Recovery of Semi-heavy Minerals in Jigs*

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SYNOPSIS

There is need for more data on the plant-scale recovery of heavy and semi-heavy minerals through the screen in jigs in relation to specific gravity, grain size and the number of cells in series. Performance data for a 4-cell jig given in a previous paper by the author covered the specific gravity range 7·0 to 4·5 from 16 mesh down to sub-sieve sizes for the recovery of heavy minerals from a sand consisting mainly of quartz. Data are now given in terms of the three minerals zircon, anatase and topaz for the specific gravity range 4·5 to 3·5 for grain sizes from 6 to 325 mesh. These results could be used to estimate the probable percentage recovery of economic and other semi-heavy minerals within this range of specific gravity. A selection of the more important minerals in this category is presented and indicates some new fields for the use of jigs in ore dressing.

The significance of the recovery efficiency of jigs is discussed in relation to certain ore-dressing practices and to the mining and treatment of alluvial, residual and primary ore deposits.

INTRODUCTION

THE FIELD PLANT INCORPORATING JIGS described in this paper is situated at Rayfield, on the Jos Plateau, Nigeria. It was formerly used for the commercial recovery of columbite and other primary accessory minerals from an intensely decomposed granite. After minor modifications it is now being used for the commercial recovery of cassiterite and columbite from a nearby alluvial lead. It has not the flexibility and sampling facilities of a pilot plant.

In accordance with established alluvial tin-mining practice the field plant is designed only for gravity concentration, which is carried out only to the stage of recovering a mixed concentrate containing a number of heavy and semi-heavy minerals with a minimum amount of sand. This concentrate is then transported to a mill equipped for the combination of gravity, magnetic and electrostatic (high tension) concentration, where cassiterite, columbite and other saleable minerals are separated. The mineral composition and grain size range of concentrate recovered in the field plant thus affects mineral-dressing practice in the mill. For some time appreciable tonnages of semi-heavy minerals, along with a little columbite and less cassiterite, were lost from the jig plant by the practice of producing very high-grade cassiterite-columbite concentrates for despatch to the mill. This course was necessary because the mill had originally been designed to handle only concentrates from field sluice boxes, in which the recovery of columbite and semi-heavy minerals is

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poor. As the result of additional mineral-dressing research, outside the scope of the present paper, the mill has since been modified to deal with a wider range of variation in the composition of the jig concentrates received.

The main purpose here is to place on record a performance analysis of primary 4-cell jigs in terms of semi-heavy minerals. This analysis may be of practical interest outside the context of the plant sampled and the actual minerals determined, as, for instance, in other cases where semi-heavy minerals have to be recovered from comminuted ores with a light gangue, such as quartz, feldspar or calcite.

A performance analysis for the range of grain size 6 to 325 mesh is made in terms of three semi-heavy minerals present—zircon, anatase and topaz—covering the specific gravity range 4·5 to 3·5, recovered from a quartz sand. These results could be used to estimate the probable percentage recovery of economic and other semi-heavy minerals within this range of specific gravity and grain size from a quartz sand or from a gangue of about the same specific gravity. This range includes the other two titanium oxide minerals rutile and brookite; some of the complex oxides of titanium, niobium, tantalum and rare earths containing uranium and thorium, such as davidite and pyrochlore; various minerals found in the oxidized zones of sulphide orebodies, such as the copper minerals malachite and azurite, the zinc minerals willemite, hydrozincite, smithsonite and calamine, and the cobalt minerals heterogenite, sphaerocobaltite and cobaltian cornetite; three manganese ore minerals, psilomelane, manganite and rhodochrosite; two iron-ore minerals, limonite and siderite; also stannite, barite, witherite, celestite, strontianite, spinel, garnets, chromite, kyanite, corundum, chrysoberyl and diamonds. This indicates a wide scope for using jigs to advantage in the recovery of semi-heavy minerals.

The cassiterite and columbite in the samples discussed were also determined and a performance analysis of the primary jigs was made in terms of these two minerals for comparison with results for lighter minerals. As would be expected there is a progressive diminution in the percentage recovery with both finer grain size and lower specific gravity. This progressive diminution in the recovery per cell progressively increases the advantage of using a number of cells in series. Recovery of cassiterite (sp. gr. 7·0) is excellent down to 325 mesh and finer and it has now been demonstrated that recovery of even a mineral as light as topaz (sp. gr. 3·5) is well sustained down to about 100 mesh. In a previous paper[1] sampling data were presented which showed that attainment of a high percentage recovery in jigs from an unsized feed is dependent on a low slime content of the feed and that slime can be effectively removed with hydrocyclones without appreciable loss of heavy mineral. The significant relationship between that paper and the present is that both give data on recovery in jigs in relation to specific gravity and grain size and the number of cells in series; the first paper for the specific gravity range 7·0 to 4·5, the

[1]etc. See list of references at the end of the paper.

second extending it to a specific gravity of 3·5. It is the fundamental significance of the research results which is important, rather than details of the plant in which the research was carried out. However, a brief description of the plant is necessary for an understanding of some of the applications and implications of the results.

It does not seem likely that there are any appreciable differences between the recovery efficiencies of such well-established types of jigs as the Harz, Yuba, Ruoss, Pan-American and Bendelari. By different mechanical means and designs they all achieve practically the same type of pulsation in the jig bed; so that, although the sampling was carried out on Pan-American jigs, the results can be interpreted as representative of jig performance in general with an unsized feed of quartz sand or a gangue of about the same specific gravity containing less than 1 per cent of free heavy and semi-heavy minerals.

The screen area of each cell of the primary jigs sampled was 40 in. by 40 in. The length of stroke was $1\frac{1}{2}$ in. and the speed 120 strokes/min. Crushed massive hematite with a specific gravity of only 4·4 was used as ragging. This was roughly screened to $-\frac{3}{4}$ in. $+\frac{1}{2}$ in. and rested on a $\frac{3}{16}$-in by $\frac{1}{2}$-in slotted screen, the bed being about 2 in. thick. The character of the bed of ragging progressively changed as other heavy and semi-heavy minerals accumulated in it, especially coarse cassiterite at the upper end of the jig.

MATERIAL TREATED

About half the overburden had been stripped from the alluvial lead to be treated, which reduced what would otherwise have been a fairly high slime content in the feed to the plant. The composition of the feed reaching the plant was very variable, ranging from maximum slime content and minimum value after a fall of the paddock face to a minimum slime content and maximum value when mainly reconcentrated wash was reaching the sump. Under these conditions it was not possible to obtain a reliably representative head sample. The decomposed granite, for which the plant had originally been designed, had contained about equal proportions by weight of sand and slime. Observation of the plant working suggested that the alluvial feed was, on the average, considerably more sandy—probably about two-thirds to three-quarters sand. The alluvial lead had been formed by erosion and concentration of a contact zone between the Jos granite and the Rayfield–Gona granite, both of the Jos–Bukuru Younger Granite Complex. The Rayfield–Gona granite is here of higher than average grade in columbite and other accessory minerals. This location determined the heavy and semi-heavy mineral content of the alluvial wash, i.e. columbite and cassiterite in about equal proportions, an appreciable amount of monazite, an abundance of equiaxial zircon with a specific gravity of only 4·5 from the Rayfield–Gona granite, a little fine acicular zircon from the Jos granite and an abundance of topaz from the contact mineralization.

The average rate of feed to the plant was roughly about 40 cu. yd/hour, i.e. 10 cu. yd/hour for each 4-cell primary jig. This is less than on tin dredges, where rates of throughput normally range up to about 40 cu. yd/hour per 4-cell primary jig. After deducting the slime removed by the primary cyclones each of the 4-cell primary jigs sampled was receiving on the average roughly about 10 tons (dry weight) of sand per hour.

FLOWSHEET

The flowsheet of the plant incorporating the primary 4-cell jigs sampled and for which performance analyses are presented is shown in Fig. 1. This plant, as already noted, had formerly been used for treating high-grade columbite-bearing decomposed granite and had subsequently been altered and simplified to treat lower-grade alluvial wash containing cassiterite and columbite. Before primary jigging the alluvial material is screened on a ½-in rod deck grizzly and partly deslimed by single-stage cycloning. The recovery efficiency of the primary jigs is thus probably rather less than the optimum for the rate of feed which might be obtained with rather finer pre-screening and two-stage desliming.

Closed-circuiting through the secondary jigs, clean-up jig and table sequence to produce a high-grade cassiterite-columbite concentrate from the product of the primary jigs tends to force some fine columbite into the tailing. One of the objectives in sampling the hutch products of the primary jigs was to ascertain the total heavy and semi-heavy mineral assemblage being recovered at the primary jig stage. Given a sufficient demand and price for columbite the subsequent stages of concentration in jigs and shaking tables and the withdrawal of concentrate could be modified for optimum recovery of columbite. But this would mean accepting the greater part of the heavy and semi-heavy mineral content of the primary jig hutch products as concentrates for despatch to the mill.

As it did not pay with alluvium to use all the tables all the time the four shown in the right-hand side of the flowsheet were brought into use only for an occasional day shift, to help remove the accumulated circulating load of heavy and semi-heavy minerals. This flowsheet is not yet regarded as final; additional experimental alterations are made from time to time.

SAMPLING PROCEDURE

Equipment for the automatic sampling of the primary jigs could not be installed. To try and average out the effects of the variables already mentioned the total flow from each hutch spigot was taken for 5 seconds every half-hour over an 8-hour shift on four successive days, sampling one 4-cell jig each day. The four samples finally accumulated represented the first, second, third and fourth hutch spigot products and weighed, after desliming, 243, 150, 157 and 97 lb dry weight equivalent, respectively. At this plant it was not possible to obtain and value a similarly representative sample of the primary jig tailing, a common difficulty. It was much easier to sample the plant when it was treating decomposed granite, the grade of which was so remarkably uniform that relatively small samples taken for very short periods of time were adequately representative to give results of significant accuracy.

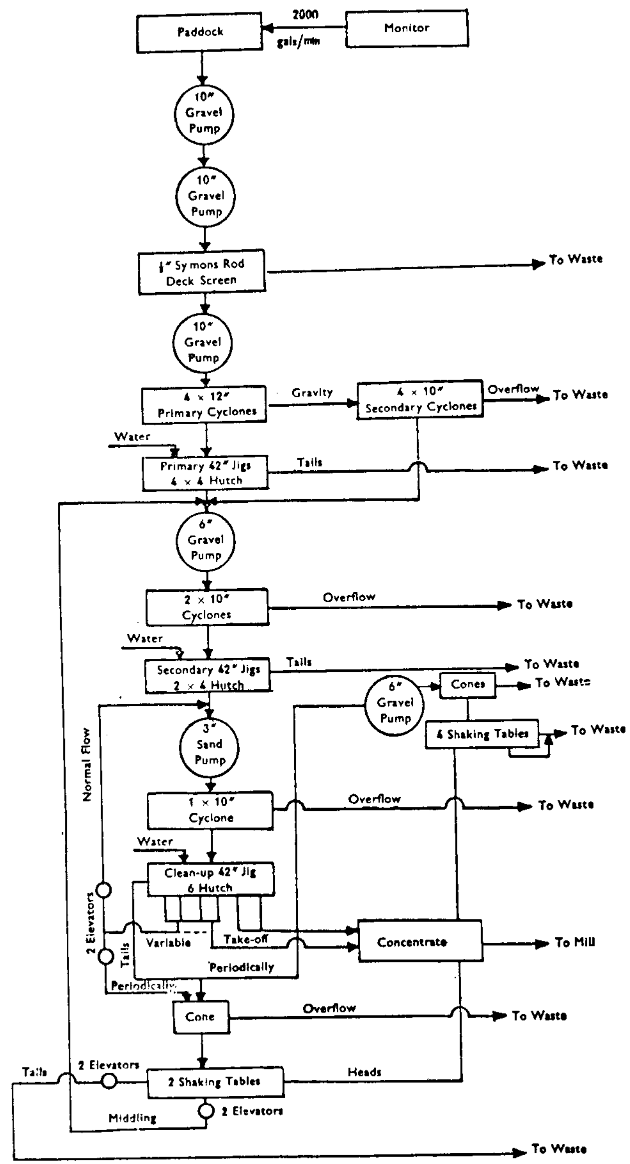

Fig. 1.—Flowsheet at the jig plant, Rayfield, Nigeria.

ANALYSIS OF SAMPLES

To deslime the samples a Mono pump delivering 8 gal/min at 8 lb/sq. in to a 75-mm cyclone fitted with a 19-mm vortex finder and a 15-mm spigot was used. This makes a split at about 20 μ for quartz and, of course, less for semi-heavy and heavy minerals. To avoid the possibility of choking the cyclone with coarse sand the slime was first thoroughly washed out of the sample. This dilute slime was then cycloned to retrieve losses of fine sand and semi-heavy and heavy mineral substantially free of slime. The material thus retrieved was then mixed again with the clean washed coarse sands. The portions of the deslimed sands taken for valuation from the samples from the four hutches in series, of progressively poorer grade, were $\frac{1}{16}$, $\frac{1}{8}$, $\frac{1}{8}$ and $\frac{1}{4}$. Later it was found that the number of grains of heavy and semi-heavy minerals present in the coarser screen sized fractions was insufficient for accurate valuation so, for grain sizes coarser than 12 mesh, half the first sample and all the remaining samples were used.

The samples taken for valuation were screen sized in a Rotap machine. Fractions coarser than 25 mesh were concentrated by hand panning and finer fractions were concentrated in a superpanner. In each case concentration was repeated several times and low-grade concentrates were accepted, in order to ensure quantitative recovery of the lightest semi-heavy mineral, topaz. After removing iron staining with dilute hydrochloric acid the heavy and semi-heavy minerals were separated as a sink product, first in bromoform and then cleaned in the heavier but more expensive methylene iodide. In the case of sized fractions coarser than 12 mesh the grains of the sink products were hand sorted and the various minerals weighed. Physical assays for the various minerals were made on the finer fractions by grain counting under a binocular microscope and converting the frequency percentages into weight percentages.

RECOVERY OF SEMI-HEAVY MINERALS

Although no tailing sample was taken it was possible to estimate roughly the percentage tailing loss of each mineral in each grain-size range from a consideration of the diminution in the amount recovered in each succeeding hutch. Where relatively very little of a specific mineral of a particular grain size reaches the fourth hutch the estimate of the quantity discharged in the tailing should not be very far out. This method is admittedly only a first approximation, particularly where the results are rather uneven, but the author feels justified in presenting the results in this form, as they can then be used most conveniently. The results obtained at least establish a case for a more thorough investigation of recovery in jigs of several cells, either by the automatic sampling of commercial plants and provision of laboratory equipment for valuing the resultant large samples or by full-scale laboratory experiments with controlled rates and composition of feed. In its coverage the present paper is essentially a preliminary exploration of a potentially wide field of investigation, which appears to warrant more intensive and extensive research.

The percentage recovery of three semi-heavy minerals, zircon, anatase and topaz, in each hutch over a range of grain sizes is recorded in Table I. This alluvial zircon was nearly all of the equiaxial type, which is abundant in Rayfield–Gona granite; its specific gravity (4·5) is lower than the average for zircon. The xenotime in the granite is also equiaxial and has a specific gravity of 4·5. As would be expected from the flowsheet and relative rates of feed, recovery of zircon in the primary jigs is not as good as that of xenotime in the secondary jigs, the figures for which have been published in the previous paper referred to.[1] It will be noted in particular from Table I that the recovery of the lightest semi-heavy mineral topaz, which has a specific gravity of only 3·5, is over 90 per cent for the coarsest sizes and is still over 80 per cent at 100 B.S. mesh. By extrapolation from these results it would appear that the recovery of some even lighter minerals in the specific gravity range 3·0 to 3·5 from a quartz sand or gangue should be worth investigating. This range includes helvite, apatite, sillimanite, andalusite, amblygonite, spodumene and fluorite. Even when the main economic mineral to be recovered is much heavier, the accompanying recovery of some semi-heavy minerals is of interest in terms of either their realizable value or their nuisance value in subsequent treatment of the concentrate.

For comparison with Table I, figures for the percentage recovery of the two heavier minerals, cassiterite and columbite, in the primary jigs are given in Table II. Here again tailing losses have been estimated on the basis of the diminution in the amount of mineral recovered in successive hutches. As would be expected from the nature of the feeds and conditions of operation percentage recoveries of these two minerals in the primary jigs was not quite as good as in the secondary jigs recorded in the previous paper.

The degree of irregularity in the results in Tables I and II illustrates the difficulty of carrying out such fundamental research on a commercial production plant with a variable feed and particularly without provision for automatic sampling and for measurement of rates of tailing discharge. The relative percentages of the various heavy and semi-heavy minerals in the total hutch products from the primary jigs are given in Table III. The amount of monazite present, although relatively small, has a potential realization value in normal times sufficient to pay for the greater part of the total mill cost of the subsequent separation of the principal economic minerals, cassiterite and columbite, at shipping grades. In this Nigerian inland minefield anatase, topaz, zircon, ilmenite and magnetite have not at present any realizable value, but the anatase at least is potentially saleable as commercial 'rutile' if it can be separated as a clean enough concentrate. Topaz may possibly be of commercial interest for conversion to mullite or as an abrasive.

The main valuable minerals, cassiterite and columbite, amount to less than 10 per cent of the total. By closed circuiting and tabling and the use of $\frac{1}{4}$-in cassiterite as ragging in the first two hutches of the clean-up

TABLE I.—*Performance analysis of primary jigs: Semi-heavy minerals*

B.S. sieve	Mineral	Sp. gr.	Distribution: Percentage recovered: Hutch number 1	2	3	4	Total: Zircon	Total: Anatase	Total: Topaz	Percentage lost: Zircon	Anatase	Topaz
+ 6	Zircon	4·5	*	*	*	*	*			*		
	Anatase	3·9	*	*	*	*		*			*	
	Topaz	3·5	68·7	17·6	7·4	3·8			97·5			2·5
− 6 + 8	Zircon	4·5	100·0	—	—	—	100·0			—		
	Anatase	3·9	*	*	*	*		*			*	
	Topaz	3·5	83·7	8·3	2·2	3·6			97·8			2·2
− 8 + 12	Zircon	4·5	92·7	7·3	—	—	100·0			—		
	Anatase	3·9	*	*	*	*		*			*	
	Topaz	3·5	78·4	8·8	5·1	4·4			96·7			3·3
− 12 + 16	Zircon	4·5	79·3	19·0	0·9	0·6	99·8			0·2		
	Anatase	3·9	*	*	*	*		*			*	
	Topaz	3·5	69·8	14·1	6·3	5·3			95·5			4·5
− 16 + 25	Zircon	4·5	77·4	19·9	1·4	1·0	99·7			0·3		
	Anatase	3·9	*	*	*	*		*			*	
	Topaz	3·5	71·5	15·1	6·0	4·3			96·9			3·1
− 25 + 52	Zircon	4·5	77·4	17·8	2·2	1·8	99·2			0·8		
	Anatase	3·9	53·9	11·8	21·4	6·4		93·5			6·5	
	Topaz	3·5	62·7	16·3	8·7	6·2			93·9			6·1
− 52 + 72	Zircon	4·5	53·9	33·4	4·9	4·4	96·6			3·4		
	Anatase	3·9	45·3	35·4	7·2	6·1		94·0			6·0	
	Topaz	3·5	50·4	16·4	10·5	9·0			86·3			13·7
− 72 + 100	Zircon	4·5	58·9	22·4	5·6	6·4	93·3			6·7		
	Anatase	3·9	40·9	25·4	7·4	9·5		83·2			16·8	
	Topaz	3·5	42·6	21·0	11·8	9·2			84·6			15·4
− 100 + 120	Zircon	4·5	37·1	24·1	15·2	9·0	85·4			14·6		
	Anatase	3·9	26·0	25·6	10·4	10·4		72·4			27·6	
	Topaz	3·5	24·3	20·3	10·7	10·5			65·8			34·2
− 120 + 150	Zircon	4·5	45·1	19·3	9·3	9·5	83·2			16·8		
	Anatase	3·9	15·7	21·3	13·9	10·3		61·2			38·8	
	Topaz	3·5	28·3	22·1	14·1	10·4			74·9			25·1
− 150 + 170	Zircon	4·5	31·5	28·7	11·2	10·2	76·6			23·4		
	Anatase	3·9	16·4	12·7	8·3	8·7		46·1			53·9	
	Topaz	3·5	8·6	10·1	6·6	6·9			32·2			67·8
− 170 + 240	Zircon	4·5	25·5	17·1	12·7	10·5	65·8			34·2		
	Anatase	3·9	12·4	14·8	7·1	11·2		45·5			54·5	
	Topaz	3·5	2·8	6·2	3·6	3·8			16·4			83·6
− 240 + 300	Zircon	4·5	9·7	10·4	8·9	7·6	36·6			63·4		
	Anatase	3·9	7·9	16·6	8·4	12·2		45·1			54·9	
	Topaz	3·5	3·7	13·8	9·2	7·1			33·8			66·2
− 300 + 325	Zircon	4·5	6·2	13·8	14·6	8·4	43·0			57·0		
	Anatase	3·9	4·6	17·8	13·1	8·5		44·0			56·0	
	Topaz	3·5	3·6	20·7	10·1	8·4			42·8			57·2
Recovery lb/hr per jig	Zircon	4·5	0·93	0·50	0·27	0·26						
	Anatase	3·9	0·06	0·07	0·04	0·04						
	Topaz	3·5	1·31	0·61	0·36	0·30						
Grade lb/ton	Zircon	4·5	3·04	2·66	1·38	1·85						
	Anatase	3·9	0·20	0·36	0·18	0·33						
	Topaz	3·5	4·30	3·24	1·82	2·50						
Tons/hr	Sand	2·6	0·31	0·19	0·20	0·12						

Notes:
*Not present in significant amounts.
Dimensions of hutches, 42 in. by 42 in.
Speed, 120 rev/min.
Stroke, 1⅛ in.
Ragging, − ⅜ in. + ⅛ in. hematite.

TABLE II.—*Performance analysis of primary jigs: Heavy minerals*

B.S. sieve	Mineral	Sp. gr.	Distribution: Percentage recovered: Hutch number 1	2	3	4	Total: Cassiterite	Total: Columbite	Percentage lost: Cassiterite	Columbite
+ 6	Cassiterite	7·0	*	*	*	*	*		*	
	Columbite	5·5	*	*	*	*		*		*
− 6 + 8	Cassiterite	7·0	100·0	—	—	—	—		—	
	Columbite	5·5	*	*	*	*		*		*
− 8 + 12	Cassiterite	7·0	96·3	2·9	0·5	0·3	100·0		—	
	Columbite	5·5	100·0	—	—	—		100·0		—
− 12 + 16	Cassiterite	7·0	93·2	4·4	2·4	—	100·0		—	
	Columbite	5·5	100·0	—	—	—		100·0		—
− 16 + 25	Cassiterite	7·0	94·8	3·7	0·4	0·9	99·8		0·2	
	Columbite	5·5	75·3	12·4	2·5	5·2		95·4		4·6
− 25 + 52	Cassiterite	7·0	91·4	4·8	2·7	0·9	99·8		0·2	
	Columbite	5·5	81·3	10·2	3·0	3·5		98·0		2·0
− 52 + 72	Cassiterite	7·0	80·1	8·8	8·6	1·7	99·2		0·8	
	Columbite	5·5	77·6	12·6	4·3	3·5		98·0		2·0
− 72 + 100	Cassiterite	7·0	68·6	5·8	8·2	7·7	90·3		9·7	
	Columbite	5·5	69·5	18·9	4·8	4·0		97·2		2·8
− 100 + 120	Cassiterite	7·0	48·2	14·7	12·0	9·3	84·2		15·8	
	Columbite	5·5	50·6	19·3	12·1	7·8		89·8		10·2
− 120 + 150	Cassiterite	7·0	50·3	11·3	8·7	9·9	80·2		19·8	
	Columbite	5·5	64·0	17·0	6·5	6·2		93·7		6·3
− 150 + 170	Cassiterite	7·0	49·2	15·9	11·3	9·0	85·4		14·6	
	Columbite	5·5	41·1	26·2	8·3	9·2		84·8		15·2
− 170 + 240	Cassiterite	7·0	58·6	12·0	7·6	8·6	86·8		13·2	
	Columbite	5·5	34·6	21·5	11·7	10·2		78·0		22·0
− 240 + 300	Cassiterite	7·0	44·6	16·4	18·3	8·4	87·7		12·3	
	Columbite	5·5	19·6	21·7	20·0	10·5		71·8		28·2
− 300 + 325	Cassiterite	7·0	31·4	13·8	18·8	10·4	74·4		25·6	
	Columbite	5·5	12·5	25·4	29·7	10·2		77·8		22·2
Recovery lb/hr	Cassiterite	7·0	0·19	0·01	0·01	0·005				
	Columbite	5·5	0·16	0·09	0·06	0·04				
Grade lb/ton	Cassiterite	7·0	0·62	0·06	0·05	0·04				
	Columbite	5·5	0·52	0·46	0·29	0·30				
Tons/hr	Sand	2·6	0·31	0·19	0·20	0·12				

Notes:
*Not present in significant amount.
For settings see Table I.

jig the average grade of concentrate withdrawn and sent to the mill is brought to over 60 per cent cassiterite and columbite together. An appreciably higher field recovery of columbite and cassiterite could be achieved by accepting a lower-grade field concentrate, but the sampling results recorded in Table III indicate that the lower limit in this direction, even if excluding more than a small quantity of quartz, would be a very low-grade concentrate indeed. Alternatively, both high- and low-grade concentrates could be produced concurrently, the first for immediate treatment and the second for stockpiling. The introduction of jig plants has of necessity therefore been accompanied by research work on mineral

TABLE III.—*Heavy and Semi-heavy Minerals in Total Hutch Products*

Mineral	*Relative Percentages*	
Topaz	42·90	
Zircon	31·97	
Ilmenite and magnetite	11·60	
Cassiterite	3·65	9·32
Columbite	5·67	
Anatase	3·37	
Monazite	0·81	
Xenotime	0·03	
Orangite	Tr.	
Total	100·00	

dressing practice to develop procedures suitable for various grades of jig concentrates, although details of these investigations are outside the scope of the present paper.

APPLICATIONS ON THE JOS PLATEAU

One of the purposes of the paper is to draw attention to the impact on subsequent mineral dressing practice of the remarkable efficiency of jigs to recover semi-heavy minerals. Optimum recovery of columbite in a jig plant, including some tables if necessary, will be accompanied by a high percentage recovery of all the heavy and semi-heavy minerals present in the feed. These other minerals may be considerably in excess of the amount of cassiterite and columbite and their presence tends to increase the cost of mineral dressing. The possibility of separating other saleable and potentially saleable minerals has therefore to be kept in mind. Even within the confines of the Jos Plateau the heavy mineral content varies considerably between different alluvial leads. This arises from the considerable differences in the primary accessory mineral assemblages in the various granites and allied rocks comprising the Younger Granites, as described elsewhere by the author and others.[2,3] In places the alluvial mineral content of payable leads will also include heavy and semi-heavy minerals shed from the Older Granites and from the Basement Complex.

The production of a cassiterite-columbite concentrate in the field plant utilizes only one physical property of the minerals, i.e. specific gravity. It is a cheap method, but an appreciable amount of columbite already recovered in the primary jigs is lost again during upgrading in the field plant if the circulating load of semi-heavy minerals is excessive. The loss of other saleable and potentially saleable minerals such as monazite and anatase and possibly topaz must also be taken into account. The more effective, but more expensive, procedure is to accept low-grade concentrates of heavy and semi-heavy minerals plus a little sand for transport to the mill where separations can be more effectively carried out by making use of *three* physical properties, i.e. specific gravity, magnetic permeability and electrical conductivity. Furthermore, such separations can be aided there by close sizing. Then, as a last resort, the electrical conductivities and magnetic permeabilities can, for some minerals, be modified by heat. The various alluvial minerals can conveniently be considered in descending order of specific gravity.

Cassiterite, sp. gr. 7·0

Once recovered in the primary jigs, cassiterite is not easily lost again in appreciable quantity. Closed circuiting does force a little very fine cassiterite into the clean-up jig tailing, but if this tailing is tabled then nearly 100 per cent of that loss is recovered in the black band at the head of the table. For a recovery of cassiterite alone, only slightly below the practical optimum, there is thus no need to accept very large amounts of semi-heavy minerals in the concentrate sent to the mill.

Columbite, sp. gr. 5·5

Fine columbite recovered in the primary jigs is far more easily lost in subsequent closed circuiting employed to produce a high-grade cassiterite-columbite concentrate from the field plant. Even if the clean-up jig tailing is tabled, minerals appreciably lighter than columbite cannot be rejected as a table middling without some loss of columbite.

Monazite, sp. gr. 5·1

The percentage recovery of monazite in jigs and on tables should be at least as good as that for columbite. Although slightly lighter, it is typically equiaxial, whereas even water-worn columbite still contains a lot of tabular and rather acicular grains. As monazite is normally saleable it will offset the higher cost of dressing lower-grade concentrates.

Monazite is a weakly magnetic non-conductor. The Carpco model HT 460 high-tension separators now installed in the mills make a very clean non-conductor product consisting mainly of zircon (plus topaz if present) with the subordinate monazite. A monazite concentrate can then be recovered by magnetic separation of the non-conductor product. The presence of magnetic zircon, which is abundantly shed from some areas of Rayfield–Gona granite, would tend to make the monazite concentrate low-grade. If income from monazite were sufficient it might pay to isolate and treat concentrates from leads rich in magnetic zircon separately. Alternatively, flotation might be used to separate the phosphate monazite from the silicate zircon when the latter is magnetic.

Magnetite, sp. gr. 4·8–5·1

This mineral is so easily removed by magnetic separation that increased recovery along with columbite will have only a very minor effect on subsequent mineral-dressing costs.

Ilmenite, sp. gr. 4·7

A higher recovery of columbite in the field plant will inevitably mean a higher recovery of ilmenite. If the non-conductors are first removed by high-tension separation, then the large capacity Exolon induced-roll magnetic separators installed in the mills will cheaply remove from the conductor product a magnetic product consisting mainly of ilmenite, columbite and magnetic cassiterite. Most of the magnetic cassiterite is normally separated on Airfloat tables. The magnetic fractionating of ilmenite from columbite, which is usually carried out on a belt-type magnetic separator, is slow. Some middlings which are difficult to separate may tend to accumulate. Heat treatment to increase the magnetic permeability of ilmenite[4] should speed up this separation. It is already being tried out at plant scale by one company on the Jos Plateau.

Zircon, sp. gr. 4·5–4·7

As shown in Table III, jig efficiency in recovering zircon might greatly increase the tonnage of concentrate sent to the mills. Most of the zircon *can* be rejected to tailings by closed circuiting in the clean-up jig in the field plant, but only at the cost of losing some fine columbite.

An alternative recently successfully tried out is to reduce the circulating load of zircon by withdrawing a zircon-rich jig concentrate from *above* the ragging in the clean-up jig with cup and gate fittings and also by withdrawing a zircon-rich middling from the table. Both these concentrates contain a little columbite and less cassiterite. They are currently being sent to the mill separately for stockpiling pending experiments on dressing them (neither of these recent experimental innovations is shown in the flowsheet, Fig. 1). As mentioned earlier the flowsheet is not yet regarded as final.

Although this commercial production plant has not the flexibility of a true pilot plant it is almost constantly subject to some degree of experimentation. However, zircon and particularly magnetic zircon is no longer the problem it used to be in the mills. It can now be separated effectively from cassiterite and columbite in Carpco model HT 460 high-tension separators. Big variations have been found in the amount of zircon yielded by different alluvial leads.

Rutile, sp. gr. 4·25. Anatase, sp. gr. 3·9

These two minerals have the same composition TiO_2. Coarse rutile is known to occur in several localities on the Jos Plateau. So far anatase has only been found in grain sizes finer than about 25 mesh. Both minerals are normally non-magnetic conductors, but it has been found that part of this anatase is magnetic. In view of their low specific gravities it should not be difficult to separate rutile and anatase from columbite and cassiterite on Airfloat tables. The possibility of dressing one or both to saleable grade has not yet been investigated. A likely difficulty would be the presence of iron oxides of about the same specific gravity. The purity of the minerals themselves has not yet been ascertained by chemical assay.

Topaz, sp. gr. 3·5

If topaz is present in the wash a fairly high percentage of it will be recovered in the primary jig hutch products. Thereafter, if it is not bled off, it will tend to accumulate in any system of closed circuiting. Table III gives an example of a large amount of topaz recovered in the primary jig hutch products. In another jig plant on the Jos Plateau, embodying closed circuiting in jigs, but without tables for bleeding off semi-heavy minerals, the bed of 'sand' on top of the ragging in the clean-up jig was found to be mainly topaz. This topaz-rich layer is now being bled off through cup and gate fittings. As it contains both cassiterite and columbite it is sent to the mill for stockpiling and experiments on dressing. When very rich material is being treated in the field jig plant the gate product from near the top end of the clean-up jig is sometimes rich enough in cassiterite and columbite to be bulked with the spigot product for despatch to the mill for normal treatment there.

Very little zircon was present in this topaz-rich alluvial lead. This illustrates the variation which occurs between the heavy mineral contents of different leads, as previously mentioned.

The effect of this circulating load of topaz on columbite recovery in the clean-up jig has not yet been investigated. On the basis of Taggart's 'concentration criterion' (ratio of the higher to the lower specific gravity, each diminished by one)[5] it would be expected that the percentage recovery of columbite from a topaz sand would be about the same as the percentage recovery of anatase from a quartz sand, an interesting application of the results for anatase recorded in Table I. A sample of the up-graded concentrate from the clean-up jig first and second hutches sent to the mill contained 71·2 per cent cassiterite, 12·3 per cent columbite, 8·7 per cent topaz and only 3·1 per cent zircon. The gate product contains only a few per cent of cassiterite and columbite. It has been found that this topaz can readily be removed on both wet and Airfloat tables, so that, although the reduction in the circulating load of topaz appreciably increases the tonnage of concentrate sent to the mill, its separation does not normally present any special difficulty. However, the method of dealing with it has not yet been finalized.

From what has been said it is apparent that the most profitable grade of concentrate to withdraw from a jig plant will vary with the mineral content of different alluvial leads and the market demand and price for cassiterite, columbite, monazite and possibly also rutile, anatase and topaz. The semi-heavy minerals can to some extent be rejected cheaply by closed circuiting in the clean-up jig in the field plant but only at the expense of losing some fine columbite.

OTHER APPLICATIONS

Large-scale bucket dredging is a very cheap method of mining and recovering such heavy minerals as gold and cassiterite from alluvial deposits. In some cases, as in New Zealand, the cost is as low as 5d. per cu. yd. Jigs have been used on bucket dredges for many years, but until recently inadequate attention has been paid to the effect of the slime content of the feed and also the rate of feed on tailing losses. Recoveries may therefore have been appreciably less than the optimum obtainable with jigs. A recent development in the U.S.A.[6] is the use of a bucket dredge equipped with jigs to work an alluvial deposit in which the principal ore mineral is euxenite. Dana[7] gives the specific gravity range of euxenite as 4·7 to 5·0. The performance analyses of primary jigs submitted in