

## MINERAL PROCESSING STUDIES FOR THE UTILIZATION OF IRON, COPPER AND PRECIOUS METALS BEARING ORES OF CHILGHAZI, BALUCHISTAN

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The ore of Chilghazi previously considered as iron ores have shown significant quantities of copper, gold, silver and platinum. The main copper mineral is chalcopyrite which occurs as matrix mineral in magnetite. The precious metals were found to be associated mainly with chalcopyrite as substitution. The process developed for the beneficiation of the ore was low intensity magnetic separation for the production of iron concentrate, flotation and leaching for copper and precious metals. A high proportion of the copper and precious metals reported in the non-magnetic fraction and further enrichment was obtained by flotation of the non-magnetic fraction. Rougher concentration at neutral pH and cleaning at pH 9-10 using xanthate gave a product containing 22% Cu, 45.8 ppm Ag, 5.3 ppm Au and 21.8 ppm Pt.

**Key words:** Processing, Iron-copper ore, Baluchistan.

### Introduction

The iron ore of Chilghazi area is found in Sinjrani Volcanic rocks, 51 km northeast of Dalbandin in Chagi Distt., Baluchistan. The ore which occurs in the magnetic horizon consists of magnetite, pyrite, chalcopyrite, epidote, quartz, calcite and pyrophyllite minerals. The percentage of magnetite varies from 60-80% in solid bands with Fe (total) ranging from 32-55%. Total reserves for the solid bands, averaging around 45%. Fe was calculated [1,2] at 2.5 million tonnes of proved ore and 3.4 million tonnes probable ore. Pakistan Mineral Development Corporation has found precious metals in association with mineralization during exploration studies. Research and Development work on mineralogical and beneficiation aspects on this precious metals containing ore has been conducted and is presented in this paper. The ore is reported to be basically magnetite occurring as magnetic injection and has been established to bear appreciable values of gold, silver, copper and platinum. The objective of the present work is to find a suitable method of beneficiation after determination of its chemical assay, mineralogical composition, texture and physical nature. The grade and recovery of magnetite concentrate, chalcopyrite and precious metals concentrate under optimum conditions are studied at different stages.

### Experimental

**Preparation of samples.** The weight of the representative ore samples as received from Pakistan Mineral Development Corporation was about 2 Kg. for sample numbers 1209 and 1217 and 10 kg for bulk sample number 1293. The sieve analysis of the bulk ore showed that 93.33% material was retained on 6 mesh (about 3.00 mm) sieve. The ore was subjected to crushing in Jaw and Roll crushers. A 0.5 kg ore sample was ground in a Tecma mill to about minus 80 mesh size for mineral separation, mineralogical and chemical studies. The product was sampled for chemical

assay and was further crushed to about 300 mesh in a Tecma mill. The remaining portion was kept for mineralogical and processing studies.

**Ore petrography.** The minerals in Chilghazi iron ore is magnetite with lesser amounts of sulphide ore minerals and silicate gangue. The microscopic examination showed coarse grained gangue consisting of altered ferromagnesian minerals, quartz, epidote, andesine etc. in the rock samples, alongwith coarse grained ore minerals, e.g. magnetite, haematite, pyrite and pyrrhotite, (rarely galena and sphalerite). The rocks appear to be altered by martization, sericitization and propylitization. The characteristics of the individual ore minerals as found by ore-microscopy and by observation in stereomicroscope are as follows:

**Magnetite.** The dark brown colour in the ore is due to martization of magnetite. The magnetite showed a wide variety of texture from fine grained dendritic to spherulitic and grano-blastic to massive with veining of gangue. The gangue in the magnetite is generally a mixture of ferromagnesian (grey) and felsic (black) minerals, present as interstitial mineral of 20- 200 microns size and inclusions (2-10 microns size). In the re-crystallized coarse grained massive magnetite, the inclusion and interstitial gangue is reduced probably due to the expulsion out of grain boundaries. Haematite is formed at the expense of magnetite as fine grained or replacement martite texture. The grain size of magnetite is generally 100-200 microns with inclusion of 2-10 microns consisting of mafic and felsic gangue. The inclusion rarely contain sulphide minerals.

**Chalcopyrite.** The grain size of chalcopyrite is extremely variable ranging from 5 to 400 microns. Generally it is present as flakes of 100-200 microns and as dissemination of 5 to 10 micron size. It is recognized from its deep yellow colour and from its reflectance.

**Pyrite/Pyrrhotite.** Pyrite is an important gangue min-

eral present as dissemination (10-50 microns) commonly as vein filling in these rocks. It is common in small anhedral crystals but sometimes shows cubic shape. It's colour varies from yellow to light yellow and at few places appear to have alteration relation with pyrrhotite which is anhedral and has light brown to bronze colour.

*Comminution studies.* Sample 1239 was passed through a jaw crusher for crushing and the product fed through a set of rolls. The roll product was sieved and the results are listed in Table 1. The roll product was ground in the ball mill for different time periods i.e. 5, 10, 15 and 30 min. The grinding was done in the dry condition and the results are plotted in Fig. 1 to 3 and Table 2. Sample weighing 0.4-0.8 kilograms was used for the grinding experiments.

TABLE 1. SIEVE ANALYSES OF ROLL PRODUCT.

Mesh	Weight (g)	%	Cum % Retained	Cum % Passing
+16	285.3	45.50	45.40	54.60
-16+20	28.1	04.48	49.88	50.12
-20+40	114.8	18.29	68.17	31.83
-40+60	45.9	07.32	75.49	24.51
-60+80	27.6	04.39	79.88	20.12
-80+100	21.4	03.42	83.30	16.17
-100+250	62.5	09.96	93.26	06.74
-250	42.3	06.75	-	-

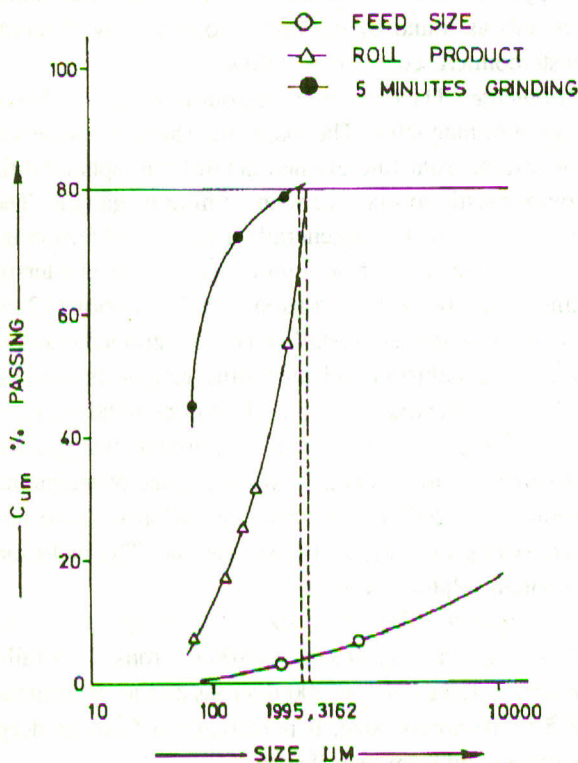


Fig. 1. Particle size distribution on crushing and grinding.

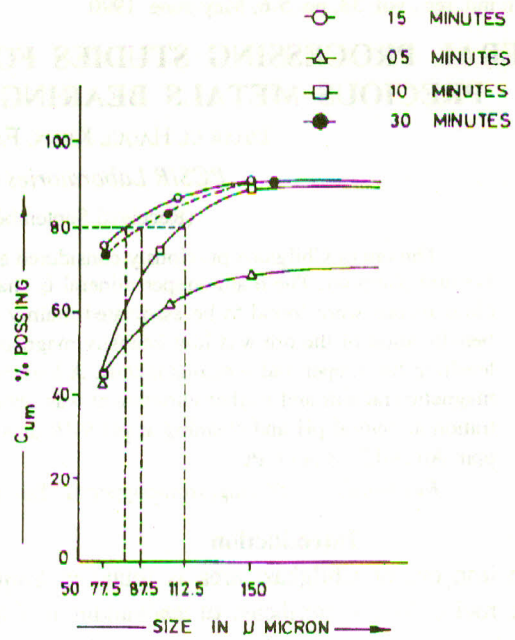


Fig. 2. Ball mills grinding.

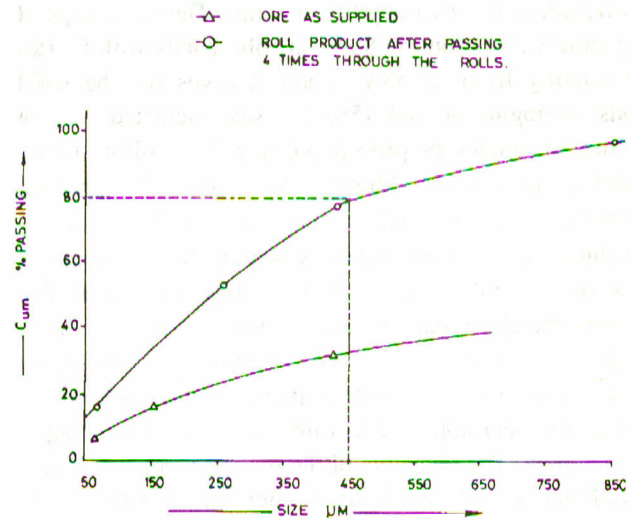


Fig. 3

TABLE 2. SIEVE ANALYSES OF BALL MILL GRINDING FOR 5, 10, 15, AND 30 MINUTES (WEIGHT OF ORE 400 GRAMS)

Mesh	Cumulative percent passing			
	5 min.	10 min.	15 min.	30 min.
+16	77.37	92.34	92.57	92.45
-16+20	76.59	92.10	92.38	92.31
-20+40	74.56	91.51	92.03	92.11
-40+60	73.46	91.20	91.87	91.54
-60+80	72.17	90.82	91.65	91.49
-80+100	69.43	90.03	91.30	91.41
-100+250	43.88	45.02	76.55	73.92
-250	-	-	-	-

The results are plotted on normal and log-normal graphs to find the behaviour of the ore on grinding. It is evident from Fig. 3 that after passing the bulk material four times in the roll mill about 80% of the ground product passed 450 microns. Fig 1 and 2 show that a single step pass in a roll mill reduced the material to about 3192 microns size (about 6 mesh), which on ball milling for 5, 10, 15 and 30 min. reduced it further to 1995, 112, 87 and 77 micron size (80% passing). The grinding of a batch of 400 gram of ore for 10 min. in a ball mill was found optimum for obtaining approximately 80% passing 120 microns (125 mesh) size material, which was considered ideal for beneficiation tests. The results of sieve analysis for 10 min. grinding is given in Table 3.

TABLE 3. SIEVE ANALYSIS OF BALL MILL GRINDING FOR 10 MINUTES (WEIGHT OF ORE 400 g)

Mesh	Weight (g)	%	Cum% Retained	Cum% Passing
+16	20.25	07.66	07.66	92.34
-16+20	00.62	0.24	07.90	92.10
-20+40	01.55	0.59	08.49	91.51
-40+60	00.82	0.31	08.80	91.20
-60+80	01.03	0.38	09.18	90.82
-80+100	02.11	0.79	09.79	90.03
-100+250	118.93	45.01	54.98	45.02
-250	118.87	45.02	-	-

*Bond index.* The grindability studies have shown that the ore is brittle and can be crushed easily. The Bond's Work Index, as determined in a "FC Special Bico Braun Mill 395-50", was found to be 11.75 Kwh for grinding it to the size of liberation of magnetite and chalcopyrite.

A bulk of 800 grams was ground in a ball mill for 10 min. and the results tabulated in Table-4. It is evident from the results given in table 3 and 4 that grinding for 10 min. produces maximum amounts of particles in the size range of -100+250 mesh. The cumulative weight percentage re-

TABLE-4. SIEVE ANALYSIS OF BALL MILL GRINDING FOR 10 MINUTES (WEIGHT OF ORE 800 g)

Mesh	Weight (g)	%	Cum% Retained	Cum% Passing
+16	137.35	17.16	17.16	82.84
-16+20	07.17	0.89	18.05	81.95
-20+40	10.85	1.35	19.40	80.60
-40+60	07.27	0.90	20.30	79.70
-60+80	09.43	01.18	21.48	78.52
-80+100	22.48	02.81	24.29	75.71
-100+250	298.12	37.26	61.55	38.45
-250	307.33	38.45	-	-

tained in this size range, which is desirable for beneficiation, were 54.98 and 61.55 respectively using 400 and 800 grams material in the ball mill.

*Chemical analysis.* Major elements were determined by standard chemical methods of mineral analyses [3,4]. For the determination of Cu, Au and Ag a 5-10 g sample was dissolved using HF- HClO<sub>4</sub> - HNO<sub>3</sub> - HCl and diluted with 20% HCl solution in a 100 ml volumetric flask. Platinum was determined [5] using the method of Stanton and Raman- kutti (1977). A 25g sample was mixed with 100 ml bromine solution and kept overnight. Excess bromine was boiled and the material diluted to 250 ml with water. A portion of clear solution was taken after settling and was subjected to solvent extraction with MIBK to remove Au and Te. A 0.25 ml solution of SnCl<sub>2</sub> (50%) was added and extraction was carried out for Pt with MIBK. The extract was washed with 25ml 2M HBR and platinum analysed by Atomic absorption technique. The chemical analyses for the three ore samples are shown in Table 5.

TABLE 5. CHEMICAL ANALYSIS OF CHILGHAZI ORE

Constituents	Sample No.		
	1209 (%)	1217 (%)	1297 (%)
Fe	43.80	41.50	49.10
SiO <sub>2</sub>	14.20	13.80	13.20
Al <sub>2</sub> O <sub>3</sub>	13.50	09.50	10.10
TiO <sub>2</sub>	00.80	00.70	00.60
CaO	03.90	07.50	05.50
MgO	02.10	01.70	01.10
P <sub>2</sub> O <sub>5</sub>	00.50	00.30	00.50
Cu	0.49	0.42	00.90
Au(ppm)	0.10	0.25	00.19
Ag(ppm)	02.00	03.10	01.50
Pt(ppm)	01.50	01.70	01.50

*Ore beneficiation studies.* The Chilghazi iron ore was found to be amenable to beneficiation by magnetic separation, as it contains separate phases of magnetite and precious metals minerals. In spite of the partial martization of the magnetite the nature and texture of the ore responded favourably to magnetic separation. The behaviour of the bulk ore No. 1293 was similar to certain extent with magnetite ore in concentration circuits. The sample No. 1209 and 1217, showed a little less recovery due to some alteration in magnetite grains, as shown in Table 6.

The iron invariably showed micro inclusions of gangue minerals in magnetite grains. The size of micro inclusions (10-20 microns) was below the practicable limit of mineral beneficiation. However, the re-cleaning of concen-

TABLE 6. EFFECT OF SULPHURIC ACID CONCENTRATION ON LEACHING  
ORE SIZE = 100#; TIME OF STIRRING = 30 MINUTES; FINAL VOLUME MADE= 500.00 M.

S.No.	Con. of acid (100ml)		Cu		Ag		Au		Pt	
			%	Rec.%	PPM	Rec.%	PPM	Rec.%	PPM	Rec.
1.	1.00%	100m	0.65	72.00	00.00	00.00	0.05	26.00	0.60	40.00
2.	2.50%	"	0.75	83.00	0.2	13.00	0.06	31.00	0.20	13.00
3.	5.00%	"	0.90	100.00	0.8	53.00	0.02	10.00	0.30	20.00
4.	7.50	"	0.80	89.00	1.2	80.00	0.02	10.00	0.40	27.00
5.	10.00%	"	0.88	98.00	1.2	80.00	0.03	16.00	0.80	53.00
6.	Total extraction method		0.90	10.00	1.5	100.00	0.19	100.00	1.5	100.00

rates showed that it only contributed to the reconcentration grade on an average 3.5%. SiO<sub>2</sub>, ranging from 2.5 to 5.5% for different types of ores. The matrix gangue mineral was found separable from the bulk of the magnetite by low intensity magnetic separation method and could be an economic by-product containing appreciable amounts of copper, gold, silver and platinum.

*Davis tube tests.* Different batches of the bulk ore (sample 1293) were ground and passed 100% through different mesh sieves. A batch of 100 gram of ore was passed through a Davis tube as slurry in water. The tailing was passed three times through the Davis tube to collect maximum amount of magnetic portion. The magnetic and non-magnetic fractions were collected, dried and weighed. The results of the tests are shown in Table 7.

TABLE 7. RESULTS OF DAVIS TUBE TESTS OF SAMPLE 1293

Mesh size	Magnetics (%)	Non-magnetics (%)
-18	65.09	34.91
-40	90.49	9.51
-60	84.21	15.79
-80	76.46	24.54
-120	74.00	26.00
-150	86.38	13.62
-250	83.23	16.77

It was seen in Table 7 that at coarse mesh size, the weight percent recovery of magnetite particles in the Davis tube is low (65.09%) due to the presence of gangue dominated locked particles, as seen under stereomicroscope. On further grinding to 40 and 60 mesh size the weight percent of the magnetic fraction is increased to 90.49% and 84.27% percent respectively due to the liberation of magnetite and magnetite dominated locked particles. For the same field strength applied to the Davis Tube the weight recovery is expected to increase with finer particle size. Tests conducted on further ground samples, however, showed lesser recovery due to the adherence of finely ground gangue on magnetite particles.

The product obtained by magnetic separation were chemically analysed. The chemical composition and recovery of different precious metals on magnetic concentrate and non-magnetic fractions are given in Table 8.

It can be noted from Table 8 that the recovery percent of Cu, Au, Ag and Pt is high at 120 mesh size which could be a suitable grind size for rougher concentration. There is an approximate enrichment of the order of three times in Cu and greater for the precious metals. The magnetic concentration produced 74.0% magnetite and 26.0% non-magnetic fraction at 120 mesh. The non-magnetic fraction as

TABLE 8. COMPOSITION AND RECOVERY OF COPPER, PRECIOUS METALS IN MAG. (M) AND NON-MAG. (N.M.) FRACTIONS IN CHILGHAZI ORE SAMPLE No.1239.

	Wt.%	Copper		Silver		Gold		Platinum	
		%	Rec.%	PPM	Rec.%	PPM	Rec.%	PPM	Rec.%
Assay head	100.00	00.90	100.00	01.50	100.00	00.19	100.00	01.50	100.00
M	84.20	00.47	43.9	00.90	55.8	00.13	60.6	00.90	53.3
-60# N.M	15.80	03.20	56.1	03.80	44.2	0.45	39.4	04.20	46.70
Calc. head	100.00	00.90	100.00	1.36	100.0	0.18	100.00	1.42	100.00
M	74.00	00.30	24.7	00.40	17.1	00.05	16.9	00.50	24.0
-120# N.M	26.00	02.60	75.3	05.50	82.9	00.70	83.1	04.50	76.0
Calc. head	100.00	0.90	100.0	1.72	100.0	0.22	100.0	1.54	100.0
M	86.40	00.76	69.7	00.70	38.9	00.10	55.8	00.60	35.3
-150# N.M.	13.60	02.10	30.3	07.00	61.1	00.50	44.2	07.00	64.7
Calc. head	100.00	0.94	100.0	1.56	100.0	0.15	100.0	1.47	100.0

sayed 2.6% copper and has 5.5 ppm Ag, 0.7 ppm Au and 4.5 ppm of Pt. Although 7.0 ppm Ag and 7.0 ppm Pt were present in the 150 mesh non-magnetic fraction but the recover is lower. It is therefore suggested to produce rougher concentrate at coarser mesh (100- 120 mesh size) and re-clean the non-magnetics to obtain high grade concentrates with better recoveries of precious metals by magnetic separation. It is seen in Table 8 that the calculated head values are in good agreement with the assay head, particularly when the lower "precious metal" contents are taken into consideration.

**Flotation Experiments.** Denver flotation machine model D.12 was used for flotation tests, with impeller speed set at 1100 to 1200 rpm. The feed to flotation was the non-magnetic fraction obtained after the magnetic separation of the magnetite from the deslimed ore in a low intensity magnetic separator. The grind size 80% passing 120 mesh, yielded 26% non-magnetic and 74% magnetic fraction in magnetic separator (Table 8). The pH during rougher concentration was neutral but it was changed to the basic range with the addition of the lime in varying amount for cleaner concentration. The feed was conditioned for two min. with potassium xanthate as collector and flotation was commenced after adding one drop of the frother. The froth was removed for ten minutes as a copper concentrate. The pH of the pulp was adjusted between 9 to 10 with the addition of the lime after roughing and more concentrate was obtained by scraping for an additional 5 min. without further addition of any reagent such as xanthate. Ordinary tap water was used in these tests. The concentrate and tailings were decanted and dried in the oven at 105°. Xanthate are good collectors for most of sulphide including chalcopyrite. AEROFLOATS (dithiophosphates) and Z-200 (dithiocarbonate) which are often much selective and sometimes stronger in acting but usually more expensive were not needed as the copper minerals in Chilghazi ore show rea-

sonable floatability requiring no collector action. These ores can be floated without using much frother. However, small amounts of frother such as pine oil, cresylic acid (cresol), MIBC and polypropylene glycol (Dow froth-250) increase the yield, as seen from the floatability of the tailing from these reagents. However no detailed tests were conducted during this study with different reagents.

The pH regulators were used to modify the mineral surface and create a favourable condition in the pulp for successful flotation. First flotation at neutral pH was undertaken in order to recover the maximum amounts of sulphide and associated precious metals. Cleaning of the concentrate was later done at higher pH using indigenous low grade lime (CaO), so as to obtain maximum recovery of chalcopyrite. Gold and silver values and to lesser extent Pt values tended to report in the copper concentrate. The results of flotation are summarized in Table 9.

### Results

The head sample No. 1293 weighing about one Kg ore assayed 0.9% copper, 1.5 ppm silver, 0.19 ppm gold and 1.5 ppm platinum. Magnetic separation of this sample yielded about 0.25 kg of non-magnetic fraction containing 75.3% recovery of the copper, 82.9% recovery of silver 83.1 percent recovery of gold and 76% recovery of platinum.

The experiment discussed relate to single stage cleaning by magnetic separation and flotation. The cleaner concentrate obtained after flotation of the magnetic fraction assayed 22.0% copper, 45.8 ppm silver, 5.3 ppm gold and 21.8 ppm of platinum. These results are encouraging because the gradess of copper and precious metals were obtained in a single cleaning. The present investigation is preliminary in nature and further studies are in progress, however, it was theoretically calculated on the basis of mineralogical particle analyses that after re-cleaning a grade containing 25-30% copper with 55-65 ppm silver, 7-8 ppm

TABLE 9. FLOTATION OF NON-MAGNETIC FRACTION (FLOWSHEET AS PER FIG.4)

	Weight		Copper		Silver		Gold		Platinum	
	(gms)	%	%	Rec.%	PPM	Rec.%	PPM	Rec.%	PPM	Rec.%
Orig. ore		100.0	0.9	100.0	1.5	100.0	0.19	100.0	1.5	100.0
Non-magnetic fraction (assay head) feed to flotation		26.0	2.6	75.3	5.5	82.9	0.7	83.1	4.5	76.0
<i>Flotation</i>										
Cleaner conc.	25.4	11.1	22.0	87.3	45.8	90.0	5.3	78.8	21.8	56.6
Cleaner tail	10.3	4.5	1.3	2.1	5.0	4.0	0.5	3.1	3.5	3.4
Rougher tail	193.0	84.4	0.35	10.6	0.4	6.0	0.16	18.1	2.4	44.0
Feed (calc.)	228.7	100.0	2.80	100.0	5.6	100.0	0.7	100.0	4.6	100.0
Cleaner conc. recoveries on a whole ore basis		2.9		65.7		74.6		65.5		40.0

gold and 20-35 ppm platinum should be possible. Using the flowsheet (Fig. 4) a high grade iron concentrate can be obtained (a useful raw material for the steel industry) as well as a marketable copper/precious metal concentrate.

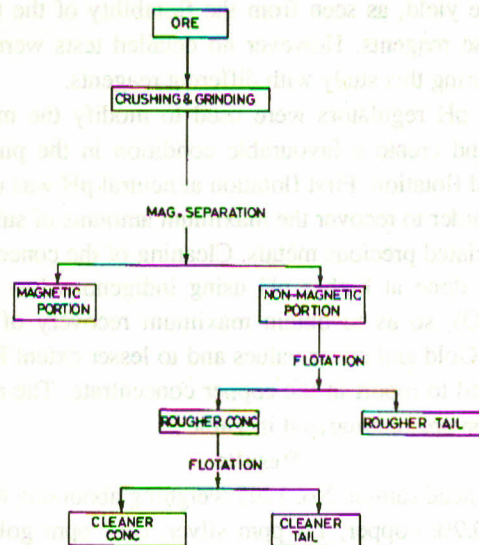


Fig.4. Flow Sheet for the concentration of the Chilghazi ore.

The recoveries obtained for copper, silver, gold and platinum in concentrate were 87.3, 90.0, 78.8 and 52.6% respectively. The overall feed recoveries on the feed basis for both magnetic and flotation processes with one cleaning stage were 65.7% for copper, 74.6% for silver, 65.5% for gold and 40.0% for platinum.

In conclusion it may be observed that the cleaning operation, especially with such rougher concentrate, produces a concentrate of reasonable grade with good recoveries. The concentrate produced is a mixture of low and high grade ore particles. Grinding of the cleaner concentrate is therefore essential to liberate chalcopyrite from gangue and regrinding of the cleaner concentrate to 80% -150 mesh is indicated by microscopic particle counting.

### Conclusion

The main minerals in Chilghazi iron ore is magnetic with lesser amounts of sulphide ore minerals (e.g. pyrite, and chalcopyrite containing copper and precious metals) and silicate gangue. The grain size of ore and gangue was found to be generally coarse. The chemical analysis showed 41.5 to 49.1% Fe, 13.2 to 14.2 %  $\text{SiO}_2$ , 0.42 to 0.9% copper, 0.1 to 0.25 ppm Au, 1.5 to 3.10 ppm Ag and 1.5 to 1.7 ppm Pt. The ore was found to be amenable to beneficiation by magnetic separation producing a concentrate suitable for iron manufacture, containing 61 - 67% Fe, 2.5 - 5.5%  $\text{SiO}_2$  with 86.1 to 97% recovery.

The non magnetic fraction obtained from Davis tube tests showed enrichment in copper and precious metals i.e. 2.6% Cu, 5.5 ppm Ag, 0.7 ppm Au and 4.5 ppm Pt. The flotation of the non- magnetic fraction using xanthate showed a good grade and recovery of sulphide minerals. The cleaner concentrate obtained after flotation assayed 22.0% copper, 45.8 ppm Ag, 5.3 ppm Au and 21.8 ppm Pt. Further it was theoretically calculated on the basis of mineralogical particle analyses that after recleaning a grade containing 25-30% copper with 55-65 ppm silver, 7-8 ppm gold and 20-35 ppm platinum should be possible. Using the flowsheet (Fig. 4) a high grade iron concentrate can be obtained (a useful raw material for the steel industry) as well as a marketable copper/precious metal concentrate.

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