A NOTE ON THE MORPHOLOGY OF MONAZITE

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INTRODUCTION

In connection with some work on Swiss monazites (turnerites) a general statistical analysis of the mineral's morphology was carried out; it is proposed here to summarize and discuss briefly the results obtained. The investigation was made on the published drawings of monazite crystals, most of which are reproduced in Goldschmidt (1920). Several figures are, however, not included in the atlas or have been published subsequently and are contained in papers by Lacroix (1915; 1918; 1922), Palache, Davidson and Goranson (1930), Schoep (1930), Sekanina (1933), Thoreau, Breckpot and Vaes (1936), Ungemach (1916), Wherry (1919). In all 133 figures were examined and 127 of these were found suitable for statistical purposes.

Forty-two forms were identified on the drawings and of these 38 are quoted by Goldschmidt (1920) while 4 come from newer publications as follows: $p=(211)$, contained in Goldschmidt (1897), deleted by him in 1920, found on a crystal from Madagascar by Ungemach (1916); $\Delta=(122)$ and $U=(\bar{1}13)$ found by Ungemach on crystals from Madagascar; $\Phi=(\bar{3}02)$ found by Sekanina (1933) on a Moravian crystal. This author also gives $S=(102)$ but does not figure the form. The letters attached to these forms have been added by the present writer. Eight forms quoted by Goldschmidt (1920) were not found in the drawings. They are the following: χ, π, Γ υ, ϕ, Σ, and two doubtful forms.

THE FORMS AND THEIR PERSISTENCE

According to Niggli (1922) the most satisfactory method of assessing the importance of a form is to determine the degree of its persistence on the crystals under varying conditions of development. For this purpose as many different crystals as possible must be examined and a selection of individuals made, such that every available combination of forms is represented once and once only. If D be the total number of these (different) combinations and d the number containing the given form, the persistence P of the latter is expressed by

$$P=\frac{d\cdot 100}{D}. \qquad (1)$$

The monazite crystals shown in the drawings examined belonged to 99 different combinations, varying in complexity from 2 forms (*a-v* on crystals from Söndeled, Norway) to 16 forms (on crystals from "Mont

Sorel," Floitental and the Tavetsch valley). The greatest variety of combinations was found when 8 forms are present, though nearly as many variations occurred with 4, 5, 6 or 7 forms. A maximum comprising 55% of the total number of combinations is, therefore, reached between 4 and 8 forms. This corresponds to the observations made on other minerals, which nearly always show their greatest variability in the moderately complicated combinations. It may be added that the individual combinations most frequently met with were *a-b-e-m-w-x* and *a-m-r-v-w-x*.

The application of equation (1) to each of the 42 forms resulted in the values given in the third column of Table 1, which is arranged according to decreasing values of P. It will be seen that $a=(100)$ occupies a rather isolated position with the extremely high value $P=97$, and that 16 units separate the form from $v=(\bar{1}11)$ the next highest. The latter is one of a group comprising *v*, *m*, *x*, *e*, *w*, *b*, whose P-values gradually decline to 60.

TABLE 1

Letter	Symbol	P	S	I	II	III
a	(100)	97	97	93.5	4	2.5
v	($\bar{1}$11)	81.5	65.5	29	39	32
m	(110)	75.5	68	32	33.5	34.5
x	($\bar{1}$01)	72.5	72	36	43.5	20.5
e	(011)	65.5	59	19	38.5	42.5
w	(101)	63	73	40	39	21
b	(010)	60	61	23	36.5	40.5
u	(021)	46	49.5	13.5	21.5	65
z	($\bar{3}$11)	39	44	0	32.5	67.5
r	(111)	37	53	12.5	33.5	54
l	(210)	27.5	45.5	0	36.5	63.5
c	(001)	25.5	59	24	28	48
o	($\bar{1}$21)	22.5	41	0	23	77
i	($\bar{2}$11)	22.5	37	0	11.5	88.5
g	(012)	18.5	36.5	0	9	91
n	(120)	9	44.5	0	33	67
y	(310)	9	36.5	0	9	91
s	(121)	5	37.5	0	12.5	87.5
d	($\bar{1}$12)	4	33.3	0	0	100
f	(112)	3	33.3	0	0	100
t	($\bar{2}$12)	3	33.3	0	0	100

At this point another sharp drop of 14 units marks the transition to a further group consisting of *u*, *z*, *r*, *l*, *c*, *o*, *i*, *g*, which show P-values between between 46 and about 20, while all other forms have P-values below 10 and in very many cases show the lowest figure (1 combination). A comparison of this sequence with those found on other minerals (see, for instance, the data collected by the present writer, 1930) shows that while the forms very generally tend to separate into groups, the size of these and their position in the scale of *P*-values vary somewhat and thus constitute individual features of each mineral. The highest group, containing what Niggli (1923) has called the characteristic key-forms ("Leitformen"), is for monazite reduced to the one very typical and constantly recurring form $a=(100)$. The second group may be said to contain the chief auxiliary forms, one or more of which accompany a in the majority

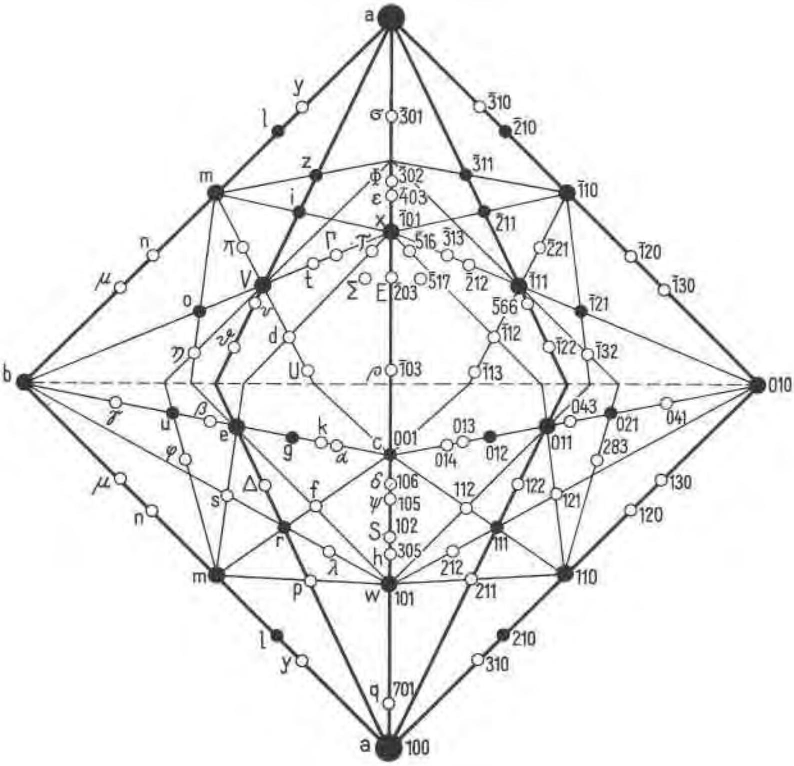

FIG. 1. "Triangular" gnomonic projection of the monazite forms. The persistence of the forms and the importance of the zones is indicated by the thickness of the points and lines.

of the combinations, while those of groups three and four may be referred to as supplementary and incidental forms respectively. Whereas the former are still fairly widespread, the latter are of exceptional character and mostly restricted to some few individuals. It is interesting to find $r=(111)$ and especially $c=(001)$ among the supplementaries and ranking among forms with slightly complex symbols. On the other hand all the highly persistent forms have simplest indices and are in this respect unusually homogeneous.

These facts are brought clearly by figure 1 which is a gnomonic projection of the triangular type advocated by Niggli. The construction was carried out on the principles recently suggested by the present writer (1936) and the plane of projection so chosen that the fundamental triangle is right-angled and isosceles. This enables the triangles representing each quadrant to be fitted together, with the result that a figure is obtained showing similar distribution of the faces as the stereographic projection while preserving the zone-lines characteristic of the gnomonic. The forms are marked in various sizes according to their persistence and various zones have also been drawn and their importance indicated by lines of different thickness. The method adopted for grading the zones was to form the sum of the persistence-values of the forms occurring in each one.

$$Z=\Sigma P. \tag{2}$$

The application of this equation results in the values collected in Table 2 and reveals a distinct maximum for [011] with $Z=346$. [001] and [100] follow and six other zones have values over 200. All others are of lesser importance.

TABLE 2

Zone	Number of forms	ΣP
[011]	10	346
[001]	7	279
[010]	14	270
[111]	7	246
[112]	6	244
[101]	6	240
[11$\bar{1}$]	7	231
[110]	8	228
[100]	10	220
	75	
deduction for forms counted more than once	25	
	50	

The projection shows that in spite of the rather pronounced obliquity of the axial cross ($\beta=103°40'$)[1] the general distribution of the forms and zones is a markedly regular one and possesses a distinct similarity to certain cubic projections. This is partly due to the approximation to cubic angles resulting from the axial ratio $a:b:c=0.9693:1:0.9256$ (metrical pseudosymmetry) and partly due to the peculiarities of the form-selection. It will be noted, however, that the distribution shown by forms of similar persistence and zones of similar importance conforms

[1] This is clearly shown in the projection by the eccentric position of $c=(001)$.

less well to that required by cubic pseudosymmetry. The high and somewhat isolated *P*-value of the pinacoidal form $a=(100)$ and the fact that the chief zones converge in this form introduce tetragonal traits into the projection, which indeed rather closely resembles the type-projections given by Niggli (1926) for the "tabular" mode of that morphological group. The morphology of monazite may, therefore, be described as belonging to the hypocubic type with distinct tendencies towards the last named mode. It may be noted that these relations are best brought out by the setting first chosen for the "turnerite" crystals

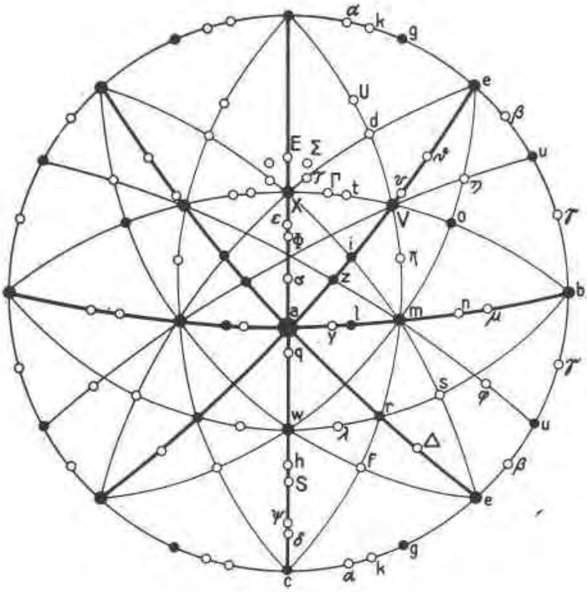

FIG. 2. Stereographic projection of the monazite forms. The mineral is set with the *a*-axis vertical to bring out the pseudo-tetragonal form development.

from the alpine localities, according to which the pinacoids $a=(100)$ and $c=(001)$ of Dana's monazite setting were interchanged. Figure 2 is a stereographic projection orientated in this fashion, and the pseudo-symmetric features referred to above come out very clearly.

The Size-Relations of the Forms

If the forms present in each drawing be divided according to size into three groups, I (large), II (medium) and III (small), three characteristic numbers, r, s, t, may be calculated for each form showing how often on the n crystals examined it appears in each group respectively. According to Goldschmidt (1923) the relative size of each form can then be expressed by a number G such that

$$G = \frac{100\,(3r+2s+t)}{3n}. \qquad (3)$$

It may be pointed out that this number does not furnish a wholly satisfactory expression for the size-relations because it is not independent of the frequency of the forms. Thus, if on 100 crystals two forms have $r=30$, $s=30$, $t=30$, and $r=20$, $s=20$, $t=20$, respectively, the two G-values work out to 60 and 40 respectively, in spite of the equal distribution among the three groups which obtains in each case. A better insight into the size-development of each form is given by the quotient

$$S = \frac{100\,(3r+2s+t)}{3\,(r+s+t)} \qquad (4)$$

which gives values lying between 100 (group I only) and 33.3 (group III only) and for cases such as those given above works out to 66.6 quite independently of the frequency. For graphical purposes the three expressions:

$$\frac{100\cdot r}{r+s+t}; \quad \frac{100\cdot s}{r+s+t}; \quad \frac{100\cdot t}{r+s+t}$$

may be calculated for each form. As the sum of the three terms is always 100, triangular coordinates may be used for plotting and a point in the diagram assigned to the form which at once shows the distribution among the three groups. This has been carried out for the important forms of monazite in figure 3, while the S-values are quoted in the fourth column of Table 1.

The most conspicuous fact that emerges is the completely isolated position of $a=(100)$ which very rarely appears except in group I and in the great majority of the crystals considered is a dominant form. The estimation of importance according to persistence and size leads here to the same result, but this is only partly true as regards the other forms. Thus the group of auxiliary forms, though as a whole ranking next in the order of S-values and forming a typical group in the centre of the diagram, shows some very marked changes in sequence, the position of $w=(101)$, for instance, being noticeably higher than before. The supplementary forms again appear as a group and occupy the field around pole III of the diagram, but here also the order is changed and $c=(001)$ and $r=(111)$ occupy considerably higher positions by size than by persistence. Nearly all the incidental forms appear exclusively in group III and therefore concentrate on that pole. They are omitted from the diagram.[2]

These indications may suffice to prove that while certain connections do, evidently, exist between the persistence and size sequences, they are of no very precise character and hardly go beyond the general grouping

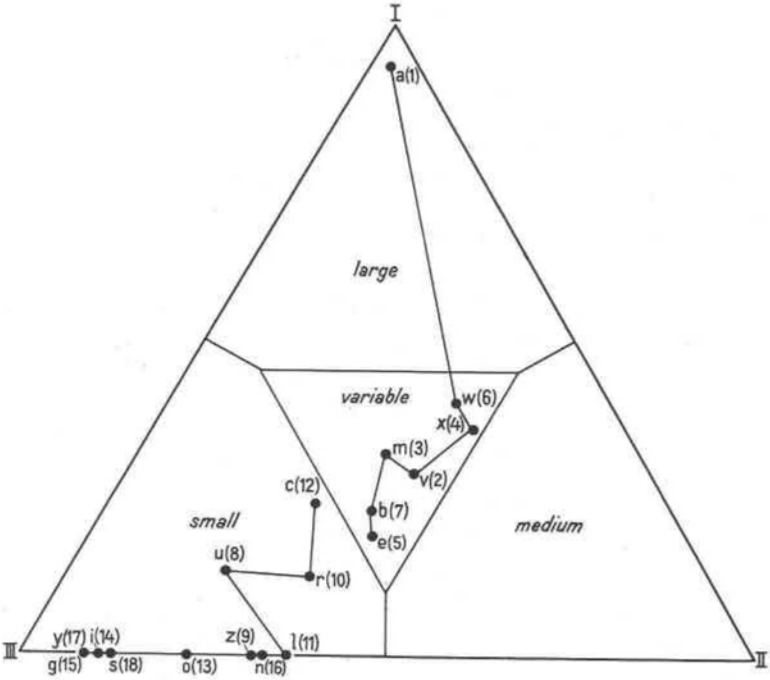

FIG. 3. Size-relations of the monazite forms. The numbers in brackets give the positions of the forms in the sequence of persistence-values.

of the forms discussed above. Results obtained by similar methods on other minerals quite bear out this conclusion though the use of *G*-values as a basis of discussion has often tended to obscure the facts. These values being dependent both on persistence (or frequency) and size may, perhaps be appropriately used to strike a mean between the two corresponding sequences and according to them the monazite form's appear in the following order: $a-x, m, v, w-e, b-r, u, z, c, l, o, i, g, n, y, s,$ etc.

[2] A few of these forms do, however, possess high *S*-values, which show that although of extreme rarity they have been observed with large faces. They are the following: $h=(305)$, Binnental by Trechman; $\delta=(106)$, Madagascar by Duparc; $\epsilon=(\bar{4}03)$ and $\beta=(043)$, Madagascar by Lacroix; $\Phi=(\bar{3}02)$, Moravia by Sekanina; $\rho=(\bar{1}03)$, Queensland by Anderson.

When viewed from the standpoint of pseudosymmetry, figure 3 bears out the results previously obtained in a rather remarkable way. The three pseudoequivalent forms, $w=(101)$, $x=(\bar{1}01)$, $m=(110)$, which represent the tetragonal form (101) are quite close together in the diagram, as are $b=(010)$ and $c=(001)$ representing the pseudoprism (100). The form $e=(011)$, which represents the prism (110), occupies a position close to *b*. These facts show that the pseudosymmetry may be expected to manifest itself in the habit of the mineral, and an inspection of the drawings at once brings a number of such cases to light. Thus crystals are often found on which *a-w-m-x* are simultaneously present in dominant development and the similarity to a tetragonal combination can then be a very marked one. The group *a-b-c* is much rarely dominant though Lacroix (1922) has given a typical case of this sort. The group $a\text{-}b\text{-}e \pm c$ is a further group which is frequently well developed on the crystals and can also produce tetragonal habit. Although Miers has described a crystal from Cornwall, which besides *a* and other forms shows *v* and *r* in a development suggesting the pseudoform (111), these two forms are widely separated in the diagram and rarely combine in this way. Instead the two forms *a* and *v* often produce crystals of pronounced prismatic habit which like the very frequent case of dominant *a-x* (prismatic with elongation after [010]) and some others must be considered as highly typical for the mineral though lacking the pseudosymmetric character discussed here.

Summary

A statistical analysis of the form-development of monazite by persistence and size brings out the dominant role of $a=(100)$ and establishes sequences for the other forms which are broadly speaking similar though by no means identical for the two methods of approach. The results indicate that the morphology of monazite is of a hypocubic type with a distinct tendency towards the tabular mode of the tetragonal group.

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