GEOLOGY OF TOQUEPALA, PERU

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Toquepala is a porphyry copper deposit in which mineraliz tion is localized by a large breccia pipe formed in close gene tic relation to intrusive rocks. The deposit is in southern Pe ru, 55 airline miles north of the small city of Tacna and the same distance inland from the port of Ilo. Quellaveco and Cuaj ne, geologically similar deposits, lie 12 and 19 miles north o Toquepala. Chuquicamata is 400 miles to the south.

The deposit is high on the southwestern slope about 20 mi les from the crest of the Cordillera Occidental of the Andes - Chain. It lies in a mountainous desert where the steep southwe terly slope of the of the Andes is dissected by a succession o rapidly downcutting, deep canyons. Local topography is modera ly rugged with a dendritic drainage pattern and an elevation o 8000 to 14,000 ft. Volcanic peaks along the crest of the Cordi llera rise over 19,000 ft.

Local precipitation, including a little snow, amounts to about 10 in. during January and February, but general runoff i the region is slight. Throughout southern Peru the springs and streams are widely separated. Crude canals irrigate small farm on terraced slopes along the streams and provide sparse subsis tence to the semi-nomadic inhabitants.

During the past decade, engineering and geological explor ations of the region, as well as the mineral deposits themselv es, have required construction of a network of several hundred miles of roads. Before this, roads extended only a few miles - inland. Many areas still can be reached only by trail.

Toquepala was briefly described in 19th century geographi cal literature as a copper deposit, and it received desultory attention from Chilean prospectors early in the present centur It was first recognized as a mineralized zone of possible real importance by geologist O.C. Schmedeman during an exploration trip for Cerro de Pasco Copper Corp. in 1937. The discovery wa late as compared to earlier recognition of Chuquicamata, Potre rillos and Braden of Chile and Cerro Verde of southern Peru. - This was due partly to the region's difficult accessibility bu principally to the obscure character of the outcrop evidence o copper.

From 1938 until 1942 Cerro de Pasco Copper Corp. partially explored the deposit by adits and diamond drillholes. This campaign was supplied by a 60- mule pack train continuosly shuttling over a 30-mile trail. Northern Peru Mining & Smelting Co, a wholly owned subsidiary of American Smelting & Refining Co., undertook regional engineering studies in1945 and drill exploration in 1949. According to published data the deposit contains 400 million tons of open pit ore averaging a little over 1 pct Cu. It is currently undergoing large-scale development by Southern Peru Copper Corp., which is owned by American Smelting & Refining, Phelps Dodge, Cerro de Pasco, and Newmont Mining.

Summary of Geology: The deposit is situated in a terrane composed of Mesozoic (?) and Tertiary volcanic rocks intruded by dioritic apophyses of the Andean Batholith. These formations are exposed in a northwesterly trending belt about 15 miles wi Along the northeast they are unconformably overlain by Plio--- Pleistocene pyroclastic rocks, which occupy much of the crest of the Andes, and along the southwest they are covered by the Moquegua formation of Pliocene (?) age.

The mineralized area, oblong in shape and about 2 miles long, has been a locus of intense igneous activity. Several small intrusive bodies having irregular forms occur within and adjacent to a centrally located, large breccia pipe. The mushromshaped orebody consists of a flat-lying enriched zone of predominant chalcocite with a stem-like extension of hypogene chalcopyrite ore in depth within and around the pipe.

This breccia pipe is relatively large and has been formed by repeated episodes of brecciation. Small satellitic pipes occur at random within a 2-mile radius of this central pipe. These too were individual sourceways of mineralization, although not always of ore grade. Within and around the zone of breccia pipes and mineralization there are a few faults and veins, but these are discontinous random structures of minor significance. There are no regional or local systems of faults or other planar structures recognized which could account either for the mechanical development of the breccia pipes or for their localization as a group or as individuals.

Hydrothermal alteration is pervasive in the zone of mineralization. Clay minerals appear to be abundant in places, but their percentages are undertermined. Quartz and sericite are the principal alteration products, and in many instances original rock textures are obliterated. The principal sulfides, hypogene pyrite and chalcopyrite and supergene chalcocite, occur mainly as vug fillings in the breccia and as small discrete grains scattered through all the altered rocks.

Sulfide veinlets are relatively scarce. Sulfides are more abun- dant and alteration is more intense in certain rock units, suc as the diorite and most of the breccias.

Although the Toquepala mineral deposit is similar in most respects to the porphyry copper deposits of southwestern U.S., it most closely resembles the Braden deposit of Chile, as des- cribed by Lindgren and Bastin. Judging from their statements o the forms and textures of the breccias and their postulations of age relationships, the intrusives, the breccias, and the mi neralization of Braden have many counterparts at Toquepala.

Rock Units and Structure: Layered volcanics having a tota thickness of more than 5000 ft are the oldest rocks in the are The lowermost unit is a massive, rhyolitic flow with an expose thickness of 500 ft, locally named the Quellaveco formation. I base has not been observed. Lithologically and structurally th formation is similar to the rhyolite porphyry at Cuajone, whic Lacy has tentatively assigned to Late Cretaceous. The volcanic sequence, with the various field names assigned, is as follows

Name	Thickness, Ft	Character
Alta series	3000	Mainly pyroclastics ar ignimbrites
Toquepala series	1500	Mainly rhyolite and an site flows (?)
Major Unconformity	----	-------
Quellaveco quartz Porphyry	500	Rhyolite porphyry flow

Gentle folds occasionally are seen, but regional dips of 5° to 10° SW are persistent. Lenticularity of certain horizons has been noted within the Alta and, more particulary, the Toque pala series. This is explained by minor erosional disconformite On structural and lithologic grounds the Alta and Toquepala se- ries may correspond to the Tacaza volcanics (Tertiary) of Jenks and Newell. These men have recognized the erosional interval between the Sillapaca and older Tacaza volcanics as an importan one in southern Peru and a correlative of McLaughlin's Puna su face is described as "late mature" or "old age". High accordant summits representing this surface are seen a few miles north of Toquepala. Projected to Toquepala this surface may have existed only a couple of hundred feet above the present highest point of the modern surface over the orebody.

This puna surface is believed to have played an important part in the enrichment history at Toquepala.

In the Toquepala region apophyses of the diorite batholith of the Andes intrude the Quellaveco, Toquepala and Alta volcanics and comprise half the surface exposures within a radius of several miles of the mine. Contacts with the flow rocks are discordant and usually sharp but sometimes gradational. There are small-scale irregularities in the shape of the contact, but dikes of diorite are not seen. Composition of the diorite varies somewhat, but a consistent border facies is not apparent. The volcanics seldon show any special, well-defined contact effects due either to metamorphism or structural disturbance, although throughout they have undergone a very low grade, uniform metamorphism. It is inferred that the diorite batholith underlies the entire locality and that it was implaced mostly by assimilation rather than injection.

Within the zone of hydrothermal alteration, the volcanics and diorite are intruded by small stocks and dikes of dacite porphyry. This formation is not found elsewhere in the region. The stocks are steepsided and notably irregular in shape, although one dike forms an even quarter-ring near the south-east edge of the alteration zone. The form, composition, and spatial connection with the disseminated copper mineralization suggests correlation between this formation and the monzonites of the porphyry copper deposits of western U.S.

A rock termed dacite agglomerate, with the same composition and texture of matrix as the dacite porphyry, intrudes a large volcanic neck and marks the north edge of the ore zone. This intrusive contains abundant small inclusions of dacite porphyry and other material and a few large sunken blocks. The writers class this rock unit as an agglomerate and not a breccia.

The youngest intrusive formation is a group of aphanitic porphyries ranging in composition from andesite to latite and named latite porphyry. They are post-mineral in age. They sometimes occur as small stocks, but mainly as steep dikes. Although most of these intrusive bodies are found within the neck of dacite agglomerate, a small swarm of thin latite porphyry dikes extends southward into the ore zone.

Fractures: Numerous small faults and quartz-tourmaline-sulfide veinlets of random orientation are scattered through the orebody, but these are appreciably less abundant than in most deposits of this type.

Sulfide veins more than 3 in. wide are rare. In only one locality the southern and southeastern area lying inside the dacite -- ring dike is a system of parallel fractures evident. This system of close-spaced veinlets has a trend parallel to the ring dike, being arranged concentrically around the main breccia pipe and - dipping steeply toward it.

A few post-mineral faults are present, but these are only minor features in the structural pattern. Displacements of a few feet were noted on two faults cutting layered volcanics along -- the west edge of the zone of alteration. Elsewhere fault planes with a few inches of gouge were occasionally observed, but now-- here in the district do relationships indicate displacements of consequence. This lack of major faulting is clearly evidenced by the undisturbed continuity of marker flows in the region.

Breccias: The writers restrict the term breccia to formations composed entirely of fragmental material in which the fragments have been rotated and displaced, in contrast to rock that has been merely intricately jointed, and also to rock that was - emplaced in a fused condition.

As shown on the geologic map and and selections, there are two main types of pipe breccia, termed ore and pebble breccia, - which are texturally distinct and have somewhat different modes of formation. The pebble breccia is characterized by rounded --- fragments, whereas the ore breccia is made up essentially of angular fragments. The matrix of the ore breccia is largely composed of quartz, tourmaline, and sulfides, whereas that of the pebble breccia is a sandy, mud-like material with disseminated rather than vuggy mineralization. In texture and color the pebble - breccia closely resembles a freshly broken surface of sidewalk - concrete.

Commonly the ore breccia fragments are all of the same roc type, corresponding to whatever formation lies immediately adjacent, but the main breccia mass contains a large central portion that is characterized by heterogeneity of rock type. Apparently this core of mixed rock fragments represents the conduit whithin which the most violent disturbances took place, and the surroun ing breccia represents the shattered periphery of the pipe, although rotation of fragments is evident in the shattered zone as well as within the central conduit. The outer margins of the brecias in places are indistinct, suggesting that there was a gradual transition to undisturbed rock.

As evidenced by textural features, ore-type brecciation -- took place in a number of episodes, both before and after intrusion of the dacite porphyry.

The mechanics of formation of the Toquepala ore breccia - are uncertain, as is the case with most mineralized breccia pipes. However, the occurrence of large masses of angular, mixed fragments without evidence of melting and in an environment -- essentially free of faulting indicates an origin related to -- gaseous explosion. Evidence suggests that the process was episodic. First, there may have been a leak of gas to the ground - surface, possibly along a joint system. This leak may have triggered an explosion that evacuated a small tube-a diatreme. Then the tube was filled by avalanching of the walls. Repeated explosion, partial evacuation, and avalanching could then have increased the horizontal dimensions of the pipe to its present large diameter.

Since the pebble breccia consists of hard pebbles in a matrix of rock flour, it would seen to have been produced by a milling action in which the rock fragments were semi-suspended in an actively circulating medium such as water or gas. In this -- state this pebble breccia may have had intrusive mobility, although portions of it may also have been formed more or less in - place.

Although appearing on the map as a single unit cutting all formations except latite prophyry, pebble breccia actually consists of intrusions of at least two, and possible three ages. - The mapped outline marks, for the most part, a young pebble breccia. The pebble dikes cutting the dacite agglomerate may be --- still younger. Existence of an earlier breccia of the pebbly -- type is indicated by inclusions of a pebble breccia with a mud-like matrix in ore breccia. Because hybrid ore breccia has in-- distinctive textures and because its distribution is not accurately known, it has not been differentiated from typical ore breccia on the geologic map. It occurs around the pebble pipe, possibly in large masses, and it may constitute deeper portions of the pebble pipe itself.

Late in the sequence of brecciations, a large explosion - vent was formed and filled with intrusive dacite agglomerate - containing large sunken masses of older flow rocks and diorite. This activity removed a large portion of the main breccia pipe.

Alteration-Mineralization: The mineral deposit is areally defined by hydrothermal alteration of all rocks, except latite porphyry, within an elliptical zone enclosing the orebody, as - shown on the geologic map and sections. The transition to unaltered rock around the margins is gradational rather than sharp, and several small areas of alteration occur outside the main - zone.

In contrast to most porphyry copper orebodies, which are sur-- rounded by large alteration zones, the Toquepala zone is only slightly larger than the orebody.

The hydrothermal alteration products chiefly assemblages - of quartz, sericite, and clay are those characterizing most deposits of the porphyry copper type. Sulfides impregnate all altered, unleached rocks. A major portion of the Toquepala is considered to be strongly altered and is characterized by almost - complete conversion to quartz and sericite-clay and partial to complete destruction of original rock textures.

Weaker alteration facies occur mostly near the edges of -- the deposit away from the breccias. Prior to leaching and enrichment, the areas of stronger alteration contained more sulfides in general and more chalcopyrite in particular.

The most pronounced alteration effect is found in the diorite. The fresh rock is composed of feldspar, ferromagnesian minerals, and minor quartz with a medium granotoid texture, whereas the altered rock consists of a sugary mosaic of quartz and sericite. In contrast, the dacite porphyry usually retains remnants of original texture, the alteration products being more argillic.

As in many deposits of this type, the principal hypogene - sulfides are pyrite and chalcopyrite, with very minor amounts of such minerals as bornite, molybdenite, and sphalerite. The history of mineralization-alteration at Toquepala, however, is more complex than the average. Earliest mineralization consisted of abundant tourmaline and quartz with minor sulfides. Later, but prior to the intrusion of dacite porphyry, deposition of sulfides and quartz with minor tourmaline began. This continued, with successive interruptions by periods of brecciation and by intrusions. Late in this sequence the formation of the dacite agglomerate-filled vent removed the northeast portion of the ore zone. Subsequent alteration-mineralization was weak, as shown by the feeble nature of its effect on agglomerate.

Irrespective of rock types involved, the ore breccia contains the strongest mineralization. The hybrid ore breccia is - somewhat weaker in hypogene copper content, probably due to its mud-like, less permeable matrix. The pebble breccias are still weaker, for the same reason, but contain about the same amount of hypogene copper as does the average protore outside the breccia zone. Among the unbrecciated rocks, diorite was the most receptive and the flow rocks the least. A portion of the dacite - porphyry is well mineralized, but elsewhere particulary around the southwest side of the main breccia pipe it is low in copper

Enrichment: The chalcocite zone, a major part of the open pit orebody, ranges from 500 ft in thichness in the interior to only a few feet on the fringes. Although irregular in detail its upper surface has a generally flat-lying, sharp contact with the leached zone above. The lower limit is indistinct, the transition to clean primary mineralization being almost imperceptible except in a few instances where the chalcocite terminates abruptly against a gouge slip or a post-ore dike. The highest grade chalcocite ore was formed by enrichment of the zone of stronger primary mineralization, the surrounding protore being overlain by chalcocite ore of moderate grade.

As indicated on Section B of the accompanying map, only a negligible amount of enrichment occurred in the pebble breccia. The relative impermeability to supergene solutions is evident - in the rise in the base of oxidation and the abrupt pinching of the chalcocite zone at the periphery of the pebble pipe.

The leached outcrops at Toquepala are similar in many respects to those found over other porphyry copper orebodies. Certain anomalous features exist, however. Limonite-after-chalcocite with characteristic color and texture is present, but its distribution in the outcrops reflects only in part the amount of chalcocite below. The most abundant development of this limonite occurs high on canyon walls and along ridge crests 600 to 1000 ft above the top of the chalcocite zone. The leached rock intervening, in drillholes as well as in outcrops, appears originally to have contained little other than low grade primary mineralization excepting the main breccia pipe, which for the most part shows outcrop evidence of strong primary mineralization. The high-lying horizon may represent a relatively ancient chalcocite zone one that formed below the water table of a pre-existing, - mature erosion surface. It is suggested that this may have been the Puna surface.

Over most of the ore area the leached zone contains only - about 0.10 pct Cu in an unidentified form. This zone represents essentially complete leaching down to the sharp-line contact - with the top of the chalcocite zone. There is no mixed zone of copper silicates, oxides, and sulfides. However, minor amounts of copper silicates are seen in surface outcrops in some of the less strongly altered areas, particulary near the fringe of the zone of alteration.

In most enriched copper deposits, the supergene chalcocite blanket seems to have migrated downward to its present position through progressive stages of leaching and precipitation, leaving behind a more or less continuous record of diagnostic limonites.

At Toquepala the paucity of such limonites in several hundred feet of leached capping above the base of oxidation can best be explained by assuming a relatively rapid and permanent drop in the water table to somewhere near its present level just above the present base of oxidation. Under such conditions the copper derived by leaching of the ancient chalcocite blanket, and the primary chalcopyrite inmediately underlying it, would have been carried down in solution until it reached the reducing environment at the water table. Here accumulation of the present chalcocite orebody took place. Subsequently erosion cut deeply in the capping, forming the modern topography without modification of the chalcocite orebody.

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