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THE MAGNETIC SEPARATION OF SOME ALLUVIAL MINERALS IN MALAYA*

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ABSTRACT

This paper presents the results of a series of magnetic separations which have been investigated for a number of minerals occurring in Malayan alluvial concentrates. The purpose of the investigations was to establish, by the isolation of individual mineral species, a reproducible and reliable method for the identification and quantitative estimation of minerals in alluvial concentrates examined by the Geological Survey in Malaya. In particular was sought the isolation of columbite from ubiquitous ilmenite. All the separations were made on the small, highly sensitive Frantz Isodynamic Model L-1 laboratory separator. The minerals which have been successfully separated include allanite, anatase, andalusite (and chiastolite), arsenopyrite, brookite, cassiterite, columbite, epidote, gahnite, garnet (pink), ilmenite, manganese oxide (51.6% Mn), monazite, pyrite, rutile, scheelite, siderite, staurolite, thorite, topaz, tourmaline, uranoan monazite, wolframite, xenotime, and zircon.

PROCEDURE

When using an inclined feed, the Frantz Isodynamic separator (see Figs. 1(A) & (B)) has three inherent variables. These are the field strength (current used), the side slope, and the forward slope.

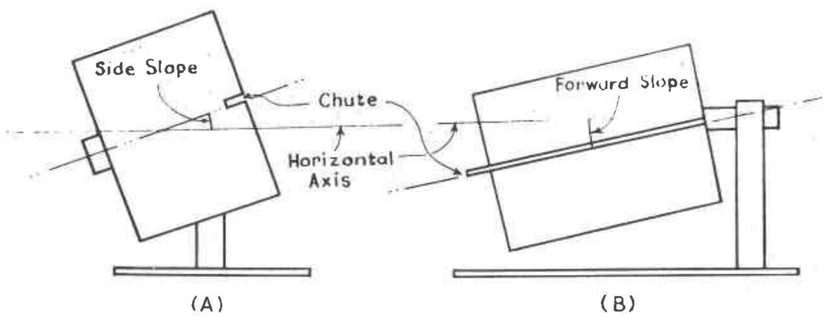

FIG. 1. Diagrammatic representation of side slope and forward slope.

The field strength is increased by means of a rheostat which raises the current from zero in stages of 0.05 amps. to 1.4 amps. Early in the investigations it was decided that steps of 0.1 amp. would be sufficiently gradual.

The side slope can be varied continuously from 0 to 90° and can also be given a reverse slope, as much as 90°, for the diamagnetic separation of minerals such as zircon. Results of a few separations made by my

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colleagues when the separator was first installed showed that, for the purpose of these investigations, side slopes varying by less than 5° would produce no significant differentials, and further, that side slopes greater than 15° showed more promise, as regards the separation of columbite from ilmenite, than did slopes of less than 15°. Accordingly a series of tests was carried out at side slopes of 15°, 20°, 25°, and 30°.

The forward slope and a fourth, independent, variable, the rate of feed, control the rate of flow of the sample. The steeper the slope, the faster is the flow. The rate of flow of a sample is not critical provided that it is slow enough to allow the mineral to remain long enough in the magnetic field for the magnetic pull exerted by the separator to be fully effective. A forward slope of 15° was chosen for, and maintained throughout, the investigation.

Much more critical is the uniformity of grain size of the sample, as the larger grains tend to "suppress" the finer material. For the purpose of simple identification and the estimation of mineral percentages in an alluvial concentrate a grain size of 0.4 mm. or 0.0166 inch (36 mesh B.S.S.) is considered a satisfactory upper limit. With larger grains difficulty is experienced in distinguishing amongst the opaque minerals and between the opaque minerals and the translucent minerals such as gahnite, cassiterite and rutile. The grain size of 0.2 mm. or 0.0083 inch (72 mesh B.S.S.) was selected as a suitable lower limit. This gave uniformity to the sample and provided finer material for a parallel series of tests to be conducted, thereby ascertaining whether a difference in grain size gives rise to any significant difference in results.

For each mineral the same sample was used for all the separations, thus eliminating variations independent of the change in side slope. Each sample, averaging 2 to 3 gms., was dried before being passed through the separator. After separation the fractions were examined under the microscope and the weight percentages recalculated to allow for any impurities, which were estimated visually.

Assessment of Results

On the basis of the separations carried out the minerals tested can be divided into two groups, the "magnetic" and the "non-magnetic." The "non-magnetic" minerals are those that are not attracted at a value of 1.4 amps. giving the maximum field strength of the separator. They are anatase, andalusite (and chiastolite), arsenopyrite, brookite, cassiterite, pyrite, rutile, scheelite, topaz, and zircon. The "magnetic" minerals are given in Tables 1 to 8.

A study of these tables shows that, for the purpose for which the investigations were effected, side slopes of 20° (Tables 3 and 4) and 30°

TABLE 1. WEIGHT PERCENTAGES SEPARATED BY INDICATED CURRENT STRENGTHS USING 15° SIDE SLOPE, 15° FORWARD SLOPE ON −36+72 MESH BSS MATERIAL

Current (Amps.) Strength	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	Non
Allanite	1.8	6.4	14.4	74.7	2.7	Tr.									
Columbite		Tr.	0.2	99.1	0.7	Tr.									
Epidote			Tr.	7.3	78.1	14.6	Tr.								
Gahnite					10.4	69.5	16.9	2.2	1.0	Tr.					
Garnet (pink)		5.4	94.6												
Ilmenite		Tr.	90.0	10.0	Tr.										
Mn. oxide		Tr.	13.5	54.1	32.4	Tr.									
Monazite					Tr.	5.1	92.8	2.1	Tr.						
Siderite		89.2	10.8	Tr.											
Staurolite				Tr.	42.7	57.3									
Thorite						0.3	3.0	24.5	43.4	23.8	4.4	0.3	0.3		
Tourmaline			Tr.	Tr.	21.8	75.7	2.5								
Uran. Monazite				Tr.	Tr.	91.3	8.7								
Wolframite			0.3	97.4	2.3										
Xenotime			2.5	83.0	12.5	2.0	Tr.								

TABLE 2. WEIGHT PERCENTAGES SEPARATED BY INDICATED CURRENT STRENGTHS USING 15° SIDE SLOPE, 15° FORWARD SLOPE ON −72 MESH BSS MATERIAL

Current (Amps.) Strength	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	Non
Allanite	3.1	5.7	10.7	57.6	22.9	Tr.									
Columbite			Tr.	99.2	0.8										
Epidote				Tr.	85.7	14.3	Tr.								
Gahnite					Tr.	42.3	53.9	3.8	Tr.						
Garnet (pink)			100.0	Tr.											
Ilmenite		1.0	93.8	4.7	0.5										
Mn. oxide		Tr.	7.7	61.5	30.8	Tr.									
Monazite						13.7	85.6	0.7	Tr.						
Siderite		58.8	41.2												
Staurolite		1.0	1.4	6.9	83.1	7.6	Tr.								
Thorite							Tr.	5.7	40.5	43.0	7.2	3.6			
Tourmaline			0.3	3.1	87.0	8.5	1.1	Tr.							
Uran. Monazite				Tr.	Tr.	97.8	2.2								
Wolframite			2.5	96.0	1.5										
Xenotime				88.3	11.7	Tr.									

TABLE 3. WEIGHT PERCENTAGES SEPARATED BY INDICATED CURRENT STRENGTHS USING 20° SIDE SLOPE, 15° FORWARD SLOPE ON −36+72 MESH BSS MATERIAL

Current (Amps.) Strength	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	Non
Allanite	Tr.	3.0	8.8	19.0	19.0	50.0	0.2								
Columbite		Tr.	Tr.	63.8	36.0	0.2									
Epidote				2.6	52.7	44.7	Tr.								
Gahnite					3.5	22.1	49.4	22.5	1.8	0.7					
Garnet (pink)			88.1	11.9											
Ilmenite		Tr.	75.1	24.6	0.3										
Mn. Oxide			8.3	38.9	52.8	Tr.									
Monazite						Tr.	42.7	56.5	0.8	Tr.					
Siderite		10.3	89.7	Tr.											
Staurolite						99.4	0.3	0.3							
Thorite							0.3	3.5	4.6	46.0	33.3	10.2	1.5	0.6	
Tourmaline			0.9	0.9	1.8	16.5	79.0	0.9							
Uran. Monazite				Tr.	Tr.	7.1	55.8	36.4	0.7						
Wolframite			0.3	78.1	21.6										
Xenotime			Tr.	5.3	94.7	Tr.	Tr.								

TABLE 4. WEIGHT PERCENTAGES SEPARATED BY INDICATED CURRENT STRENGTHS USING 20° SIDE SLOPE, 15° FORWARD SLOPE ON −72 MESH BSS MATERIAL

Current (Amps.) Strength	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	Non
Allanite	1.3	2.4	5.4	10.8	80.0	0.1									
Columbite			Tr.	38.9	60.6	0.5									
Epidote				Tr.	14.3	85.7	Tr.								
Gahnite						12.5	75.0	6.3	6.2	Tr.					
Garnet (pink)			16.7	83.3											
Ilmenite		0.8	92.0	5.7	1.5	Tr.									
Mn. Oxide			9.0	27.3	45.5	18.2									
Monazite						0.3	27.5	64.2	8.0	Tr.					
Siderite		15.3	84.7												
Staurolite		Tr.	1.2	1.8	8.9	82.4	5.7	Tr.							
Thorite								Tr.	5.8	34.3	36.5	18.3	3.6	0.8	0.7
Tourmaline			Tr.	Tr.	65.5	28.9	3.1	2.5	Tr.						
Uran. Monazite						1.2	98.8	Tr.							
Wolframite				98.3	1.5	0.2									
Xenotime				2.5	97.3	0.2									

TABLE 5. WEIGHT PERCENTAGES SEPARATED BY INDICATED CURRENT STRENGTHS USING 25° SIDE SLOPE, 15° FORWARD SLOPE ON −36+72 MESH BSS MATERIAL

Current (Amps.) Strength	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	Non
Allanite		3.0	7.5	17.2	20.5	51.4	0.4								
Columbite			Tr.	0.5	97.7	1.4	0.4								
Epidote					7.1	64.3	26.2	2.4							
Gahnite						Tr.	42.9	51.2	3.5	1.7	0.7				
Garnet (pink)			65.4	34.6											
Ilmenite		Tr.	67.4	25.9	6.7	Tr.									
Mn. oxide			Tr.	14.3	38.1	42.9	4.7								
Monazite							Tr.	49.6	48.9	1.5					
Siderite			100.0	Tr.											
Staurolite						30.2	58.0	11.8							
Thorite								Tr.	1.9	6.0	47.4	19.3	16.3	4.7	4.4
Tourmaline					1.4	6.0	43.4	45.4	2.7	1.1	Tr.				
Uran. Monazite					Tr.	Tr.	Tr.	96.4	3.6	Tr.					
Wolframite			0.4	0.9	90.6	8.1									
Xenotime				1.3	53.7	43.7	1.3								

TABLE 6. WEIGHT PERCENTAGES SEPARATED BY INDICATED CURRENT STRENGTHS USING 25° SIDE SLOPE, 15° FORWARD SLOPE ON −72 MESH BSS MATERIAL

Current (Amps.) Strength	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	Non
Allanite	1.4	1.4	3.5	6.1	13.5	73.7	0.4								
Columbite			Tr.	Tr.	72.7	27.3	Tr.								
Epidote					7.0	67.6	25.4	Tr.							
Gahnite							18.7	31.3	43.8	6.2					
Garnet (pink)			40.0	60.0											
Ilmenite		0.4	77.5	19.8	2.3	Tr.									
Mn. oxide			Tr.	30.0	30.0	40.0									
Monazite							0.3	44.3	54.8	0.6	Tr.	Tr.			
Siderite		0.7	89.5	9.8											
Staurolite		Tr.	0.3	1.0	3.9	34.8	56.8	3.2							
Thorite									Tr.	5.7	18.6	37.9	22.7	14.1	1.0
Tourmaline			Tr.	Tr.	Tr.	95.5	2.4	2.1	Tr.	Tr.					
Uran. Monazite							3.7	94.4	1.9						
Wolframite				2.1	96.7	1.2									
Xenotime					38.7	60.1	1.2								

TABLE 7. WEIGHT PERCENTAGES SEPARATED BY INDICATED CURRENT STRENGTHS USING 30° SIDE SLOPE, 15° FORWARD SLOPE ON −36+72 MESH BSS MATERIAL

Current (Amps.) Strength	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	Non
Allanite		2.2	4.5	9.3	24.5	58.6	0.9								
Columbite			Tr.	Tr.	62.7	32.4	4.9	Tr.							
Epidote					2.5	22.5	72.5	2.5	Tr.						
Gahnite						2.0	20.5	30.7	40.0	5.8	1.0				
Garnet (pink)			Tr.	53.2	31.5	15.3									
Ilmenite		Tr.	17.9	37.5	23.2	19.4	2.0	Tr.							
Mn. oxide				13.2	31.6	50.0	5.2	Tr.							
Monazite								15.5	43.0	20.8	20.7				
Siderite			38.9	61.1											
Staurolite							51.5	37.1	11.4						
Thorite								Tr.	0.6	7.9	8.4	28.1	15.4	14.6	25.0
Tourmaline						4.2	27.2	38.1	26.3	4.2	Tr.				
Uran. Monazite						Tr.	Tr.	33.8	64.7	1.5					
Wolframite			Tr.	0.6	76.0	20.5	2.9								
Xenotime					26.6	59.6	12.9	0.9	Tr.						

TABLE 8. WEIGHT PERCENTAGES SEPARATED BY INDICATED CURRENT STRENGTHS USING 30° SIDE SLOPE, 15° FORWARD SLOPE ON −72 MESH BSS MATERIAL

Current (Amps.) Strength	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	Non
Allanite	Tr.	2.0	2.9	5.7	12.4	47.0	30.0								
Columbite				Tr.	98.0	2.0	Tr.								
Epidote					11.1	55.6	33.3	Tr.							
Gahnite							Tr.	40.0	40.0	20.0	Tr.				
Garnet (pink)				100.0	Tr.	Tr.									
Ilmenite		0.5	6.8	58.4	29.0	5.3	Tr.								
Mn. oxide				Tr.	11.1	88.9	Tr.								
Monazite								9.3	46.2	23.0	14.5	7.0	Tr.	Tr.	Tr.
Siderite			64.7	35.3											
Staurolite		Tr.	0.8	1.0	2.3	10.2	66.7	19.0	Tr.						
Thorite										Tr.	6.3	15.0	31.5	19.6	27.6
Tourmaline				Tr.	Tr.	68.6	26.5	3.5	1.1	0.3	Tr.				
Uran. Monazite								96.8	3.2						
Wolframite				0.6	99.1	0.3									
Xenotime					33.5	49.0	17.5								

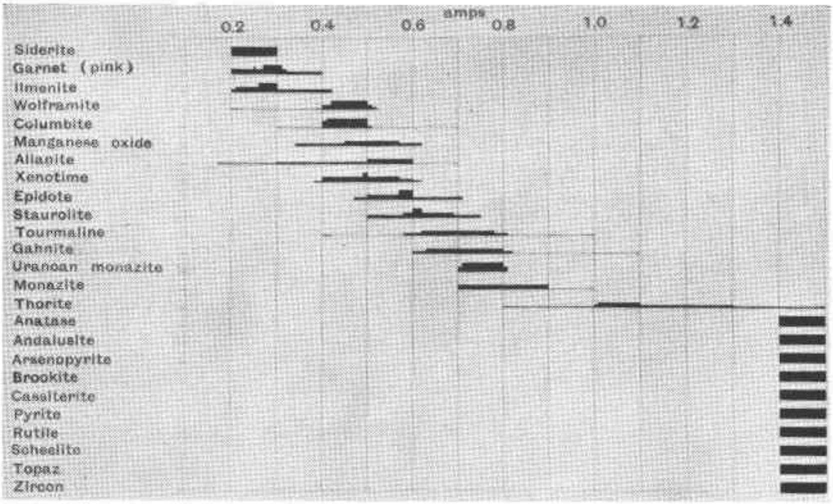

FIG. 2. A plot of data from Table 5. Side slope 25°, forward slope 15°; grain size $-36+72$ mesh B.S.S.

(Tables 7 and 8) can be disregarded, because there is too much overlapping of the mineral species, particularly columbite and ilmenite, and that at a side slope of 30° (and therefore above) effective separation cannot be achieved because the magnetic attraction at the lower amperages is not strong enough to overcome the effect of gravity.

However, side slopes of 15° (Tables 1 and 2) and 25° (Tables 5 and 6) give convenient breaks at amperages of 0.3, 0.5 and 0.8 and 0.4, 0.7 and 1.0 respectively, and these separations are summarized in Fig. 2.

Although most of the minerals tested give rise to some variation due to grain size, in nearly all cases these variations become negligible over a suitable range of amperages. For a side slope of 15° and amperages of 0.3, 0.5 and 0.8, only four minerals (gahnite, staurolite, thorite and tourmaline) show a marked variation, and for a side-slope of 25° and amperages of 0.4 , 0.7 and 1.0, the only two minerals showing a marked variation are gahnite and tourmaline. For this reason, and because of the better separation of columbite from ilmenite and monazite from xenotime, a side slope of 25° is preferable to one of 15°.

EXCEPTIONS

Occasionally an anomalous result is encountered. The most common cause is the presence of a partial coating of iron oxide, which can be removed by treating the mineral with hydrochloric acid, when it will behave normally. A less frequent cause is the presence of very fine inclusions of a more magnetic mineral. Notable examples of this are zircon and monazite and, in columbite areas, cassiterite (due to inclusions of the columbite). Both these causes result in the mineral becoming more magnetic.

It is known that, from certain localities in Malaya, cassiterite and ilmenite will give anomalous results. Cassiterite from these localities is attracted at all fractions, from 1.4 amps. to 0.1 amps. and is also attracted by a horse-shoe magnet. This magnetic cassiterite is found in areas of major iron-ore development. No inclusions are discernible at high power in transmitted light, but it is thought that this apparently inherent magnetism, which can be destroyed by heating to a temperature of a few hundred degrees Centigrade, is due to micro-fine exsolution lamellae of magnetite.

Ilmenite, on the other hand, becomes less magnetic. This is due to its alteration to "arizonite." The greater the degree of alteration, the less magnetic is the ilmenite. The maximum current so far required to attract Malayan material (at a side slope of 25°) is 0.7 amps.

Rutile is often quoted as being magnetic. Magnetic rutile is commonly encountered in Malaya. Exhaustive tests have shown that the magnetism is due to the ionic substitution of Ta/Nb (and therefore Fe). These Ta/Nb-rutiles range, in Malaya, from non-magnetic material to material attracted at a current strength of 0.7 amps. depending on the amount of substitution present. The increase in magnetism is accompanied by an increase in opacity. Pure rutile is non-magnetic.

The Estimation of Magnetic Behavior from Known Results

The results given in Tables 1 to 8 represent the mass magnetic susceptibilities of the minerals tested. The mass magnetic susceptibility (K_M) of a mineral is given as (1):

$$\frac{\text{magnetic susceptibility}}{\text{density}}$$

An approximate value for K_M can be obtained from the equation

$$K_M = \frac{20 \sin a}{I^2} \times 10^{-6} \text{ c.g.s.}$$

where

a = the angle of slide-slope

and

I = the current in amperes, provided that K_M is much less than 1 and that determinations are made at amperages lower than 1.3, as saturation sets in above this value.

An important application of this rule is that, once the K_M value for

TABLE 9. MASS MAGNETIC SUSCEPTIBILITY (K_M) IN 10^{-6} C.G.S.

I Amps. \ a	Side Slope 15°	20°	25°	30°
0.1	517.64	684.04	845.24	1000.00
0.2	129.41	171.01	211.31	250.00
0.3	57.52	76.00	93.92	111.11
0.4	32.35	42.75	52.83	62.50
0.5	20.71	27.36	33.81	40.00
0.6	14.38	19.00	23.48	27.78
0.7	10.56	13.96	17.25	20.41
0.8	8.09	10.69	13.21	15.63
0.9	6.39	8.44	10.44	12.35
1.0	5.18	6.84	8.45	10.00
1.1	4.28	5.65	6.99	8.26
1.2	3.59	4.75	5.87	6.94
1.3	3.06	4.05	5.00	5.92
1.4	2.64	3.49	4.31	5.10

any mineral is known, the current at which it is attracted can be calculated for any other side slope or because of any compositional variation affecting the specific gravity. In order that the information contained in this paper can be so used, the K_M values for the various amperages, at side slopes of 15°, 20°, 25° and 30°, are given in Table 9.

The application of this relationship to the results given in the tables shows that the most significant factor influencing the magnetic susceptibility of a mineral is the percentage of ferrous iron (Fe^{2+}) present in its composition. Thus ilmenite and siderite, both with a high percentage of Fe^{2+} (and a fairly low density) have similar high values of K_M. The pink garnet, with its high mass magnetic susceptibility, is a highly ferroan variety (almandite). The increased amperage needed to attract ilmenite when it is altering to "arizonite" can be foreseen because of the decreased value for K_M resulting from a loss in Fe^{2+} content whereas the specific gravity remains similar.

The columbite/tantalite mineral series is very interesting. Although no tantalite has been separated it would presumably be attracted at higher amperages than columbite because of its much higher specific gravity, and it should be possible to obtain, from the current used, the tantalum/niobium ratio of the mineral. Research in hand on the Ta/Nb-rutile minerals indicates that a relationship exists between the ferrous iron content, the ratio of tantalum to niobium and the specific gravity. With the Ta/Nb-rutile minerals, however, a variable amount of substitution is possible, with correspondingly variable amounts of ferrous iron, which give rise to an added complication which must be taken into account.

Conclusion

The effective separation of minerals according to their mass magnetic susceptibility depends principally upon a fine balance between gravity (controlled by variation in the side slope), and field strength (controlled by the current used). Other factors such as forward slope, rate of feed, and grain size, are subsidiary provided they fall within certain fairly broad limits.

For the routine examination and estimation of the approximate percentages of minerals in Malayan concentrates it has been shown that electromagnetic separation is effective and that the best separation is achieved by using a side slope of 25° and current strength of 0.4, 0.7 and 1.0 amps. on material less than 36 mesh B.S.S.

In order of decreasing mass magnetic susceptibility the minerals separated are siderite, garnet (pink), ilmenite, wolframite, columbite, manganese oxide (51.6% Mn), allanite, xenotime, epidote, staurolite, tourmaline, gahnite, uranoan monazite, monazite and thorite, with anatase, andalusite (and chiastolite), arsenopyrite, brookite, cassiterite, pyrite, rutile, scheelite, topaz, and zircon being non-magnetic.

Reference

(1) H. H. Hess, 1956 "Notes on operation of Frantz Isodynamic Magnetic Separator." Pamphlet published by S. G. Frantz Co., Inc., p. 8.

Manuscript received October 15, 1958.