The morphology of cerussite

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Summary. The observed order of importance of the forms of cerussite has been determined by the methods introduced by Donnay and Harker, used in a modified form. The space group derived by morphological analysis is *Pmcn*, as determined by X-ray diffraction. For the more common forms good agreement is found between the observed and theoretical orders of importance. The rank distribution of the more important forms is given.

THROUGH the work of J. D. H. Donnay and D. Harker[1, 2, 3] it is potentially possible to determine the space group of a mineral by a statistical study of its form development. The observed morphological aspect, a list of observed forms in order of decreasing importance, is first prepared, from which the space group can often be determined by a study of the zonal development.

The method of establishing the observed morphological aspect that is used in this paper has been described in detail in 'The morphology of the baryte group'.[4]

Morphological data. Most of the morphological data were obtained from V. Goldschmidt's 'Atlas der Krystallformen', which gave details of the habit of 241 crystals of cerussite with an aggregate of 1670 forms from 71 localities. No drawings of crystals of which the locality was unknown were used, and drawings of incomplete crystals were also rejected. The 'Atlas' provides information on the frequency of occurrence of forms, and by listing all the forms on each crystal in order of rank it is possible to calculate mean ranks and form rank indices. C. Hintze's 'Handbuch der Mineralogie' provided information on the habit of 187 crystals of cerussite, showing an aggregate of 1339 forms, all from known localities. The 'Handbuch' forms a valuable ancillary

[1] J. D. H. Donnay and D. Harker, Amer. Min., 1937, vol. 22, p. 446.
[2] J. D. H. Donnay and D. Harker, Naturaliste Canadien, 1940, vol. 67, p. 33.
[3] J. D. H. Donnay, Ann. Soc. géol. Belgique, 1938, vol. 61, p. B 260.
[4] A. F. Seager, Min. Mag., 1959, vol. 32, p. 63.

source of information on the frequency of occurrence of forms, but it is not possible to obtain data on rank, since the relative development of forms is often unknown.

TABLE I. Summary of form and rank and frequency data for cerussite. Axial ratios $a:b:c = 0{\cdot}6100:1:0{\cdot}7230$.

R_o	Form	ρ	$\bar{R}$	N_x	F %	F' %
1	010	0·534	2·15	64	90	83
2	110	0·313	3·81	69	93	87
3	111	0·270	4·09	67	88	84
4	021	0·251	3·62	57	68	70
5	001	0·176	3·98	40	41	36
6	012	0·148	4·94	45	50	51
7	100	0·132	4·66	39	39	41
8	011	0·128	4·95	47	52	49
9	130	0·100	5·33	39	41	47
10=	102	0·057	6·18	29	34	35
10=	031	0·057	5·46	19	16	18
12	121	0·040	10·55	11	10	10
13	112	0·021	9·22	21	17	20
14	113	0·009	9·73	13	8	7
15	211	0·008	9·36	9	6	8
16	041	0·005	8·64	8	5	14

Table I gives the observed rank (R_o), form rank index (ρ), mean rank ($\bar{R}$), locality frequency (N_x), and percentage frequency of occurrence (F %) calculated from data in the 'Atlas' for forms with frequencies of occurrence of 5 % or more. The percentage frequency of occurrence of these forms derived from the 'Handbuch' (F' %) is also given.

The rank of the rarer forms has been obtained by combining data from the 'Atlas' and the 'Handbuch', as in 'The morphology of the baryte group'. Forms are listed in order of decreasing locality frequency, but when this has the same value for two or more forms they are placed in order of decreasing frequency of occurrence. All forms are shown that have frequencies between 5 % and 1 % in the 'Atlas'. After the symbol of each form the locality frequency is shown in brackets, followed by the frequency of occurrence: {051} (10) 18, {023} (8) 11, {120} (8) 10, {221} (6) 6, {131} (5) 11, {061} (4) 8, {071} (4) 5, {114} (4) 4.

Table II shows the actual form frequency (Σn_x) of all forms in the three 'central zones' which intersect in {111}, namely $[1\bar{1}0]$, $[0\bar{1}1]$, and $[\bar{1}01]$ containing forms of the type {*hhl*}, {*hkk*}, and {*hkh*}, respectively, as derived from the Atlas (A) and the Handbuch (H).

Table III shows the actual form frequency of all forms in the three 'axial zones', [100], [010], and [001] containing forms of the type

$\{0kl\}$, $\{h0l\}$, and $\{hk0\}$, respectively, as derived from the 'Atlas' (A) and the 'Handbuch' (H).

The few forms that are not recorded in one or more of the three tables have little morphological significance. From the 'Atlas' there are

TABLE II. Development of the central zones. Actual form frequencies derived from the 'Atlas' (A) and 'Handbuch' (H).

$\{hhl\}$	*A*	*H*	$\{hkk\}$	*A*	*H*	$\{hkh\}$	*A*	*H*
114	3	2	377	2	—	313	—	1
113	19	13	122	—	1	111	211	158
112	42	37	111	211	158	121	25	19
111	211	158	322	1	—	131	8	7
332	—	1	211	15	15	161	1	—
221	3	4	311	2	1			
331	2	2						
441	—	1						
14.14.1	1	1						

TABLE III. Development of the axial zones. Actual form frequencies derived from the 'Atlas' (A) and 'Handbuch' (H).

$\{0kl\}$	*A*	*H*	$\{h0l\}$	*A*	*H*	$\{hk0\}$	*A*	*H*
013	2	3	104	1	—	180	1	—
025	—	1	103	1	1	160	—	1
012	121	95	102	81	66	150	—	1
023	6	6	304	1	1	130	100	87
034	1	—	101	2	6	380	—	1
011	126	91	302	2	6	120	3	9
032	2	2	201	2	4	350	1	1
095	1	1	401	—	1	110	223	162
021	163	131				530	—	3
031	39	34				210	—	1
041	13	26				310	—	1
051	12	14						
0.11.2	2	2						
061	5	6			*Pinacoids*	*A*	*H*	
0.25.4	1	1			100	94	76	
071	3	5			010	217	155	
081	1	1			001	100	68	
0.14.1	—	1						

eight examples of the general form $\{hkl\}$ that are each mentioned once, and the 'Handbuch' quotes four of the same forms; three are recorded once each and a fourth $\{hkl\}$ form is recorded twice.

Morphological analysis of cerussite

Determination of the lattice type. The lattice type is determined from the three central zones. Frequency and rank data for the more common forms are given in table I, and for some less common forms in the text above. The actual frequency of all forms recorded in these zones is shown in table II.

The zone [1$\bar{1}$0] of forms {*hhl*}. The observed morphological aspect for forms with frequencies over 1 % is {111}, {112}, {113}, {221}, and {114}. The form {111} is dominant. There is a fairly well-developed primary series in the harmonic segment of the zone, in order of decreasing importance, from {111} to {114}. In the poorly developed arithmetic segment of the zone there is a complete primary series from {111} to {441} and the simplest possible representative of the secondary series, {332}. This is a simple zone with the unit form dominant.

The zone [0$\bar{1}$1] of forms {*hkk*}. The observed morphological aspect for forms with frequencies over 1 % is {111} and {211}. The unit form, {111}, is clearly dominant. There is a short but continuous primary series from {122} in the harmonic segment through {111} to {211} and {311} in the arithmetic segment of the zone. The importance of the forms in each segment decreases rapidly away from the dominant form {111}. One form is recorded for the secondary series and one for the tertiary series. This is a simple zone with the unit form dominant.

The zone [$\bar{1}$01] of forms {*hkh*}. The only forms with frequencies over 1 % are {111}, {121}, and {131}, in order of rapidly decreasing importance. These forms belong to the primary series, together with the rare forms {313} and {161}. This is a simple zone with the unit form dominant.

Since each of the central zones can be shown to have the unit form dominant and be of the simple type, it may be concluded that the lattice is primitive and that satisfactory axial ratios were chosen.

Determination of the space group

The space group may be deduced from the form development of the three axial zones. It has already been established on morphological grounds that the point group of cerussite is *mmm*, therefore mirror planes or glide planes must be present parallel to each of the three pinacoids. The morphological analysis will attempt to determine the existence of any mirror planes and the nature of any glide planes that may be present.

The zone [100] of forms {0*kl*}. This is the most richly developed zone on crystals of cerussite. The observed morphological aspect for forms with a frequency of occurrence over 1 % is {021}, {012}, {011}, {031}, {041}, {051}, {023}, {061}, and {071}. The development of this zone is anomalous, but still seems to be interpretable without ambiguity. {021} is without doubt the dominant form. {012} and {011} are of nearly equal importance, although {012} has a slight superiority. There is a marked decrease of importance from {011} to {031}, and from {031} to {041}, and a gradual decline of importance through {051}, {061}, and {071}. The arithmetic segment of the zone is very well developed. If *n*-glide planes were present parallel to {100} the dominant form of the zone should be {011}, and the arithmetic segment would show a preponderance of forms having $k+l$ even, with {031}, {051}, and {071} in order of decreasing importance. If *b*-glide planes are present {021} should be the dominant form of this zone, and forms with the second index even should predominate, such as {041}, {061}, and {081}. If *c*-glide planes are present the dominant form should be {012}, and the more important forms should have the third index even. If *m*-planes are present the dominant form should be {011}, and in the arithmetic segment of the zone there would be a series of forms {021}, {031}, {041}, {051}, etc., in order of decreasing importance. The observed morphological aspect clearly rules out *n*-glide planes and *c*-glide planes. The presence of *b*-glide planes is suggested by the dominance of {021}, but the rest of the zonal development does not indicate that this is the case, as {041}, is less important than {031} and {061} is less important than {051}. The long series of forms {011}, {021}, {031}, {041}, . . ., {071} very strongly suggests that this is a primary series of forms in the arithmetic segment of a simple zone. On this interpretation {012} is the only primary form in the harmonic segment of the zone, and {023} is the only secondary form in this segment. The evidence fits this interpretation much better than any other, and it has only one anomaly—that {011} is not more important than {021}. It may therefore be concluded that there are *m*-planes parallel to {100}.

The zone [010] of forms {*h*0*l*}. {102} is the dominant form, and it is the only one which has a frequency over 1 % in the 'Atlas'. This suggests the presence of a simple zone in which the dominant form has the last index even. The theoretical morphological aspect for such a zone in cerussite is {102}, {101}, {302}, {104}, {201}, {304}, {106}, etc. The observed morphological aspect (based only on frequencies in table III) is {102}, {101} = {302}, {201}, {103} = {104} = {401}. The agreement is quite good, considering the rarity of most of the forms. It may be concluded that there are *c*-glide planes parallel to {010}.

The zone [001] of forms {*hk*0}. The observed morphological aspect is {110}, {130}, and {120} for forms having frequencies over 1 % in the 'Atlas'. {110} is the second most important form on cerussite, and is clearly dominant in this zone; {130} has approximately half the frequency of {110}, and {120} has a frequency of only 1 % in the 'Atlas'. This is a double zone in which the unit form is dominant, indicating the presence of *n*-glide planes parallel to {001}.

The *pinacoids*. The observed morphological aspect is {010}, {001}, and {100}, which is the order to be expected from the axial ratios used.

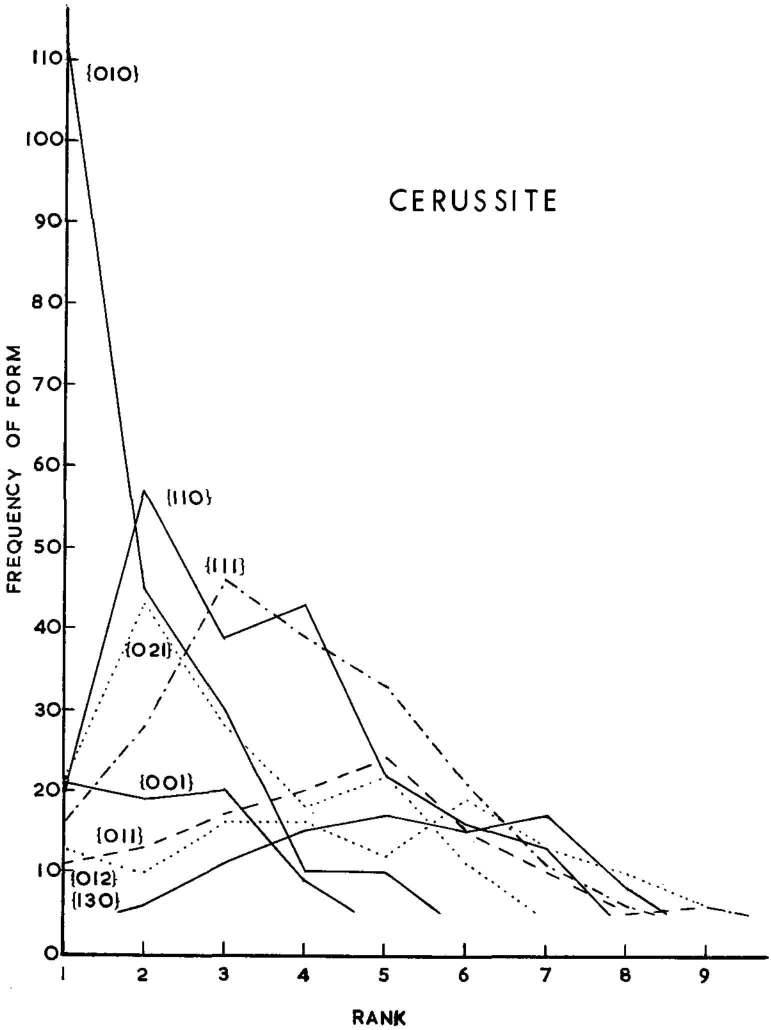
It has been deduced by means of the morphological analysis that the space group of cerussite is *Pmcn*, in its usual setting with the axial ratios 0·6100:1:0·7230. This is in complete agreement with the space group determined by X-ray diffraction.

TABLE IV. Theoretical and observed ranks and S^2 for cerussite.

R_t	R_o	*Pinacoids*	{0*kl*}	{*h*0*l*}	{*hk*0}	{*hhl*}	{*hkk*}	{*hkh*}	S^2
1	8		011						0·56
2	2				110				0·71
3	1	010							0·78
4	3					111	111	111	1·08
5	4		021						1·15
6	5	001							1·49
7	12							121	1·67
8	6		012						1·68
9	10=			102					2·01
10	7	100							2·09
11	10=		031						2·12
12	13					112			2·20
13	9				130				2·27
14	21							131	2·64
15	15						211		2·65
16	—						122		2·79
17=	—		032						3·24
17=	20					221			3·24
19	16		041						3·48
20	—		013						3·54

Comparison of theoretical and observed morphological aspects

Table IV shows the first twenty forms of the theoretical morphological aspect. The left-hand column gives the theoretical rank (R_t), the second column the observed rank (R_o), and the last column is the value of S^2. S represents the reticular area of a lattice plane. Let a, b, and c represent the parameters of the three crystallographic axes, then, for orthorhombic crystals $S^2_{hkl} = h^2b^2c^2+k^2c^2a^2+l^2a^2b^2$. The symbols of forms are modified, where necessary, by the conditions imposed by the lattice or space group. In the space group *Pmcn* no restriction is imposed by the lattice, nor is there any in the zone [100] due to the



mirror planes parallel to {100}. In the zone [010] the c-glide planes impose the condition 'last index even' on all forms $\{h0l\}$; when this is not obeyed all indices are doubled for the calculation of S^2. In the zone [001] the n-glide planes parallel to {001} impose the condition '$h+k$ even' on all forms $\{hk0\}$; when this is not obeyed all indices are doubled. The frequencies of all forms in table IV will be found in tables II and III.

No forms $\{hkl\}$ appear in the theoretical morphological aspect until rank 22, and only eight such forms are recorded.

In table IV it will be seen that there is very satisfactory agreement between the theoretical and observed ranks of forms, and it is particularly good in the first six places of the theoretical rank, the only marked disagreement appearing for {011}. Only four forms in the first twenty places of the observed rank are not present in the first twenty of the theoretical rank. For each of these the observed rank (R_o) and theoretical rank (R_t) are: {113} (R_o 14, R_t 25); {051} (R_o 17, R_t 32); {023} (R_o 18, R_t 26); and {120} (R_o 19, R_t 31).

The zone [100] shows several interesting features. Of the fifty-eight forms recorded in this paper eighteen, or nearly a third, belong to this zone. When the eight rare $\{hkl\}$ forms (not shown in the tables) are taken into account the forms $\{0kl\}$ comprise 27 % of all the forms. This rich development of the zone [100] is due in part to the presence of mirror planes parallel to {100}, which do not impose any 'morphological extinctions'. However, the development of $\{0kl\}$ forms exceeds the demands of the space group; in the first 220 forms of the theoretical morphological aspect only 16·4 % belong to this zone. Since more forms are observed than are expected, some forms have high theoretical ranks compared with their observed ranks, as in the following sequence; {051} (R_o 17, R_t 32), {061} (R_o 22, R_t 56), and {071} (R_o 23, R_t 80).

Rank distribution of forms. The rank distribution of some of the more important forms in cerussite is shown in fig. 1. The frequency of occurrence of a form in each rank is plotted against the rank. The figure shows the rank distribution of the same population of crystals as was used in the morphological analysis, which were derived from Goldschmidt's 'Atlas'. The plots have been terminated where the values first fall below five.

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