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NICKEL ORES FROM KEY WEST MINE, NEVADA.

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In March 1919 a suite of twelve specimens of ore stated to represent average nickel ore of the Key West Mine, in Southern Nevada, was transmitted to us by Dr. Charles L. Whittle, with the request that an examination be made to determine the minerals contained and their relations.

The Key West Mine, in Clark County, in Southern Nevada, was briefly described by Bancroft in 1909.[1] The district lies about twenty-four miles east southeast of Moapa on the Salt Lake and San Pedro railroad line. As described by Bancroft the deposits are contained in basic dikes of probably pre-Cambrian age intruded in gneisses of the same age. The strike of the dikes conforms in general with that of the gneisses and trends northeasterly. The Great Eastern dike is described as an enstatite-mica picrite, a variety of peridotite. The rock contains magnetite, pyrrhotite, and chalcopyrite; assays of the rock showed 0.26 per cent. nickel and a trace of platinum. The workings show much oxidation with large quantities of the oxides and sulphides of copper.

An analysis of the ore-bearing dike by Ledoux & Company runs as follows:

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[1] Bancroft, Howland, "Platinum in Southeastern Nevada," Bull. 430, U. S. Geol. Survey, pp. 192–199, 1909.

ANALYSIS OF DIKE IN LOWER GREAT EASTERN ADIT.

Silica	24.88	Copper by electrolytic assay	2.01
Iron	19.35	Nickel	5.38
Alumina	4.21	Cobalt	.04
Lime	4.51	Platinum metals, 0.17 ounce.	
Magnesia	13.94	Gold, trace.	
Sulphur	18.02	Silver, trace.	

Another dike showed the composition of a hornblendite, a holocrystalline rock with 3 millimeter grain.

The Key West dike proved to be extremely decomposed and Bancroft does not determine its original character. The decomposed dike near the surface contained 0.1 ounces of platinum to the ton and 1.47 per cent. nickel, no gold or silver being present. One specimen of ore assayed 0.12 ounces of platinum to the ton and 5.6 per cent. nickel with no gold or silver, copper content not being determined. At the time of Bancroft's visit the workings of the Key West Mine amounted to 3,000 linear feet, the deepest shaft being 312 feet. Some trial shipments have been made.

Bancroft concludes that the basic dikes which are from 10 to 50 feet wide contain primary magnetite, pyrite, chalcopyrite, platinum, and pyrrhotite. No pyrrhotite was found in the Key West dike and Bancroft suggests that this mineral may have been transformed to pyrite by the action of infiltrating solutions. The deposits are considered to be of magmatic origin similar to the nickel deposits of Sudbury, Ontario. This closes the extracts from Bancroft's report.

The present paper does not deal with the content of the ore in platinum metals, but it may be stated that there is much more palladium than platinum. An analysis of the best ore by Professor E. E. Bugbee of the Institute of Technology showed that concentrates contained 0.125 ounces platinum and 0.275 ounces palladium per ton.

Almost all of the twelve specimens from the Key West Mine submitted to us contain pyrite and chalcopyrite in considerable amount but as far as could be observed no pyrrhotite is present. The specimens vary greatly in appearance, some being in the main greenish, granular igneous rocks; others dark grey, hard and quartzose; others soft and chloritic or largely made up of a dolomitic carbonate. All of them contain about the same association of sulphides.

The determination of the sulphides was made by metallographic methods. The relation between sulphides and gangue were studied in thin sections.

COMPOSITION OF THE ORES AS SHOWN IN THIN SECTION.

The freshest material is a dark green granular hornblendite almost free from decomposition. The size of grain is about 1 to 2 millimeters. The sulphides, as seen in the specimen, appear to fill the interstices between the silicates.

In thin section the grains are stout prismatic or equidimensional and now consist mainly of pale greenish brown hornblende with normal extinction and slight pleochroism. There are a few grains of augite remaining and some indication that a rhombic pyroxene was also originally present. The rock crystallized as a pyroxenite and the change to hornblende was evidently a late magmatic process. Close to the sulphides the silicate changes abruptly to a colorless amphibole which often has exactly the same optical orientation as the adjoining greenish hornblende. The sulphides fill triangular interstices or druses in the rock and consist of pyrite, chalcopyrite and pentlandite; the latter containing grey reticulating veins of "polydymite." There are also a few grains of magnetite. In many places the sulphides are molded on the prisms of pyroxene or amphibole, retaining the prismatic striations of these minerals. In other places the sulphides distinctly corrode the silicates.

This specimen is held to prove the late magmatic origin of the ore minerals. We believe that they formed part of the magma of the dike and consolidated as the last of its minerals of igneous origin.

The other specimens show, however, that alteration by hot waters continued after the congealing of the dike. This alteration is expressed in extensive development of chlorite with some serpentine and talc. The chlorite is sometimes replaced by quartz. One specimen contains about 50 per cent. quartz in large individuals and residual chlorite with pyrite grains averaging 0.2 millimeters in diameter. Rutile and probably a little molybdenite were also observed.

The last process of deepseated origin, which affected the ore, consisted in dolomitization. The chlorite is sometimes almost wholly converted into carbonate; one sample, for instance, containing about 75 per cent. of this calcium-magnesium carbonate.

Oxidation resulting in partial alteration of pyrite and chalcopyrite to limonite is observed in several specimens.

The history of the ores then comprises:

1. A late magmatic stage when most of the sulphides were introduced.
2. A subsequent hydrothermal stage during which the original silicates were replaced by chlorite, serpentine talc, quartz, and dolomite but during which the sulphides were not greatly changed. It is possible, however, that the introduction of the "polydymite" belongs in part to this stage.
3. A period of oxidation to a depth extending, at least, to the water level, that is about 200 feet below the surface. During this period the pentlandite was oxidized to nickel sulphate which descended in the deposit and probably produced sulphide enrichment by replacing pentlandite by "polydymite," which is the richer sulphide. This at least is the view that is tentatively held by us though we have no field evidence, with which to corroborate it.

COMPOSITION OF THE SULPHIDES AS SHOWN IN POLISHED SECTION.

Polished sections prepared from the samples submitted for examination revealed the presence of the following ore minerals: Pyrite FeS_2, Chalcopyrite $CuFeS_2$, Pentlandite $(FeNi)S$ normally 36 per cent. nickel, "Polydymite" Ni_4S_5(?) normally 59.4 per cent. nickel (calculated), Sphalerite ZnS, Magnetite Fe_3O_4.

Pyrite.—This mineral occurs scattered widely throughout all of the material examined and usually in the form of interstitial fillings molded about and sometimes corroding the primary gangue minerals. It is usually much fractured and subjected to all degrees of replacement by chalcopyrite and possibly pentlandite. In such cases it is found as irregular residual masses in the younger minerals. (See Pl. VIII., *B*.) A few highly polished areas of pyrite appear to be abnormally white as viewed under the microscope, and it was at first thought that it might be a nickeliferous variety. However, carefully applied microchemical tests with dimethyl glyoxime failed to reveal any nickel in this pyrite.

Chalcopyrite.—This is the most abundant mineral in the samples examined, being found in every specimen and usually in large amount. It is comparatively coarse in size and contains residual pyrite as well as veins of " polydymite " and pentlandite, the areas of the latter sometimes equalling the chalcopyrite in extent. (See Pl. VII., *C*.) The chalcopyrite is entirely normal and tests applied showed it to be free of nickel.

Pentlandite.—This cream colored nickel mineral is present in all except one specimen examined and in some localized areas is equally abundant as the chalcopyrite with which it is closely associated and which it has replaced, as indicated by the prevailing structural relations. In a few cases networks of veinlets in fractured pyrite are filled with pentlandite, but since it is very common for the chalcopyrite to occur in this manner it is possible that these are cases of replacement of the chalcopyrite which originally filled the veinlets. It has been stated in preceding paragraphs that no nickel could be detected in the pyrite or chalcopyrite. On the other hand, large amounts of nickel were revealed by tests applied on the pentlandite. Pentlandite which somewhat resembles pyrrhotite is, however, easily distinguished from it by microchemical methods.

"Polydymite."—This rich nickel mineral was observed in two specimens, where it occurred in abundance, replacing both pentlandite and chalcopyrite (Pls. VII., *A* and VIII., *A, B, C*). It has developed chiefly by the replacement of pentlandite. The

photographs show all stages in this replacement from minute veinlets of "polydymite" cutting pentlandite to masses of the former with small residual patches of the latter. In one place it was distinctly observed that these veinlets occasionally penetrate into the chalcopyrite at the contact between it and pentlandite. The "polydymite" is slightly harder than the chalcopyrite, but is very brittle and during polishing chips out readily.

The mineral has a violet grey tinge in polished section and is tarnished blue with slow effervescence by dilute nitric acid. Other reagents are negative except that hydrochloric acid applied to the mineral turns green. It has been termed "polydymite" in this report due to its similarity in appearance and reactions to one of a mixture of nickel sulphides from the Vermilion Mine, Ontario, analyzed by F. W. Clarke and Charles Catlett.[2] At that date these authors had no means of knowing that they were not dealing with a pure material and they proposed the formula Ni_3FeS_5 for their mineral. Examination of material such as they analyzed reveals a nickel-iron sulphide (pentlandite or an undescribed mineral very closely related to it) replaced by a network of veinlets of a violet grey mineral identical with the mineral termed "polydymite" in this report. In the specimens from Key West it is present in sufficient quantity to account for a large proportion of the nickel shown by the analyses if it is a pure nickel sulphide similar to the original polydymite Ni_4S_5, described from Westphalia, Germany. The mineral gives a strong nickel reaction with dimethyl glyoxime; unfortunately it proved impossible to obtain it pure enough for analysis. It contains little iron and no bismuth or arsenic.

Sphalerite.—The zinc sulphide occurs very sparingly as a primary mineral associated with chalcopyrite. It is not sufficiently abundant in the specimens examined to be of any importance in a commercial consideration of the ore.

Magnetite.—This iron mineral is also present in minor amounts only. It seems to be rather uniformly distributed throughout both the gangue and sulphides.

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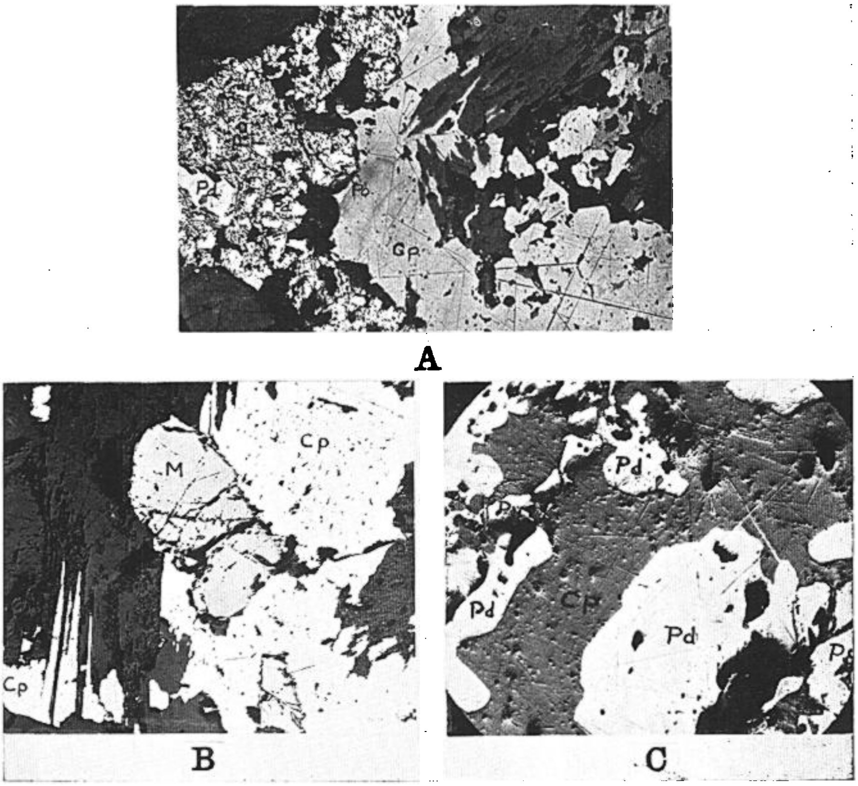
[2] *American Jour. Sci.* (3), vol. 37, 1889, p. 372.

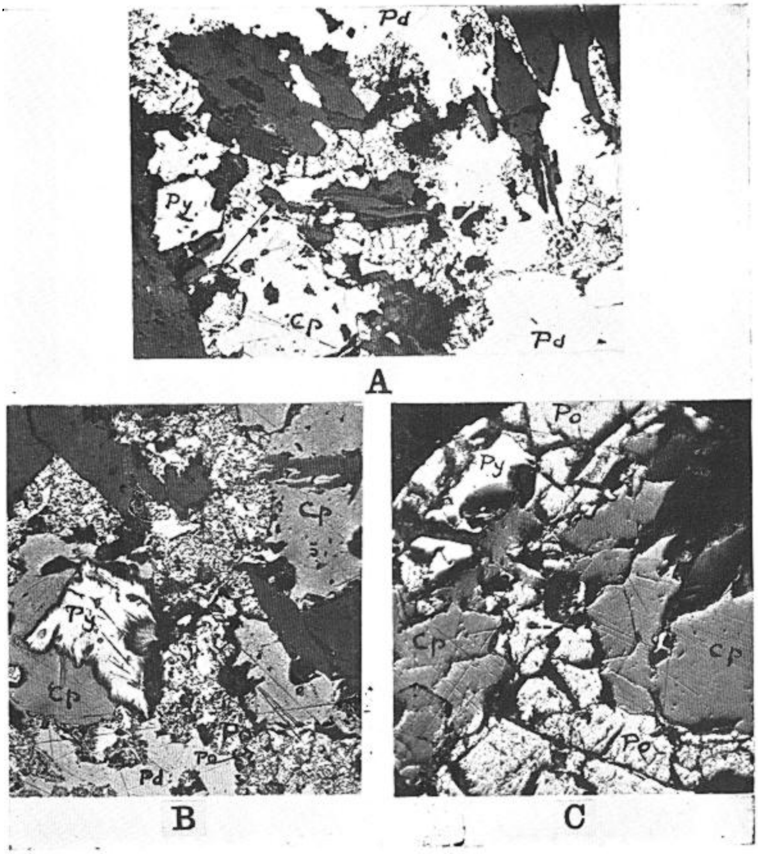


A. Corroded remains of magnetite crystal (M) in gangue (G). Chalcopyrite (Cp) molded about gangue and replaced by pentlandite and polydymite. Residual grains of pentlandite (Pd) remain in younger polydymite (Po). × 65.

B. Prisms of primary gangue minerals (black) molded about grain of magnetite (M). Chalcopyrite (Cp) molded about projecting needles of hornblende. × 83.

C. Residual pyrite (Py) in chalcopyrite (Cp) which is replaced by fresh pentlandite (Pd), illustrating the characteristic appearance of sulphide ore in which enrichment by polydymite has not begun. × 129.

PLATE VIII.



A. Chalcopyrite (Cp) replaced by pentlandite (Pd), which is being replaced by polydymite (Po). Note typical secondary structure shown by distinct veinlets of polydymite in pentlandite. × 87.

B. Pyrite (Py) residual in, and partly replaced by chalcopyrite (Cp), which is cut by veins of pentlandite (Pd) and polydymite (Po), the former in process of replacement by the latter. × 87.

C. Residual pyrite (Py). Chalcopyrite (Cp) cut by a vein of polydymite (Po), illustrating most advanced enrichment. Primary pentlandite entirely altered to polydymite. × 136.

GENESIS OF THE ORE MINERALS.

Magnetite, as indicated by its uniform distribution throughout both gangue and sulphide, and by the manner in which primary gangue crystals are molded about it, was the first mineral to separate from the magma (Pl. VII., *B*). Pyrite, which is residual in, and older than the other sulphides, has formed after the solidification of the primary gangue minerals. It occurs associated with the other sulphides and is not distributed uniformly as is the case with the magnetite. The presence of pyrite as a mineral of magmatic origin is worthy of note, as is also the absence of pyrrhotite. Chalcopyrite next separated out, surrounding and replacing the older pyrite. It is commonly observed molded about absolutely sharp and unaltered crystals of the primary gangue minerals (Pl. VII., *B*, VIII., *A*) indicating that it formed during the solidification of the magma rather than by deposition of solutions in fissures, in which case considerable alteration and formation of new gangue minerals would be expected. The separation of the nickel appears to have occurred in the final stage of solidification. Pentlandite, the primary nickel mineral, replaces chalcopyrite quite extensively in practically all of the material examined. Minor amounts of sphalerite were likewise formed during this last primary stage.

At a later period the ores were exposed to the action of descending waters which dissolved nickel and precipitated it as "polydymite" when reduced by the pentlandite in lower levels. The development of this rich nickel sulphide in marginal and reticulated replacements suggests to us a case of secondary enrichment of nickel and may possibly have an important commercial significance. The degree to which this enrichment has proceeded and the depths to which it extends can not be determined in examination of specimens.

REMARKS ON POLYDYMITE.[3]

There can be no reasonable doubt that the "polydymite" described above is a pure or almost pure nickel sulphide. Whether

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[3] For the following concluding remarks the senior author must bear the sole responsibility.

it is identical with the normal polydymite of mineralogy is another question.

It is certain that our "polydymite" is identical with the mineral known under this name from Sudbury, Ontario. The mixture of this mineral with pentlandite and a little pyrite and chalcopyrite has, as stated above, been analyzed by Clarke and Catlett,[4] and has been given the formula Ni_3FeS_5. That this is a mixture is evident; Tolman and Rogers [5] describe this ore in polished sections as follows:

> In Fig. 37 is represented a supposed specimen of polydymite from the Vermilion Mine. This contains pyrite in the form of veinlets. . . . The relation of the polydymite to the magmatic sulphides is not entirely certain, but the examination of a very fresh specimen suggests that the Sudbury polydymite is a mixture of three minerals: Pentlandite, an unknown violet grey mineral and the true polydymite. The polydymite and the violet grey mineral are probably due to the breaking down of the pentlandite.

I can not confirm from my observations the occurrence of true polydymite from this place but that the violet grey mineral and the pentlandite are the principal components is certain. Chalcopyrite is always present as well but that mineral was eliminated in the calculation of the analysis by Clarke and Catlett. It is probably impossible to isolate this "polydymite" for there will always be more or less pentlandite present. Most of my specimens contain about equal quantities of pentlandite and "polydymite."

The question now arises whether this mineral is identical with the normal polydymite from Grüneau, Westphalia. The identity of the "polydymite" from Key West, Nevada, with that of Vermilion Mine, Sudbury, is beyond doubt. The mineral described under the name of polydymite in the tables of Davy and Farnham [6] is that from Vermilion Mine and Key West. That described by Murdoch [7] is the normal mineral from Grüneau. The

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[4] Clarke, F. W., and Catlett, C., *American Jour. Sci.* (3), vol. 37, 1889, p. 373.

[5] Tolman, C. F., and Rogers, A. F., "A Study of the Magmatic Sulphide Ores." Leland Stanford Univ. Publ., University series, Stanford University, 1916, p. 33.

[6] "Microscopic Determination of the Ore Minerals," New York, 1920, p. 87.

[7] Murdoch, J., "Microscopical Determination of the Opaque Minerals," New York, 1916, p. 82.

polydymite from Grüneau is steel grey, decidedly harder than chalcopyrite and effervesces extremely slowly with dilute nitric acid. The other reagents are negative. It is not very brittle. The mineral is very resistant to alteration; polished sections of it retain their luster for long time. Type specimens from the U. S. National Museum and from Krantz, in Bonn, show no alteration and an association with chalcopyrite and siderite in undoubtedly primary ore.

The "polydymite" from Vermilion and Key West is distinctly violet grey, a color shared by no other mineral. It has about the same hardness as chalcopyrite. It is extremely brittle. It alters rapidly in the air to a pulverulent mass and polished sections tarnish quickly. It effervesces somewhat more readily than the Grüneau species, but otherwise agrees with it in reactions used for work on polished sections. These differences indicate, I believe, that the two species should be separated.

Regarding the composition of the "polydymite" from Vermilion we have of course the analysis of Clarke and Catlett; that the material contained admixed pentlandite may be regarded as certain. The following table shows the relations between the various minerals.

TYPICAL ANALYSES OF NICKEL SULPHIDES.

	S.	Ni.	Co.	Fe.	Gangue.	Total.
1. Polydymite $\mathrm{Ni\ (Fe.Co)_4S_5}$	41.09	54.30	0.63	3.98		100
2. Pentlandite	33.42	34.23	0.85	30.25	0.67	99.42
3. "Polydymite"	41.35	43.18		15.47		100

1. Laspeyres, *Journal f. Chem.*, 1876, 14, p. 397. Grüneau $\mathrm{Ni_4S_5}$.
2. Penfield, *American Jour. Sci.*, (3), vol. 45, 1893, p. 494. Sudbury NiFeS. *Trans. Min. Eng.*, vol. 34, 1904, p. 21.
3. Clarke and Catlett, *American Jour. Sci.*, (3), vol. 37, 1889, p. 373. Vermilion Mine. $\mathrm{Ni_3FeS_5}$.

While it is true that even the purest "polydymite" from Vermilion Mine appears to contain some iron it is certain that the figure given by Clarke and Catlett—15.47 per cent.—is too high.

If we assume that the pure "polydymite" contains no iron the percentages in the mixture belonging to pentlandite would be

$$\text{S } 16.8 \quad \text{Ni } 17.5 \quad \text{Fe } 15.5 = 49.8$$

and the mixture would contain about 50 per cent. pentlandite. This would leave for "polydymite"

$$\text{S } 24.55 \quad \text{Ni } 25.68 = 50.23$$

which would indicate a molecular proportion of $S : Ni = 0.77 : 0.43$ or not far from $2 : 1$ or NiS_2.

It is realized of course that this conclusion rests on two assumptions: That the polydymite is practically free of iron; and that the mixture contained pentlandite and polydymite in equal proportions. Neither of these assumptions is exact.

Thus far no NiS_2 is found in nature, and it has even been argued that it could not exist because it can not be obtained by the melting together of nickel and sulphur.[8]

The calculation may stand for what it is worth. At any rate it has been shown that the "polydymite" from Vermilion, Ontario and Key West, Nevada, is not identical with polydymite; that it developed very late in the mineral succession; and that its mode of occurrence suggests very strongly the action of descending or "supergene" nickel solutions on pentlandite and chalcopyrite. It might conveniently be designated as *violarite* from the latin adjective violaris, alluding to its violet grey color in polished section.

The known nickel sulphides then comprise the following species:

Beyrichite NiS. Same composition as millerite but differing specific gravity. Laspeyres holds all millerite to be paramorphic after Beyrichite.

Millerite NiS. Ni 64.7%. Rhombohedral. In part secondary by supergene waters. Thus from Lancaster, Antwerp, Sudbury. Reported to occur as ore at Benton, Arkansas.

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[8] I. and L. Bellucci, *Chem. Abstr.*, 1909, p. 293.

Polydymite Ni_4S_5. Ni 59.4%. Isometric. Siegen district, Westphalia.

Violarite NiS_2(?). Ni 48%. Vermilion Mine, Sudbury; Key West Mine, Nevada. Occurs as ore mineral of some importance.

Pentlandite (Fe, Ni)S. Ni 34.23%. Isometric. Many occurrences. Most important nickel sulphide.

Nevada. Occurs as ore mineral of some importance.

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