INFLUENCE OF TWINNING ON THE USABILITY OF QUARTZ FROM VARIOUS LOCALITIES

Cornelius S. Hurlbut, Jr.
*Harvard University, Cambridge, Massachusetts.**

Abstract

In the execution of a development contract for the Long Branch Signal Laboratory over 3,000 quartz crystals from sixteen localities were studied. The purpose of the study was to determine, if possible, which localities yielded the best quartz for the manufacture of oscillator plates. The determination of the percentages of Dauphiné and Brazil twinning constituted the main part of the problem. Considerable variation in amount of twinning was found from one locality to another. Crystal habit can be correlated in a general way with the percentage of Dauphiné twinning. The presence of minor elements, determined spectrographically, appears to be unrelated to other observed properties.

Introduction

During the war years of 1942 to 1945 quartz crystals of high quality were in tremendous demand for manufacture into oscillator plates for the control of radio frequencies. The phenomenal rise of this industry and methods used to convert laboratory techniques into industrial processes are described in a symposium in the May-June 1945 issue of The American Mineralogist.

Of the several Government agencies procuring crystal oscillators, the Signal Corps obtained by far the largest quantity and was thus vitally interested in perfecting high quality oscillators at lower cost. To this end the Long Branch Signal Laboratory† devoted its efforts. The data presented in this paper were obtained in the carrying out of a development contract for the Signal Laboratory by the Cambridge Thermionic Corporation of Cambridge, Massachusetts. It was the writer's privilege to direct the work and correlate the results.

The effort to locate and develop domestic sources of quartz crystals was unsuccessful and thus all but minor amounts were imported, mostly from Brazil.

Because of the method by which quartz is mined, collected, graded and sold, any given shipment reaching the United States is a fairly good cross-section of Brazilian quartz. That is, it contains crystals of comparable size and quality, but from many different and unknown localities. Since it is impossible to determine the presence or absence of Dauphiné twinning by usual inspection methods, it plays no part in the normal quality

* Contribution from the Department of Mineralogy and Petrography, Harvard University, No. 279.

† Now Frequency Control Branch of the Squier Signal Laboratory.

grading. Might it not be true that quartz from one Brazilian locality is of superior quality while that from another is decided inferior from the point of view of Dauphiné twinning?

If a careful study could be made of quartz taken from different localities, it might show each lot to have a group of properties peculiar to itself. These properties considered collectively might show quartz from one locality to be much more desirable than that from another for the manufacture of quartz oscillator plates. If mining development work is to be done in the future, the report of characteristics of quartz from various localities would serve as a sound basis for predicting which locality would give the greatest return for money and effort expended.

Of the several individuals in the Signal Corps interested in such a study of quartz, Lt. Colonel Allyn C. Swinnerton, Captain Joseph S. Lukesh and Dr. Richard E. Stoiber were most instrumental in initiating the program. Minerals Division of Foreign Economic Administration was likewise highly interested in the determination of quartz characteristics as related to locality. In this agency Dr. Carl Tolman in Washington and Dr. Robert D. Butler in Brazil arranged for the collection and identification of specimens and for the special handling required.

The securing of various lots of quartz from known localities and transporting them to the United States presented many difficulties of considerable magnitude. That portion of the problem which was taken care of by FEA, as well as the geologic nature of the deposits, is beyond the scope of this report and is not touched upon.

Procedure

Altogether 3015 quartz crystals weighing 2157 pounds were studied. They came from 16 localities, 13 of which were in Brazil, 2 in Guatemala, and 1 in Columbia, as listed in Table 1.

It should be pointed out that lots were representative of the localities and no effort was made to grade them. Indeed, it was only with considerable difficult that the Foreign Economic Administration was able to collect and ship these sample lots to the United States and at the same time preserve their identity. Thus in a given lot were crystals of all sizes, some high quality, some low quality if such were representative.

Each crystal on arrival was inspected visually and a record made of crystal forms and habit, flaws, ghosts and any unusual features. Before cutting, each lot was photographed; a typical sample lot is shown in Fig. 1. Wafers suitable for oscillators, about .050″ thick were then cut from the crystals and etched in ammonium bifluoride to make twinning visible.

TABLE 1. QUARTZ STUDIED*

Lot No.	No. of Crystals	Weight in Pounds
1	200	116.05
2	200	123.86
3	200	116.27
4	200	115.72
5	199	132.55
6	200	144.10
7	170	109.01
8	146	226.93
9	350	185.35
10	135	197.11
11	173	109.23
12	166	86.79
13	200	123.09
14	175	110.81
15	195	165.20
16	106	94.83
	3015	2156.90

* Lots 1 to 13 are from Brazil, lot 14 from Colombia, and lots 15 and 16 from Guatemala. The names of specific localities are withheld for security reasons.

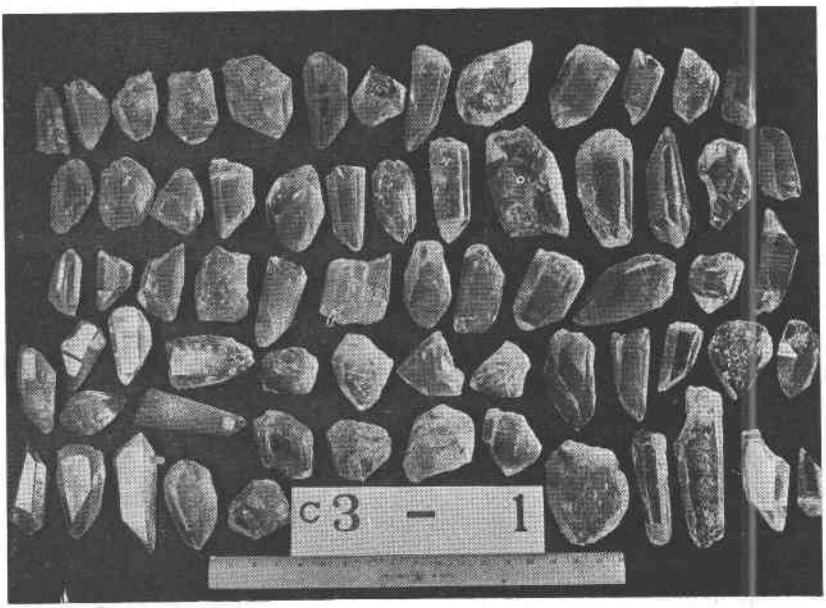

FIG. 1. Typical sample lot of quartz.

Those portions of the wafers that were in twinned position to the main part were marked out with pencil as shown in Fig. 2. Although emphasis was laid on determining the percentage of Dauphiné (electrical) twinning, since etching is the only way to render it visible, Brazil (optical) twinning was also marked out and recorded. The determination of the volume percentages of these two types of twinning in the lots from the various localities was the chief purpose of the investigation. It also proved to be the most time-consuming part, for over 52,000 slices were examined individually. After trying several methods that proved impractical, the

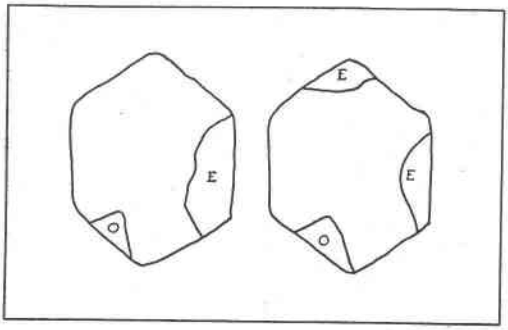

FIG. 2. Twinning marked out in quartz wafers.
E is Dauphiné twinning; *O* Brazil twinning.

following procedure was used to obtain the volume percentage of both types of twinning in each crystal.

After being marked for twinning, the slices were inserted in a photographic enlarger in the position where one would normally place the film. The images of the slices, magnified to three times the area, were projected on white paper and a tracing made. Figure 2 is such a tracing reduced to one-sixth, or to one-half the size of the slices themselves. After all the slices from a given crystal had been thus outlined, the tracings were cut out with scissors and separated into three groups: 1. That representing the good portion of the slice, 2. That representing Dauphiné twinning, 3. That representing the portion rendered useless by Brazil twinning. Each of the above groups was then weighed separately on a chemical balance; and, making the assumption that a given sheet of paper was of uniform thickness and weight, the percentages of Dauphiné and Brazil twinning were then determined for the whole crystal.

The above method was checked against a similar one using a polar planimeter to determine the areas of the projected slices. The two methods showed a remarkably close agreement and it is probable that the percentages of twinning are accurate to within one or two per cent of the markings on the slices. Additional error is obviously involved in the original marking out of the twinning, but it is believed that that is no more than two or three per cent; thus making the accumulative error not greater than five per cent.

The number of oscillator plates that could be obtained from a pound of quartz from a given locality was of as much interest to the Signal Corps as the percentage of twinning. One might expect a direct relation of the two but other things such as flaws, shape and distribution of twinning enter in as complicating factors. Thus a record was kept of blanks cut from each crystal. A "blank" as spoken of here is an oriented rectangular portion of a slice that will yield a finished oscillator 0.5×0.6 inches. From the manufacturer's point of view the best quartz is that yielding the most blanks per pound or rather per dollar. In general, the larger the crystal the more blanks per pound but not necessarily per dollar, for the cost per pound rises rapidly in the larger sizes.

The handling of large quantities of quartz crystals from known localities presented a unique opportunity to obtain data of interest even though they were not pertinent to the main problem. Consequently, blanks were selected from each lot of quartz and finished to a frequency of 7640 KC. Two of these finished oscillators from each lot of quartz were then exposed to x-ray irradiation, after the method described by Frondel,* to determine the maximum change in frequency. After irradiation one of the two oscillators was powdered and subjected to spectrographic analysis to determine the presence of minor elements.

* Clifford, Frondel, Final frequency adjustment of quartz oscillator-plates: *Am. Mineral.*, 30, 427–431 (1945).

Data Obtained

In Table 2 the grading of the National Bureau of Standards for each lot is listed together with the percentages in each size group. Table 3 summarizes the data obtained on twinning, and the yield of blanks per pound. It is believed that the method of cutting gave the highest possible

Table 2. Grades and Sizes of Quartz

Lot No.	Wt. % of Faced Quartz	National Bureau of Standards Grades in Weight Per Cent					Size of Crystals in Per Cent		
		1	2	3	BG	S8	100–200 g.	200–300 g.	300–500 g. & over
1	100.0		31.8	38.4	15.7	14.1	29.1	2.3	68.6
2	100.0	2.1	51.7	15.3	10.0	20.9	30.0		70.0
3	100.0	2.1	51.6	13.1	21.5	11.7	30.6		69.4
4	100.0	2.9	48.3	4.9	38.0	5.9	29.5		70.5
5	72.3	11.1	74.5	14.0	.4			39.6	60.4
6	46.7	4.8	72.2	18.5	4.5			41.1	58.9
7	35.5	41.2	44.0	12.2	2.6			52.4	47.6
8	17.4	1.2	92.0	6.8				4.3	21.7
									3– 500 g.
									74.0
									500–4000 g.
9	94.9		49.7	11.6	15.5	23.2	37.3		62.7
10	93.1		81.0	18.2	.8			10.6	89.4
									300–5000 g.
11	100.0	1.7	61.4	12.5	9.4	15.0	22.5	.5	77.0
12	100.0	3.3	53.3	8.2	20.7	14.5	34.0	66.0	14.8
13	100.0		70.2	3.4	16.4	10.0	26.2		73.8
14	100.0	23.7	43.7	10.9	12.8	8.9	8.9	40.2	50.9
									300–2000 g.
15	54.7		4.1	95.9				28.9	71.1
									300–2000 g.
16	51.3	5.5	81.8	10.7		2.0	2.0	27.5	75.5
									300–3000 g.

yield. It should be pointed out, however, that there are several methods of sectioning quartz and that another manufacturer using a different method might have obtained fewer blanks from the same quartz.

In Table 3 can be found the answer to the main question, namely; Is quartz from one locality better than that from another for the manufacture of oscillator plates? Neglecting the Guatemala and Columbian quartz* (Lots 14–16), which proved to be definitely inferior, the yield of blanks per pound ranged from 57 to 85. One can see at a glance that there is far from a perfect correlation between percentage of twinning and blanks per pound. Such a condition might well be expected since locality

TABLE 3. ANALYSES OF SLICES

Lot No.	Volume % Not Twinned	Volume % Twinning		No. of Blanks per Pound	Scrap Wt. %
		Dauphiné	Brazil		
1	78.41	20.07	1.52	69.9	9.34
2	86.72	11.91	1.37	85.2	10.31
3	79.58	16.59	3.83	68.7	9.86
4	90.70	8.27	1.03	74.1	8.26
5	84.99	12.90	2.11	76.9	11.41
6	85.94	6.62	7.44	57.4	18.46
7	84.07	12.07	3.86	57.3	16.57
8	90.57	9.24	.19	56.8	22.34
9	85.40	8.56	6.04	66.9	12.54
10	80.03	9.24	10.73	63.0	9.51
11	85.28	3.43	11.29	63.7	11.27
12	89.60	2.91	7.49	65.7	14.84
13	91.19	4.79	4.02	68.9	13.20
14	70.88	8.53	20.59	47.3	13.37
15	15.31	84.41	.28	6.8	11.50
16	75.11	21.45	3.44	49.2	16.61

is only one of several variables involved. The other major variables are:

1. Proportion of faced and unfaced quartz
2. Grade
3. Size
4. Distribution of twinned area

1. *Proportion of faced and unfaced quartz.* In cutting faced quartz, the crystals were mounted on natural faces and no preliminary cuts were made. Unfaced quartz required that a face be sawn parallel or nearly parallel to $\{11\bar{2}0\}$ on which to mount it and a face be cut parallel to $\{0001\}$ for orientation purposes. The amount of scrap from unfaced quartz was thus large, reducing proportionally the amount to be cut into wafers.

* It would be unfair from this study to make the generalization that all quartz from Guatemala and Columbia is low grade, since such limited quantities were available.

2. *Grade.* Since each lot of quartz was a representative sample of the locality from which it came, several grades were present in each. The amount of quartz of each grade in the various lots had been determined both in Brazil and at the National Bureau of Standards in Washington. The grade was based on the estimated usable percentage from the point of view of flaws, inclusions and Brazil twinning. In Table 1 the area of of the slices listed as "not twinned" means that it is usable as far as twinning is concerned. It does not mean that it is free from flaws and imperfections that might render it useless for cutting a blank. When blanks were marked out on the slices, the flaws were avoided as well as the twinning; and thus a badly flawed crystal even with very little twinning would show a low yield of blanks.

3. *Size.* The crystals in all lots showed a considerable range in size, and an even greater range from one lot to another. The weight of individual crystals varied from 100 grams to over 4000 grams. For a fair comparison of one lot with another, only those crystals of comparable size should be considered, for, other things being equal, it appears that the 300- to 500-gram quartz has the best yield of blanks per pound.

4. *Distribution of twinning.* The areal distribution of twinning in a given slice has almost as great an effect on the number of blanks obtained as the percentage of twinning. Isolated patches of Dauphiné twinning or long slender spines of Brazil twinning may render the slice useless even though the total area of twinned portion may be only a few per cent.

Comparison of Lots

It is interesting to note the effects of the differences in the four variables mentioned above in comparing one lot with another. Although it is difficult to specify how one variable affects the results, or how much one offsets or supplements another, still some lots in comparison show definite reasons for the results obtained.

For example, compare Lots 2 and 4. Both are 100 per cent faced and roughly the same as to size; the only major difference lies in the grade, with Lot 2 having a considerably better average. Even though Lot 4 has less twinning, the yield of blanks per pound for Lot 4 is 74.1 against 85.2 for Lot 2. The best explanation seems to lie in the grade difference (although the areal distribution of twinning in the slices may have influenced the results), and one can conclude the locality of Lot 2 yields a somewhat higher grade of quartz than the locality of Lot 4.

Again, comparing Lot 5 with Lot 6, the former has 25.6 per cent more faced quartz and also an advantage of 6.3 per cent of grade 1. The sizes and other grades are roughly comparable. Both lots have about the same percentage of twinning, yet Lot 5 yielded 19.5 more blanks per pound. This large difference may be in the fact that Lot 6 is only 46.7 per cent faced as against 72.3 per cent for Lot 5. This would also account for the difference in scrap, 18.46 per cent for Lot 6, 11.41 per cent for Lot 5. Similar results in blanks per pound and in per cent scrap are noted for all lots with low percentages of faced quartz, even when the percentage of twinning is low.

Compare Lot 6 and Lot 7. Lot 6 has 11.2 per cent more faced qaurtz and 11.3 per cent more in 300–500 gram size. Against these advantages is a disadvantage of 36.4 per cent in Grade 1. The percentages of twinning are comparable. Blanks per pound in the two lots are the same, and it appears that here the variables offset each other almost exactly.

Likewise a comparison of Lots 1 and 3 shows a similar yield of blanks. Both are 100 per cent faced and the sizes and percentage of twinning are comparable. The variation in the grades of the two lots is the only major difference and these equalize one another to make quartz from both localities equally desirable.

Each lot of quartz as received was packed in several boxes and each box was handled separately. Two boxes in Lot 2 and one in each of Lots 4 and 5 gave approximately 90 blanks per pound, the highest yield. In each of these the quartz was 300–500 gram. In none of the boxes containing smaller or larger quartz did the number of blanks approach this figure.

Effect of Habit on Twinning

In the initial inspection of the quartz a record was made of the habit. Crystals were divided into two groups: one "candle" quartz, long relatively slender crystals with tapering prism faces; and, two, "equidimensional," in which the dimension along the *c*-axis was roughly equal to the dimension along the *a*-axis, and the prism faces were not markedly tapered. Obviously, unfaced quartz could not be classed in either group. It appeared as work progressed that in general the "candle" quartz was superior to the equidimensional types of similar weight and an analysis of the final data was made to determine whether or not this was a valid conclusion.

This seemed particularly true of Lots 1–4, which were 100 per cent faced and records were available on the eleven individual boxes that comprised them. In Fig. 3 the percentage of Dauphiné twinning is plotted against the percentage of "candle" quartz. There is far from a regular distribution of points, but there is a trend showing that the higher percentage of "candle" quartz, the lesser the amount of Dauphiné twinning.

Among those who have examined large quantities of quartz crystals, it is common knowledge that Brazil twinning tends to be located near the borders of the crystals. It is usually observed on etched slices as triangular-shaped areas with the base of the triangle at the edge and with the apex pointing toward the center. The sides of the triangle are parallel

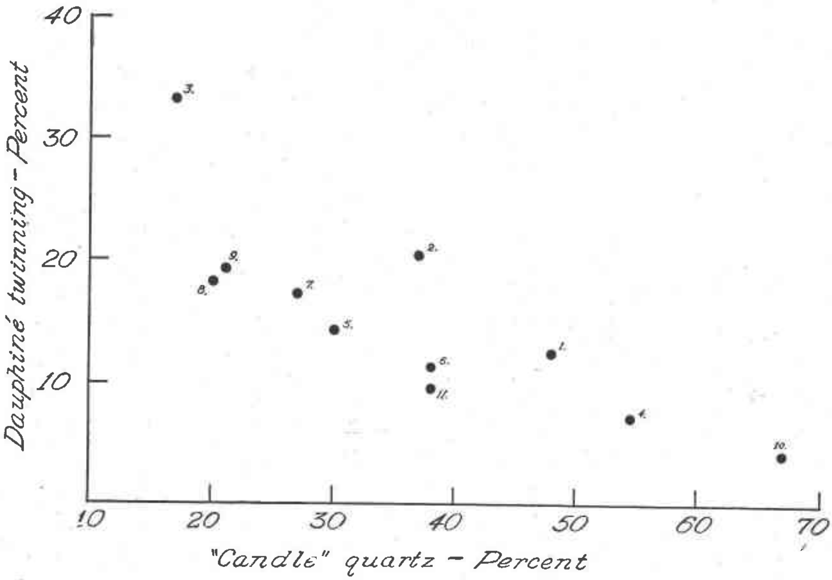

FIG. 3. Relation of "candle" quartz to Dauphiné twinning.

to the *a*-crystallographic axes. Therefore, the percentage of Brazil twinning in unfaced quartz is usually low because much of it has been broken off. Thus in Lot 9 with only 17.4 per cent faced quartz, Brazil twinning amounted to only 0.19 per cent. In order to have a comparison of the two types of twinning significant from the crystallographic point of view, only faced quartz should be considered.

Eight of the lots (1, 2, 3, 4, 11, 12, 13 14) studied contained only faced quartz and these were made up of 26 individual boxes on which records were kept separately. Of these, 9 had less than 2 per cent Brazil twinning, but with Dauphiné twinning making up as much as 33 per cent. In the remaining 16 boxes, Brazil twinning varied up to 38 per cent and only in one of them did Dauphiné twinning amount to more than 9 per cent. Since the weight of quartz varied considerably in the different boxes, the amount of twinning in terms of pounds was calculated and is listed in the tables below.

TABLE 4. BOXES IN WHICH BRAZIL TWINNING WAS LESS THAN 2 PER CENT

Lot No.	Box No.	Dauphiné Twinning Pounds	Brazil Twinning		Total Weight Pounds
			Pounds	Volume %	
1	2	8.40	.43	1.04	41.0
1	3	13.60	.33	0.80	41.0
2	2	8.20	.30	0.50	59.9
2	3	3.58	.63	1.84	34.2
3	1	6.09	.22	0.62	35.8
3	2	6.15	.43	1.08	39.4
4	1	1.46	.44	1.28	34.2
4	2	1.89	.24	0.87	27.5
4	3	6.18	.51	0.95	54.0
		55.55	3.53		367.0
		15.14%	0.96%	Total twinning 16.10%	

TABLE 5. BOXES IN WHICH BRAZIL TWINNING WAS GREATER THAN 2 PER CENT

Lot No.	Box No.	Dauphiné Twinning Pounds	Brazil Twinning		Total Weight Pounds
			Pounds	Volume %	
1	1	4.11	1.04	3.06	33.9
2	1	3.52	.85	2.24	37.7
3	3	7.04	3.66	8.92	41.1
11	1	2.52	5.37	9.64	55.8
11	2	1.19	6.92	12.96	53.5
12	1	1.12	2.44	8.15	30.0
12	2	1.42	4.06	7.15	56.8
13	1	2.04	2.89	5.19	55.8
13	2	3.12	1.53	2.87	54.5
14	1	.30	.43	10.27	4.2
14	2	.30	.63	11.01	5.7
14	3	2.01	4.75	21.32	22.3
14	4	2.43	3.06	14.57	21.8
14	5	6.05	5.50	24.46	22.5
14	6	1.84	2.96	17.40	17.0
14	7	.60	3.41	27.76	12.3
14	8	.15	1.93	38.58	5.0
		39.76	51.43		529.9
		7.50%	9.71%	Total twinning 17.21%	

The figures in the above tables show that when Brazil twinning is present in only small amounts, Dauphiné twinning is abundant; and, conversely, when the percentage of Brazil twinning is greater, Dauphiné twinning is less. In several cases it appears that not only does Dauphiné twinning decrease with increase of Brazil twinning but the total percentage of twinning is less.

Right Hand vs. Left Hand

With the exception of the first three lots studied the hand of the quartz was observed and is recorded in Table 6. Of the 2414 crystals, 1224 or 50.7 per cent were left hand and 1191 or 49.3 per cent were right hand. This is what would result from a purely statistical basis if it were a matter of chance whether a quartz crystal were to be right- or left-hand. It appears obvious, therefore, that locality has no influence on this property.

An attempt to correlate the hand of the quartz with other observed data, showed that it has no apparent relation to twinning either in amount or kind and is quite independent of habit.

Table 6. Number of Right- and Left-Hand Crystals

Lot No.	Hand		Lot No.	Hand	
	Left	Right		Left	Right
4	97	103	11	83	90
5	109	90	12	83	83
6	100	100	13	97	103
7	79	91	14	88	87
8	72	74	15	84	111
9	196	154	16	62	44
10	74	61	Total	1224	1191

Spectrographic Analyses and X-ray Irradiation

Two crystals were selected at random from each lot of quartz and from each of them two oscillator plates were finished to a frequency of 7640 KC. These plates were then exposed to an intense x-ray beam in an irradiation unit built by North American Philips Company for that purpose. Such exposure lowers the frequency and tends to make the quartz smoky. The change of frequency was recorded for each oscillator plate, but it seems unnecessary to list all the data here, for no apparent correlation existed between change in frequency and the other observed properties. It is impossible to draw definite conclusions regarding the effect of x-ray irradiation of quartz from different localities, but from the limited data available it appears that there may be a correlation. Certain lots of quartz were nearly all smoky and the oscillators from these, as one would expect, changed frequency but little on exposure.

After exposure to x-ray irradiation, two of the oscillators from each lot were selected and analyzed spectrographically* for the presence of minor elements. The results of these analyses are given in Table 7 with the change in frequency induced by x-ray irradiation in that particular plate of quartz. The presence of the minor elements seems to have no influence on the change in frequency.

TABLE 7. SPECTROGRAPHIC ANALYSES OF OSCILLATOR PLATES

Lot No.	1	1	2	2	3	3	4	4	5	5	6	6	7	7
Change in Frequency in Cycles	2400	670	800	1784	580	740	000	000	840	1550	675	445	375	300
BaO	X	X	X	.001	.002	.002	X	X	X	X	.001	.002	.001	X
Cr_2O_3	.001	X	X	X	X	.001	X	.001	X	X	X	X	X	.001
CuO	.009	.01	.008	.009	.008	.007	.008	.007	.006	.006	.006	.007	.006	.01
MnO_2	X	X	X	X	X	X	.001	.001	X	X	X	X	.001	X
TiO_2	.003	.002	.003	.002	.001	.001	.001	.001	.001	.001	.001	.001	.005	.001
MgO	.006	.005	.005	.003	.005	.006	.006	.003	.006	.006	.005	.004	.003	.003
ZrO_2	X	X	X	X	X	X	X	X	X	X	X	X	.003	X
CaO	.008	.006	.002	.003	.004	.003	.002	.005	.003	.003	.002	.003	.008	.003
Na_2O	X	X	XX	X	X	X	X	.001	X	X	X	X	X	X
K_2O	.001	.001	X	X	X	X	X	.001	.001	X	X	X	.001	.002
Li_2O	.005	.006	.003	.004	.006	.005	.004	.003	.003	.002	.001	.006	.001	.001
Cs_2O	.003	.002	.002	X	X	X	.001	X	X	X	X	.002	.002	.002
Rb_2O	X	X	X	.001	X	X	X	.002	X	.002	.002	X	X	X
Ag_2O	.001	X	X	.002	X	X	.001	X	X	X	X	X	.001	X
Al_2O_3	.008	.006	.007	.006	.008	.005	.008	.003	.004	.005	.006	.007	.004	.007

TABLE 7. SPECTROGRAPHIC ANALYSES OF OSCILLATOR PLATES (Cont.)

Lot No.	8	8	9	9	10	10	11	11	12	12	13	13	14	15	16
Change in Frequency in Cycles	2200	3000	210	1480	1500	1740	000	1400	820	1110	510	1240	470	290	420
BaO	X	.001	X	.001	.002	X	.001	.001	X	X	X	.002	X	X	X
Cr_2O_3	X	X	X	X	X	X	X	X	X	X	X	X	X	X	.001
CuO	.006	.005	.008	.006	.006	.004	.006	.007	.006	.007	.008	.007	.008	.005	.007
MnO_2	X	X	.001	X	X	X	X	X	X	X	X	.002	.002	X	X
TiO_2	X	X	.001	X	.002	X	.001	X	X	.001	.001	X	X	.001	X
ZrO_2	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
MgO	.004	.003	.005	.005	.006	.002	.005	.006	.005	.004	.003	.003	.004	.004	.003
CaO	.002	.003	.005	.007	.004	.004	.006	.003	.004	.003	.004	.005	.003	.004	.004
Na_2O	X	X	X	X	X	X	X	X	X	.001	.001	X	X	X	X
K_2O	X	X	.001	.003	.002	X	.003	.001	X	X	X	.002	.001	X	X
Li_2O	.01	.004	.001	.004	.007	.005	.003	.004	.006	.005	.006	.004	.005	X	X
Cs_2O	.001	X	X	.001	.001	X	.001	X	X	.002	.001	X	X	X	X
Rb_2O	X	X	.001	X	X	X	X	.002	X	X	X	X	X	.001	.001
Ag_2O	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Al_2O_3	.004	.004	.003	.004	.005	.004	.006	.008	.005	.004	.003	.004	.006	.003	.008

* Spectrographic analyses were made by Mr. John C. Rabbitt of Harvard University.