. 7) (numbers in brackets refer to Table 1 and Fig. 8).

Either millerite or violarite may form monomineralic or bimineralic patches (for typical intergrowths see Fig. 8). Pyrite, although forming the occasional porphyroblast, occurs usually as deeply corroded inclusions in violarite/millerite. Gersdorffite shows strong tendencies to idiomorphism, particularly when on its own and is then distinctly zoned. It more often forms irregular rims around violarite/millerite. The two varieties, distinguished optically (No. 3 light grey, No. 4 brownish grey, both isotropic) vary considerably in composition (see Table 1). They may be myrmekitically intergrown with chalcocopyrite. Violarite and millerite may also be rimmed by a dis-

Table 1. Composition of major Ni-Co compounds

Mineral	wt.% Av. + simplif.		Atom. prop.	Approx. ratios	Bulk formula
No. 1 millerite	Ni	65%	1.12	1	Ni S
	S	35%	1.09	1	
No. 2 violarite	Ni	35%	0.59	6	(Ni,Fe,Co) <sub>3</sub> S <sub>4</sub>
	Co	6%	0.10	1	
	Fe	16%	0.29	3	
	S	43%	1.34	13	
No. 3 gersdorffite (cobaltian)	Ni	12%	0.20	2	Co <sub>5</sub> (Ni,Fe) <sub>3</sub> As <sub>4</sub> S <sub>6</sub>
	Co	31%	0.53	5	
	Fe	6%	0.10	1	
	As	31%	0.41	4	
	S	20%	0.62	6	
No. 4 gersdorffite	Ni	44%	0.75	7	Ni <sub>7</sub> (Co,Fe)As <sub>4</sub> S <sub>6</sub>
	Co	3%	0.05	1	
	Fe	4%	0.06	1	
	As	28%	0.37	10	
	S	21%	0.65	5	
No. 5 unnamed mineral	Ni	50%	0.85	1	(see text)
	Fe	4%	0.07		
	Sb	20%	0.16		
	S	26%	0.81		

tinctly bireflectant and anisotropic mineral (No. 5). Microprobe analyses indicated Sb and since the ratio Ni:S (resp. Ni:S+Sb) remains approximately the same as for millerite, one has to assume a substitution of some S by Sb to the effect that mineral No. 5 might be an intermediate phase in the system NiS (millerite) – NiSb (breithauptite), i.e., “antimonian millerite”. On the other hand by recalculation of atom.prop. to 8 S atoms and rearrangement it is possible to obtain approximately a formula (Ni,Fe)<sub>9</sub>Sb<sub>2</sub>S<sub>8</sub> akin to that of hauchecornite, Ni<sub>9</sub>(Bi,X)<sub>2</sub>S<sub>8</sub> (where X is As, Sb or Te), but complete substitution of Bi by Sb is said not to be allowable for “antimonian hauchecornite” according to Gait and Harris (1972). However, Feather and Koen

Fig. 3a, b. Polished face of a typical mineralized volcanic sediment under oblique (a) and near vertical (b) illumination. Note the band with accumulated calcareous fossils (*white*) into which an angular volcanic fragment (*black*) is indented. This in turn is draped over by a tuffaceous bed with flat siliceous-chloritic-hematitic-titaniferous lenses (*dark*). The dissemination of the Ni-Co mineralization (*brilliant white spots* in b) follows the layering except where enclosed in the black volcanic fragment. Top is at *right*

Fig. 4. A siliceous-chloritic lens magnified in thin section. Within lens: chlorite (*white*), titaniferous mineral and/or hematite (*grey layers and schlieren*), opaques (*black*). Surrounding lens: titaniferous mineral+chlorite+silica (*dark grey*), mixture of carbonate (*light grey*) and titaniferous mineral (*grey*), opaques (*black*). × 27

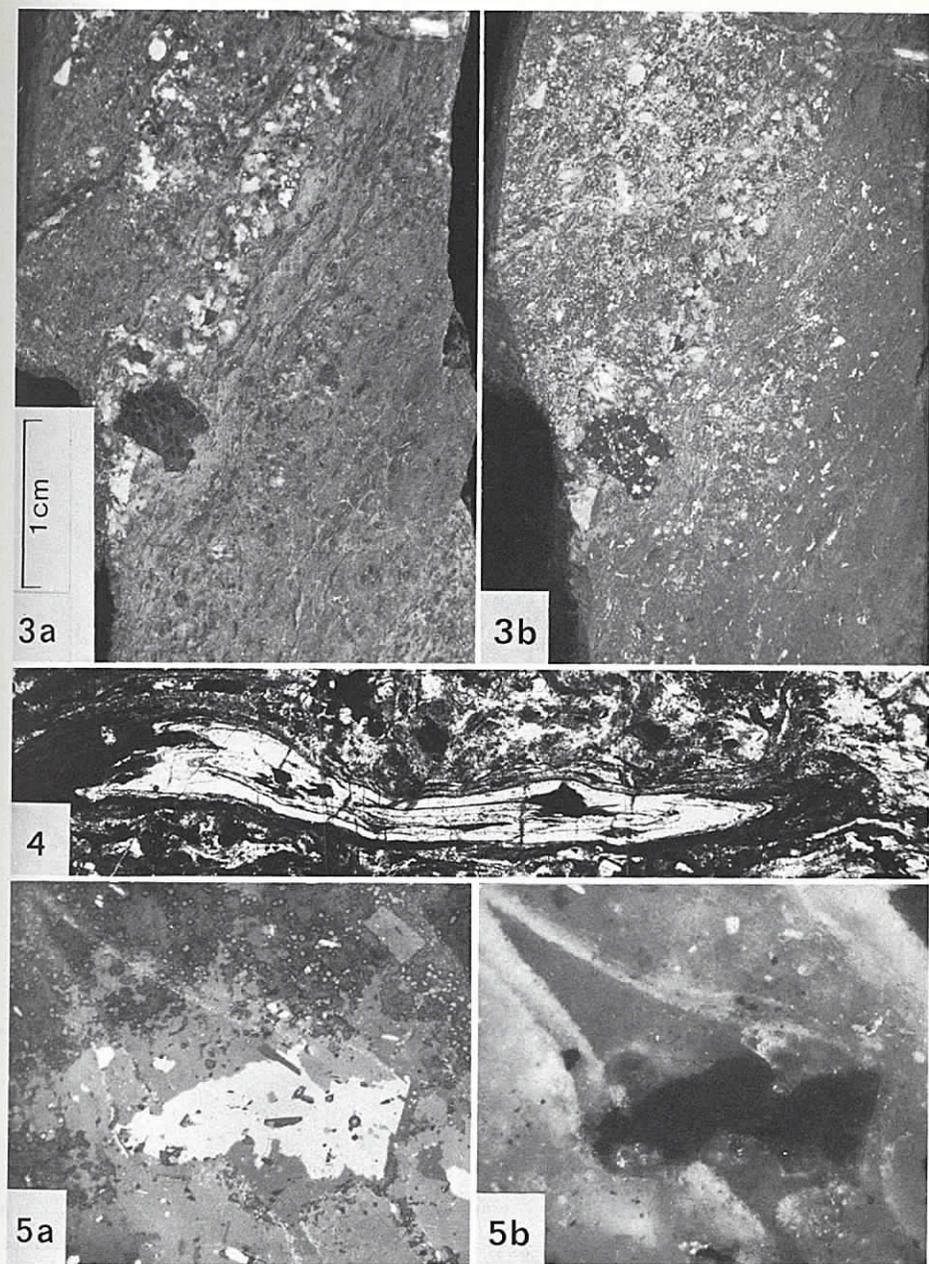
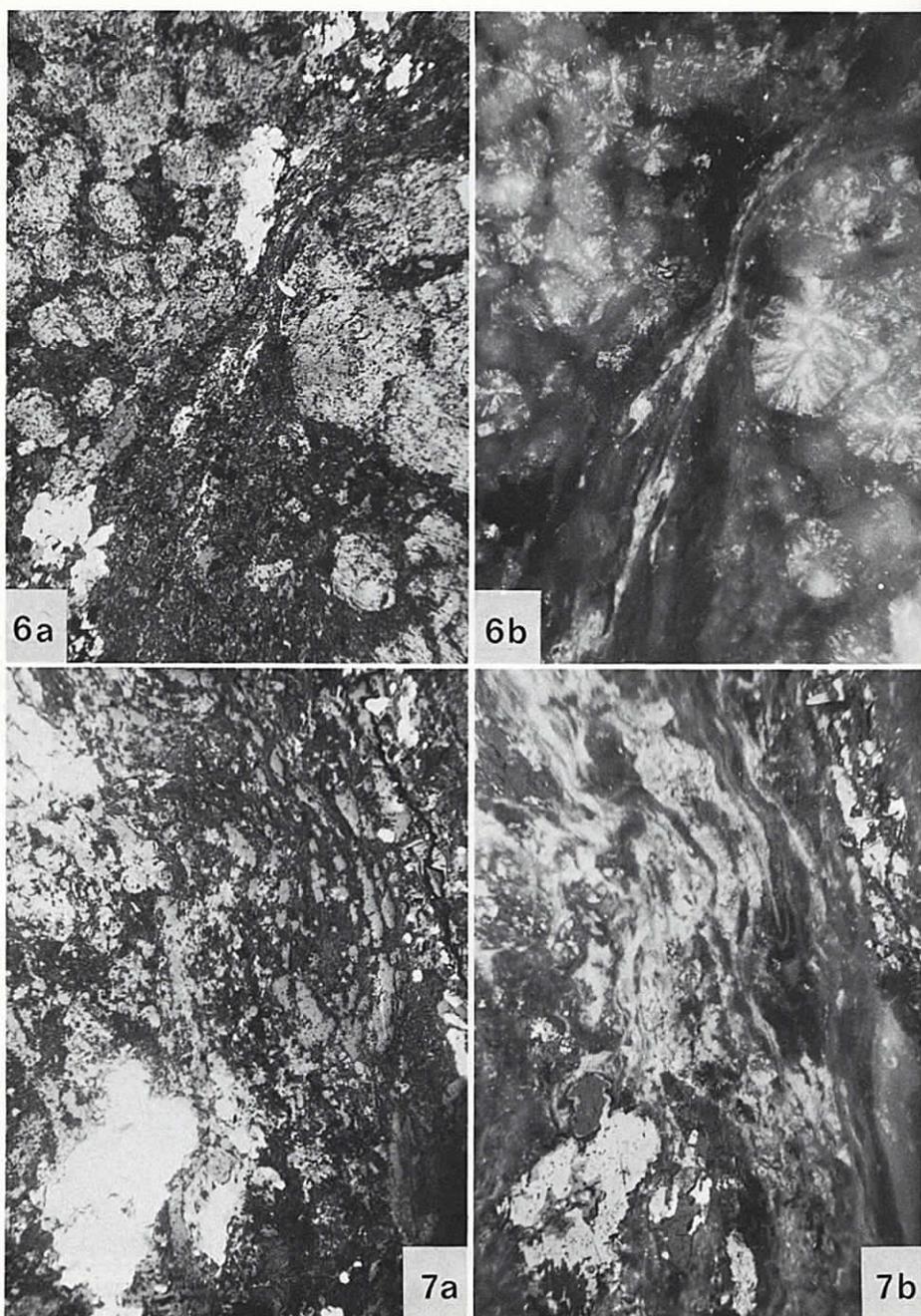


Fig. 5a, b. Polished thin section, plane polarized light (a) and with x nicols (b) showing a sulphide aggregate pushing aside layers of titaniferous mineral (anatase?) (light grey in a, white in b). Siliceous and carbonate matrix (medium grey in a) and chloritic matrix (dark grey) with disseminated equidimensional unknown mineral (light grey), sulphides (white in a, black in b).  $\times 260$



Figs. 6 and 7

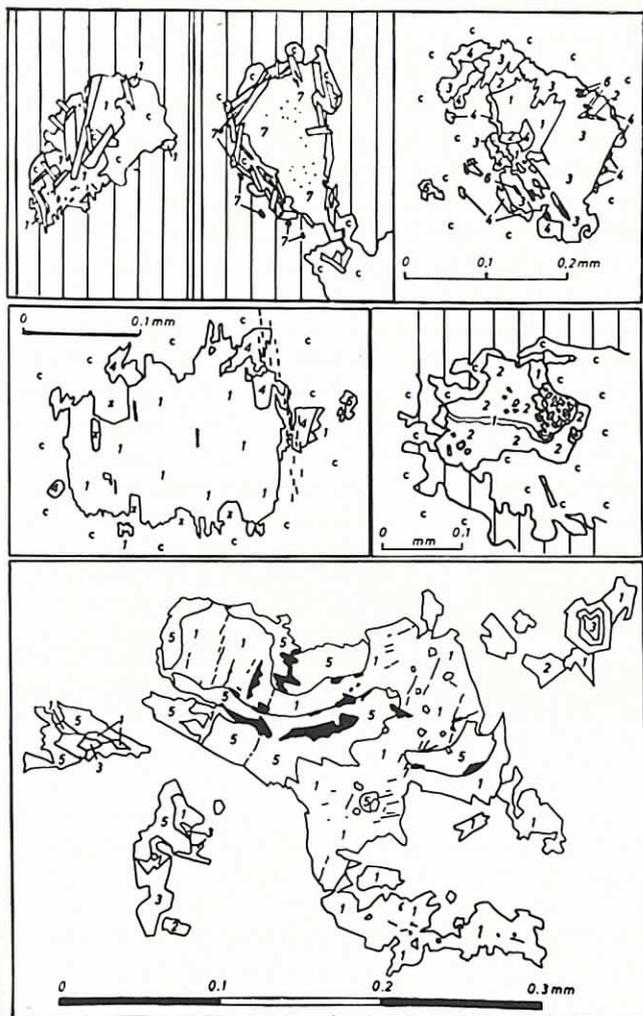


Fig. 8. Typical associations of sulphides and arsenides and their immediate surrounding. *Vertical ruling* siliceous-chloritic matrix; *c* clear carbonate; *x* idiomorphic carbonate against millerite; *1* millerite; *2* violarite; *3* gersdorffite (cobaltian); *4* gersdorffite; *5* unnamed mineral; *6* chalcopyrite; *7* sphalerite; *lath-shaped mineral* muscovite; *layers of dashes* hematite; myrmekitically corroded bodies in *1* and *2* pyrite. Camera lucida drawings

Fig. 6a, b. Polished thin section with 1 nicol (a) and x nicols (b) of mainly spherulitic carbonate bodies (grey in a) aggregated among siliceous-chloritic matrix (dark grey in a) including titaniferous mineral schlieren (light grey in b) and opaques (white in a). X 58

Fig. 7a, b. Polished thin section with 1 nicol (a) and x nicols (b). Chloritic matrix (dark grey in a) with schlieren and elliptical bodies of siliceous-hematitic material (grey in a, right third and left of frame), abundant titaniferous matter (light grey in b, belt through centre of frame), sulphides (brilliant white in a) (the largest aggregate bottom left consists of millerite surrounded by mineral No. 5). X 58

(1975) described a mineral from the Witwatersrand Reefs with the composition Ni 47.80%, Fe 3.75%, Sb 21.87%, Bi 1.02%, As 1.34%, S 25.13%, resulting in a formula  $\text{Ni}_9\text{Sb}_2\text{S}_8$ . Since its X-ray diffraction pattern is very similar to that of hauchecornite, the authors consider it to be the other end-member in the solid solution series  $\text{Ni}_9\text{Sb}_2\text{S}_8 - \text{Ni}_9\text{Bi}_2\text{S}_8$ . It appears likely that mineral No. 5 is essentially equivalent to that yet unnamed mineral of Feather and Koen (1975).

Sphalerite is only rarely in direct contact with the Ni-Co compounds, it rather forms its own aggregates with mica and calcite. Chalcopyrite occurs disseminated through silicates and carbonates, rarely associated with the Ni-Co compounds and as fine inclusions in sphalerite. The titanium-bearing compound (anatase?) forms irregular, layered, granular aggregates (see Fig. 5). Occasionally this mineral in some discrete patches is arranged in reticulate lamellae, reminiscent of the "trellis" intergrowth of ilmenite in magnetite. Thin, irregular veinlets with predominant calcite gangue carry sphalerite, chalcopyrite, pyrite and rarer millerite and violarite. The latter may be remobilization products from the surrounding Paleozoic strata-bound mineralization, while the former could be in part components of the epigenetic stibnite-sphalerite vein mineralization. Stibnite has not been found among the strata-bound mineralization.

#### 4 Metallogenetic Considerations

Mineralizations of Ni-Co-Cu-U are known and have in the past been exploited in a number of places in the Peruvian Andes (Rivera Plaza 1953; Ponzoni et al. 1969; Bellido and De Montreuil 1972) (see Fig. 9). They are classified as of the hydrothermal vein type with replacements and disseminations of millerite, violarite, gersdorffite, skutterudite, cobaltite, niccolite, arsenopyrite, loellingite and others, with chalcopyrite, sphalerite, pyrite etc. and uraninite besides quartz and calcite. The above authors suggest that the mineralization was emplaced in Paleozoic metamorphic and sedimentary rocks and genetically related to granitic intrusives of possible Paleozoic age; thus a classical epigenetic situation. However, the characteristics of the Ni-Co arsenide and sulphide mineralization in the Yauli Dome as expressed in the fabric and paragenetic relations of the rock constituents and the metallic mineralization proper, suggest a syngenetic emplacement by hydrothermal solutions related to basic volcanic activity in a submarine environment of chemical/biochemical carbonate precipitation.

The Yauli Dome Ni-Co mineralization compares well with deposits of the "Ag-Co-Ni-Bi-U formations" of Schneiderhoehn (1962, 4th edn.), particularly his account on Kongsberg (Norway), as well as with the summary and interpretation given by Jambor (1971) for Cobalt (Ontario, Canada). Even closer comes the description of the depositional environment and the suggested genesis of the Great Bear Lake silver deposits (N.W.T., Canada) by Badham et al. (1972). It appears that with respect to metallogenetic interpretation the emphasis has shifted from the plutonic to the subvolcanic-volcanic environment and from the acid to the basic igneous rock compositions, so that the basic intrusives-extrusives come to be considered not only as favourable country rocks for "topomineralic" precipitation, but the actual source of the hydrothermal mineral content. The Yauli example extends this shift to the suggestion of an

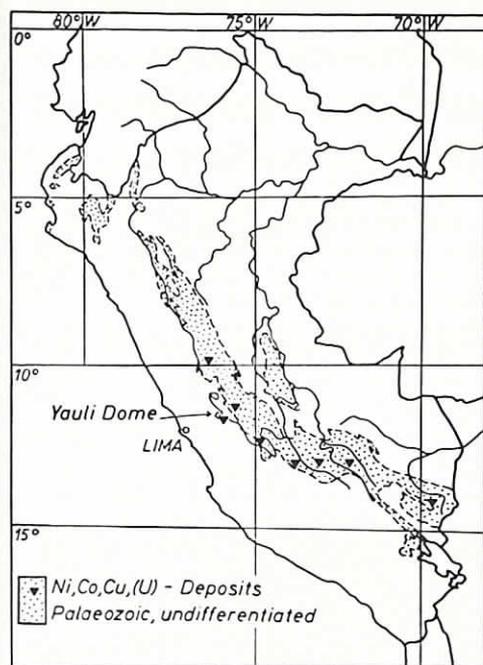


Fig. 9. Ni, Co, Cu, (U) deposits and their relation to the Paleozoic. (After the literature and supplements – Pampas and Yauli Dome – by Kobe)

essentially syngenetic mineralizing process in connection with their volcanoclastic and hydrothermal derivatives in a mixed volcano-sedimentary submarine environment.

The recognition of these relationships calls for a careful revision of the existing reports on the Ni-Co-Cu-U deposits in the Paleozoic of the Eastern Cordillera of Peru; and another attempt to ascertain the actual and not hypothetical field relations appears appropriate in order to establish new guides for exploration.

*Acknowledgments.* I wish to dedicate the present study to Prof. P. Ramdohr in remembrance of his kind interest in my work and helpful advice when on visit at the Heidelberg Institute 1966 and 1974. I acknowledge gratefully sponsorship and support by the Peruvian Institutions INCITEMI and CENTROMIN respectively and the kind liaison by Prof. G.C. Amstutz to make it possible to carry out metallogenic investigations in Central Peru 1977/78. I thank my colleagues Prof. P.M. Black and Mr. M. Little, Geology Department University of Auckland, for their assistance with electron-microprobe work and the related mineralogical interpretation, but the results as presented are my own responsibility.

## References

- Badham JPN, Robinson BW, Morton RD (1972) The geology of the Great Bear Lake silver deposits. *Abstr 24th Int Geol Conf Sect 4*:541–548
- Bellido E, De Montreuil L (1972) Aspectos generales de la metalogenía del Perú. *Serv Geol Mineral Geol Econ 1*:149
- Feather CE, Koen GM (1975) The mineralogy of the Witwatersrand reefs. *Minerals Sci Eng 7/3*: 189–224

- Gait RI, Harris DC (1972) Hauchecornite – antimonian, arsenian and tellurian varieties. *Can Mineral* 11:819–825
- Harrison JV (1940) Nota preliminar sobre la geología de los Andes Centrales del Perú. *Bol Soc Geol Perú* 10:5–29
- Harrison JV (1943) Geología de los Andes Centrales en parte del Departamento de Junín, Perú. *Bol Soc Geol Perú* 16:1–51
- Jambor JL (1971) General geology. In: Petruk W et al. (eds) The silver arsenide deposits of the Cobalt-Gowganda Region, Ontario. *Can Mineral* 11:12–33
- Kobe HW (1964) Andaychagua – San Cristobal exploration. Priv Rep
- Kobe HW (1978) Mina Ultimatum y alrededores, Geología general. Priv Rep
- Lyons WA (1968) The geology of the Carahuacra Mine, Central Peru. *Econ Geol* 63:247–256
- Ponzoni E, Postigo A, Birkbeck J (1969) Guía para el mapa metalogénico del Perú. *Soc Nac Mineral Petrol Lima*, 128 pp
- Rivera N (1964) Ten year program for the San Cristobal Division (1965–1975). Priv Rep
- Rivera Plaza G (1953) Métodos de examen mineralógico. *El Ingeniero Geólogo*, Lima, pp 341
- Schneiderhoehn H (1962) *Erzlagertstätten*, 4. Aufl. Fischer, Stuttgart, 371 S
- Stone JB (1928) Geological map of Carahuacra – San Cristobal Region. Unpubl map