On β-quartz twins from some Cornish localities.

(With Plates VIII and IX.)

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[Read June 14, 1927.]

IN their paper on 'The structure of α and β quartz',[1] Sir William Bragg and R. E. Gibbs touch on the question of twinning of quartz, showing how X-ray determination of structure can help to explain the different types of twinning. They only mention, however, twinning with parallel axes and twinning on $\xi\,(11\bar{2}2)$. It would be interesting to see this extended to the examination of all known laws of twinning of α- and β-quartz. There is, however, still much doubt about the laws of the twinning of quartz. Many varieties of twins have been described, but a number of these are much open to doubt, while some are decidedly non-existent. G. Friedel[2] has within recent years published valuable papers on the laws of twinning in general, and has made more special application of his theories to the laws of twinning of quartz. It would be interesting to see how far all cases of well-established quartz twins occurring in nature confirm his results.

I, myself, have been mainly interested in the twin-laws of β- or high-temperature quartz, and have often tried to find a locality where material would be in sufficient abundance to yield, after systematic search, examples of all laws that might possibly occur in such quartz. It seems to me necessary, when studying their twin-laws, to treat α- and β-quartz separately. The latter generally occurs as well-developed bipyramidal crystals. Their formation in the fluid magma, uninfluenced by contact with walls and other impedimenta that affect the regularity of α-quartz, makes irregular interpenetrations an exceptional occurrence. Such irregular intergrowths are certainly met with, but only as rarities, and they can generally be easily distinguished from the parallel growths or

[1] W. H. Bragg and R. E. Gibbs, Proc. Roy. Soc. London, Ser. A, 1925, vol. 109, pp. 405–427.

[2] G. Friedel, Compte Rendu des Sociétés Savantes, 1920, pp. 92–120; Bull. Soc. Franç. Min., 1923, vol. 46, pp. 79–95; Leçons de Cristallographie, 1926, pp. 457–460.

twinned elements on the specimens. Amongst the thousands of crystals from the Esterel Mts. that I have examined, only five cases of unidentified groupings could be found; in the more complex Cornish specimens about a dozen, and some of these may eventually prove to be twinned on a definite law. A great disadvantage attached to the study of these crystals is the roughness of their faces, only approximate measurements being possible. The goniometer is not of much use, and most of the measurements were made on the rotating microscope-stage, to degrees or, at best, to half degrees. A few specimens from Wheal Coates, out of the hundreds found, had faces smooth enough for measurements to be possible when fragments of cover-glass were gummed on them. These all confirmed diagnostics previously arrived at by the more primitive methods.

My attention had been brought to the possibility of good material being obtainable in Cornwall by the presence of twins amongst specimens of porphyry-quartz in the Oxford mineral collection that had been collected by Prof. H. L. Bowman at Wheal Coates near St. Agnes. When I joined the Society's jubilee excursion to Cornwall in 1926, I had such quartzes in mind. Unfortunately we did not get to Wheal Coates, but I was fortunate enough to find some twinned bipyramids scattered over the surface of the soil near Belowda Beacon. Time was short, but during the available couple of minutes 47 crystals were collected, 26 of which were twinned.

Thanks to the kindness of Sir John Flett, who re-visited the locality and collected a quantity of these bipyramids, I was able to start a more systematic study of the material. Later on, Sir John Flett sent me another lot, that had been collected by Mr. Wm. Boxhall, of St. Austell, in an abandoned clay-pit, close to Belowda Beacon. These are large and generally formed of a number of parallel elements, but well developed. They gave promise of still better material for study, and I finally decided to go myself and collect as large a number as possible. With Mr. Boxhall's assistance, I was able to collect several hundred specimens, among them some of the largest I have seen from any locality. Being within easy reach of St. Agnes, I also visited Wheal Coates and picked up about 130 twinned specimens, besides untwinned ones.

The following description relates to twins of β-quartz from these three Cornish localities:—

1. Belowda Beacon, near Roche.
2. The abandoned china-clay pit near Belowda Beacon.
3. Wheal Coates, near St. Agnes.

The first two occurrences might be treated as one, for they seem to belong to the same rock-mass, a variety of greisen. But the process of weathering of the rock appears to differ. The Belowda Beacon specimens are found scattered over the surface of the soil, and are derived from the portion of the rock that had become disintegrated by the ordinary process of weathering. The others, on the other hand, come from the quartz-dump left as a residue of working the 'china-clay rock', that had undergone deep-seated transformation. In consequence, these latter are generally whiter and sharper than the former, which have become yellow by exposure and also show signs of attrition. Otherwise they are quite similar, though those from the clay-pit are on the average larger. Both are formed of numbers of parallel elements, but even the larger ones from the clay-pit show a perfectly definite orientation of the constituent parts, either parallel or in twin-position. Some of these are as much as an inch across.

The Wheal Coates bipyramids are sharper and less complex and much smaller than the above. They average less than a quarter of an inch across, rarely attaining half an inch in some of the more complex groups. They are found scattered on the surface of the soil and are derived from a quartz-porphyry, which also contains, in places, felsp phenocrysts. Their special characteristic is the presence of well-developed prism-faces, whereas in the other localities these are absent or only rudimentary, as is generally the case in porphyry-quartz. They are associated with abundance of tourmaline needles and prisms. The Wheal Coates specimens were the best for measurement, some being very sharp and clean-cut. But even these are not up to goniometer standard. Only a few selected crystals could be measured with glass slips gummed on their faces.

The twin-laws so far known with certainty for β-quartz have been tabulated in detail in a previous paper[1] in this Magazine (vol. 19, p. 299). They are the following:

(*a*) The 'Esterel' law; twin-plane $(10\bar{1}1)$.[2]

(*b*) The 'Verespatak' law; twin-plane ξ $(11\bar{2}2)$.

(*c*) The 'Sardinian' law; twin-plane $(10\bar{1}2)$.

The above-mentioned paper gives full literature references to these twin-laws. I also mentioned a supposed 'hetero-twin', also from the

[1] J. Drugman, An example of porphyry-quartz, from the Esterel Mts., France, twinned on face $(10\bar{1}2)$. Min. Mag., 1922, vol. 19, pp. 295–300.

[2] Previously called '*R*-twins', but this is not a satisfactory designation for β-quartz, which is hexagonal and not trigonal.

Esterel Mts., and described by F. Zyndel. I have, since then, had reason to doubt whether there are such things as 'hetero-twins'; and G. Friedel, in one of his papers mentioned above, specially shows that the supposed hetero-twins of quartz are probably non-existent.

The only other references to twinning of β-quartz is by H. Wedding,[1] who found a crystal among some that had been given him in Cornwall (and described as small bipyramids from near St. Agnes) that might be twinned on (30$\bar{3}$1). G. Rose, who saw the crystal, agreed that it might be such a twin, but that it needed confirmation. The law, in itself, is doubtful. As will be shown below, another explanation can be given of this supposed law; an explanation, I find, also suggested by E. Balogh.

The Sardinian law is theoretically well founded, yet no specimen has been obtained of it amongst the Cornish material. On the other hand, four other modes of grouping occur with certainty there. These will be described farther on.

As regards frequency of twinning in these Cornish specimens, roughly, *one cluster in three shows twinning.* This is, at first sight, a large proportion; but, taking into account the large number of parallel elements that make up each bipyramid, one can conclude that twinned parts occur, perhaps two or three to the hundred, a proportion comparable with that observed in the Esterel specimens. Twinning with inclined axes is, in any case, a normal occurrence in high-temperature quartz, and not merely an occasional freak.

Of the commoner laws, Esterel twinning is about twice as frequent as ξ-twinning, here as well as in the Esterel Mts. Of about 1,500 Cornish specimens first examined, about 600 were Esterel-twinned and 300 ξ-twinned, besides some 35 of other orientations and a dozen chance intergrowths. The rest showed only parallel growths. A second collecting tour, since reading this paper, confirms these proportions, besides yielding still another new law in some dozen specimens.

A. *Twinning on (10$\bar{1}$1); 'Esterel' twinning.*

As in the Esterel Mts., this mode of twinning occurs in perfectly symmetric assemblages of two equal crystals, with composition-plane roughly parallel to the twin-plane. Plate VIII, nos. 1–2 and 7–8, show examples of this symmetric form. In these complex assemblages, however, the symmetric development is rather the exception. In the majority of specimens, a small crystal is seen on a pyramid face of a larger one

[1] H. Wedding, Zeits. Deutsch. Geol. Gesell., 1861, vol. 13, p. 139.

with one face parallel, but its apex pointing in the opposite direction. This may be repeated several times on the same specimen. As many as eight twinned portions have been seen on a single specimen. Associations of two or more twins of approximately equal crystals are also frequent, and lead to all sorts of puzzling groups. It will be sufficient to describe the more interesting ones.

Triplets of three nearly equal crystals occur, in which one crystal is Esterel-twinned on two alternate upper faces with the other two, giving a very symmetric-looking assemblage. The other two crystals have, how-

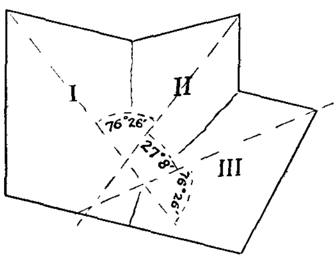


FIG. 1.

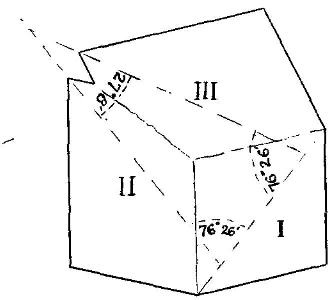


FIG. 2.

Repeated Esterel-twins of β-quartz (simulating twinning on $(30\bar{3}1)$).

ever, no definable orientation towards each other. Plate VIII, no. 11, gives an example of this association. An example of repeated Esterel twinning is shown in pl. VIII, no. 3, in which faces $(10\bar{1}1)$ and $(10\bar{1}\bar{1})$ of the middle crystal act as twin-planes. In this case, the two outer crystals also have the appearance of true twinning, for the axes of all three crystals are in one plane and they have the zone $[(10\bar{1}0), (10\bar{1}1)]$ in common. Another example of the same mode of association, but of somewhat different development, is shown in pl. VIII, no. 14. The lower crystal on the left is Esterel-twinned with each of the other two. These two have quite the appearance of a symmetric twin whose *c*-axes are at approximately 30° to each other. This is, I am convinced, the true explanation of the supposed twin on $(30\bar{3}1)$ described by Wedding. Figs. 1 and 2 give, diagrammatically, the relation of the three crystals in these two groups. It will be seen that the angle between the *c*-axes of the two crystals is 27° 8′, whereas twinning on $(30\bar{3}1)$ requires an angle of 29° 24′. This difference is quite within the limits of error in measuring such rough crystals. E. Balogh also describes such a group and comes to the same conclusion. No example of a genuine twin on $(30\bar{3}1)$ has yet come to my notice in spite of the abundance of the material collected by me at the place Wedding's supposed twin is said to have come from. I have yet another example of this grouping which has still more the appearance of a twin of two crystals with *c*-axes at about 30°. The crystal which acts as link for the other two is reduced to a minimum and appears only in the upper re-entrant angle, wedged in between these.

Another interesting example of repeated Esterel twinning is one in which two parallel faces of the middle crystal act as twin-planes. The two outer ones are, therefore, parallel to each other, and the group has a zigzag development, like a repeated albite-twin or some rutile twins. The other cases observed call for no special mention.

B. *Twinning on* $\xi\,(11\bar{2}2)$; *'Verespatak type'.*

Symmetric twins are also found here. Plate VIII, nos. 4–6 and 9–10, give examples of these. They are the exception, however, unsymmetric development being much more frequent. Generally, a small crystal is seen astride the edge of a large crystal, the adjacent pair of faces being parallel in both, but the apex of the small crystal pointing away from that of the larger one. The position of the smaller crystal can, however, be any other, in which case it is not easy to recognize at once the mode of twinning. Holding the large crystal upright, with the apex of the smaller one pointing towards the observer, the true relation of the two is readily seen. As with Esterel twinning, this law is often seen several times on the same group, giving rise to symmetric-looking assemblages. When this occurs on two alternate upper edges of the link between the other two crystals, triplets very similar to those of two Esterel-twins are formed (pl. VIII, no. 12). Triplets are also observed of an Esterel- and a ξ-twin (pl. VIII, no. 13). Another interesting case is that in which the two adjacent upper edges of the link act as twin-planes. The other two crystals almost look like an Esterel-twin. There is, however, of course, no relation between them in actual fact.

In one case of repeated ξ-twinning, in which faces $(11\bar{2}2)$ and $(\bar{2}112)$ of the one crystal act as twin-planes, this middle crystal is also almost invisible, and a group of, apparently, two equally developed crystals somewhat similar to a twin on $(21\bar{3}1)$ is obtained. There is, however, a sufficiently large difference in orientation to exclude this interpretation of the group, even though the link had been quite invisible.

Some specimens, which might be called 'stringers', show a series of crystals following each other approximately in the same direction, yet all twinned according to some definite law. One such stringer is formed of five crystals. 1 and 2 are Esterel-twinned, 2 and 3 ξ-twinned, 3 and 4 Esterel-twinned, and 4 and 5 Esterel-twinned, all in fairly symmetric twinning. In fact, the associations of these two laws with each other are about as numerous as those of two or more twins of the same law. They are also often found associated with the following rarer and new twin-laws.

C. *Twinning on* $(30\bar{3}2)$.

Although no specimen of the Sardinian law was found in these crystals, some had, at first sight, been presumed to be such, especially two that

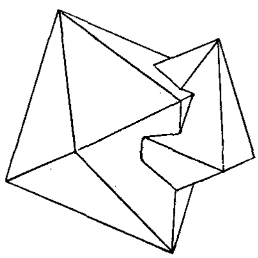


FIG. 3 *a*.

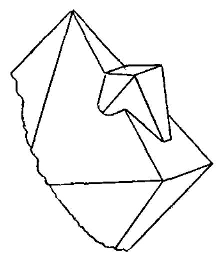


FIG. 3 *b*.

β-Quartz twinned on $(30\bar{3}2)$. (*a*) Symmetric development from Esterel Mts. (*b*) Unsymmetric development from Cornwall.

appeared identical in orientation with a crystal from the Esterel Mts. that had never been measured, but had been supposed to follow this law, being decidedly not an Esterel-twin. These two Cornish specimens were measured and gave concordant readings, but, instead of the 64° expected for the angle between the *c*-axes, an angle between 55° and 56° was found. The Esterel specimen was, therefore, also measured and gave an angle of about $55\frac{1}{2}$°. Two other crystals gave similar results; one, however, is so rough that its measurement is less certain. Enough examples, however, gave the same reading for this value to be accepted. To be quite on the safe side, the specimen of the Sardinian law, that I had previously described in this Magazine, was remeasured and the angle again found to be near 64°. The Sardinian law exists, without doubt, but another mode of twinning, with twin-plane in the same zone as those of the Esterel and Sardinian laws, also exists. The twin-plane was found to be the face $(30\bar{3}2)$ for which the angle between the *c*-axes is 55° 24′. This is in good agreement with the values observed. The law, too, is one of those predicted by G. Friedel as of likely occurrence, its 'index' being 4 and 'obliquity' 4° 43′. It is interesting to find this law at three different localities, for, of the Cornish specimens, two were from Belowda Beacon china-clay pit and the others from Wheal Coates. The first were of unsymmetric development, but the Esterel specimen and at least three from Wheal Coates are symmetric. Fig. 3 *a* shows the symmetric and 3 *b* the unsymmetric development. Two of the Wheal Coates specimens are also shown in pl. IX, nos. 15 and 16, and that from the Esterel Mts. in no. 17.

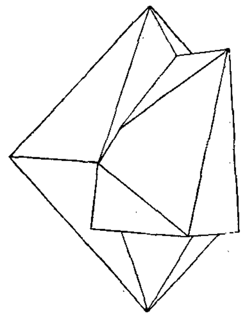


FIG. 4.
β-Quartz twinned on (20$\bar{2}$1); from Belowda china-clay pit, Cornwall.

D. *Twinning on (20$\bar{2}$1).*

A number of other specimens, both from Belowda and from Wheal Coates, had also quite the characteristics of true twinning with twin-plane also in the same zone as Esterel-twins, but the *c*-axes meet at a much smaller angle (fig. 4). The best Belowda specimens were first measured and gave concordant results, with an angle of 42° to 43° between the *c*-axes. This was confirmed by measurements of a specimen from Wheal Coates. In itself, this specimen would not be very conclusive, for it is at the same time Esterel-twinned, the three axes all lying in one plane. In conjunction with the Belowda specimens, however, the measurements can be accepted as reliable. The following table gives the measurements found in the zone of the twin-planes, while fig. 5 shows the development of the group.

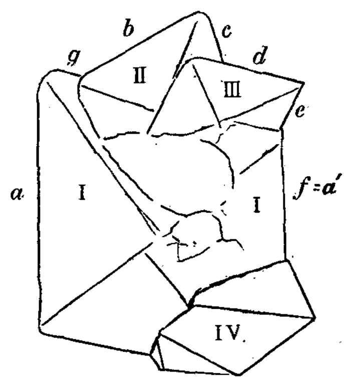


FIG. 5. β-Quartz twinned on (20$\bar{2}$1) and on (10$\bar{1}$1); from Wheal Coates, Cornwall. (I–III and I–IV Esterel-twins; II–III twinned on (20$\bar{2}$1).)

Angle between.	Found.	Theory.
a–g	77 °	76° 26′
e–f	26½	27 08
e–d	76½	76 26
d–b	43	42 58
b–c	76¼	76 26
c–d	60¾	60 36
a–b	60	60 36

The theoretical angles given in the second column are calculated for Esterel twinning and twinning on (20$\bar{2}$1), for this is the law whose characteristics agree with those found on these specimens. The angle of the axes is 42° 58′, well within the limits of error for the values actually found. There is no doubt that this law exists; it is, again, one predicted by G. Friedel. Since measuring these crystals, I have found others at Wheal Coates that confirm the law. Measurements of a number of other specimens, however, complicated matters, for a number of these and a majority of the most symmetric-looking ones from Wheal Coates gave another set of values, oscillating between 36° and 40°, but most of them near 37° and 39°. A two-circle measurement of the best of these, a very symmetric specimen with faces suitable for gumming slips of cover-glass on them, confirmed the existence of another group, other than this new law on ($20\bar{2}1$), yet so close that it appears at first improbable that both should exist. This other grouping seems to agree with the characteristics given for the Zinnwald-law; axes at 38° 13′, which brings the face ($10\bar{1}1$) of one crystal in parallelism with ($10\bar{1}0$) of the other. In a number of the specimens measured and which gave angles near this value, the parallelism did not seem very close. As E. Balogh also found specimens of this nature at Verespatak, one must conclude it is an easily-formed group. Yet the definitions given for it by G. Jenzsch, as also by Goldschmidt, rest on no scientific basis, for they rely entirely on the coincidence of certain faces, losing sight of the fact that it is the internal atomic structure that regulates both the relative importance of a face and twinning. Only when the internal structure can bring coincidence between the ultimate elements can twinning occur. This is a case where the results of X-ray examination of structure could bring out the true nature of the mode of grouping.

Only one specimen measured (neglecting one that gave an angle between the *c*-axes near 36°, but which shows traces of dislocation in such a direction that the specimen may, originally, have had an angle near 38° or 39°) diverges at all widely from these two means of $42\frac{1}{2}$° and 38°. Here, a small crystal is attached unsymmetrically on a face of a larger one, but they also have a prism-pair normal to the plane containing the *c*-axes, as in the other specimens. In this specimen the angle between the *c*-axes is about 48°, not near any probable twin-plane, and, in any case, it is an isolated specimen of doubtful orientation. I only mention it for completeness and because there seems such a strong tendency for the formation of twins, especially in this zone. Incidentally, it might be mentioned that a combination of an Esterel-twin and one on ($30\bar{3}2$) would give an angle of 48° 10′, but no external trace of such combined laws is visible on the specimen.

E. *Twinning on* ($21\bar{3}1$).

Besides the examples described above, all of which, except the Verespatak type, have their twin-planes in the same zone, two other modes of twinning were determined in the Cornish material. These have their twin-planes in another zone. In one, the twin plane is ($21\bar{3}3$), in the other ($21\bar{3}1$). The latter was discovered in the material collected since reading this paper. As it seems a more important one than the other, fifteen examples of it having been found, I will describe it first. One or two specimens had been collected already on my first trip, but, without more confirmatory evidence no definite interpretation of them could be arrived at. The occurrence of so many of the same nature made it evident that there was some genuine law responsible for their formation.

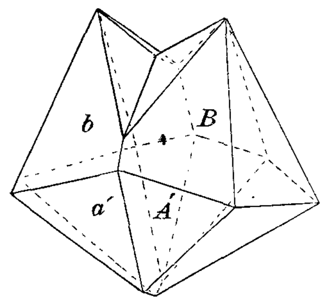


Fig. 6.
β-Quartz twinned on ($21\bar{3}1$); from Wheal Coates, Cornwall.

Their characteristics deviate from those of twins on ($20\bar{2}1$) in a similar way to that in which twins on ($21\bar{3}3$), to be described farther on, deviate from twinning on ($10\bar{1}1$). A possible twin-plane was therefore looked for somewhere in the neighbourhood of ($20\bar{2}1$) and near the zone of [($21\bar{3}0$), ($21\bar{3}3$)]. Finally, twinning on ($21\bar{3}1$) was found to show the characteristics of these specimens. The *c*-axes are rather over 30° apart and the faces *a′* and *A′* are nearly in a plane, while *b* and *B* meet at a biggish angle (fig. 6). This is the case in twinning on ($21\bar{3}1$) where the axes meet at 33° 8′. One crystal was found suitable for measuring with cover-glasses fixed on to its faces and a two-circle measurement was carried out of all six upper faces of each crystal. The larger individual is at the same time Esterel-twinned with another crystal, but the two portions do not interfere with each other. The Esterel-twin was also measured, the larger crystal being set up with its *c*-axis vertical. The measurement entirely confirmed this law, the deviations being even less than for the Esterel-twinned crystal. In this special case ($12\bar{3}1$) was the twin-plane actually found. But other specimens show the other orientation. It is interesting to note that this, again, is one of the laws predicted by G. Friedel, with 'index' 6 and 'obliquity' 2° 55′. Fig. 6 gives an idealized elevation of the group, while pl. IX, no. 21, shows one orientation, and nos. 22 and 23 the other. All three crystals are from Wheal Coates.

F. *Twinning on* $(21\bar{3}3)$.

I had found a specimen among the Esterel bipyramids, some years ago, that seemed to be a twin, but, having no other specimen of the same kind, I had kept it for future examination. It seemed to have characteristics between those of a ξ-twin and those of an Esterel-twin. It looked very much like a symmetric ξ-twin that had received a sideways

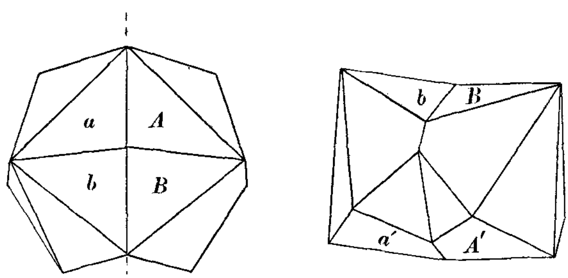


FIG. 7 *a*. FIG. 7 *b*.
β-Quartz twinned on $(21\bar{3}3)$; from Cornwall and Esterel Mts.
(*a*) Plan (the dotted line is the trace of twin-plane). (*b*) Elevation.

twist, but there was no trace of any dislocation or displacement. One of the specimens from Belowda Beacon had exactly the same disposition, and, being also a well-formed specimen, I studied it more closely and compared it with the Esterel specimen. There was no doubt about their being of identical structure. They seemed to follow a law intermediate between Esterel- and ξ-twinning, and I finally found that twinning on $(21\bar{3}3)$ gave an assemblage having these characteristics. Four faces slope together on the upper side of the group; those marked *a* and *A* are almost in one plane (figs. 7 *a* and *b*), while the other two, *b* and *B*, meet at an angle near 15°. This is the case for twinning on $(21\bar{3}3)$. The theoretical angle between the *c*-axes is 83° 32′, which agrees with that observed and accounts for the similarity between this twin and a ξ-twin in which the angle is 84° 34′. Since describing these specimens I have found a third example that still further confirms the law. It must be an exceedingly rare one, however, and only be capable of formation under the exceptionally favourable conditions in which all these numerous twins were able to develop. The three specimens are all shown on pl. IX. No. 24 is the first one found at Wheal Coates. No. 25, also from Wheal Coates, is not so well developed, but the law is still easily recognized; it is shown from below for comparison with the ξ-twin shown in the same way in no. 10 of pl. VIII. It will be seen that the edges, between the pair of faces of each crystal that meet at the junction, run in the same direction in the ξ-twin, whereas in this law they meet at an appreciable angle. No. 26 is the Esterel specimen, a two-circle measurement of which fully confirmed the law.

G. *Doubtful Twins.*

Of the remaining few specimens, some seem as though they might also be genuine twins, but they are isolated cases and not sufficiently perfect for measurements to confirm any definite law. They may belong to a series of twins with twin-faces in the same zone as $\xi\,(11\bar{2}2)$ and $s\,(11\bar{2}1)$. The second one, twinning on s, is known in α-quartz as Breithaupt's law or the 'Zwickau law', and is a very probable one. The angle between the c-axes is $48°\,54'$. A specimen from the Esterel Mts. showed an angle somewhere between 48° and 50°, but I cannot certify it, even between these wide limits. Two specimens from Cornwall were very roughly measured. The c-axes of the one were somewhere near 34°, the other near 62°. A rather improbable law with twin-plane $(33\bar{6}2)$ requires $33°\,44'$. The nearest to 62° that is the least improbable is an angle of $57°\,36'$ for the face $(11\bar{2}4)$. There only remain a few cases which are obviously chance intergrowths and a few nodular groups in which several of the constituent elements are not sufficiently visible for their relation to some of the more visible but apparently irregularly joined parts to be deciphered.

General Conclusions.

The relative importance of twinning with inclined axes in β-quartz, as well as the frequent occurrence of laws unknown or very rare in α-quartz, warrant an entirely separate treatment of the twin-laws for these two varieties of quartz.

In β-quartz, Esterel twinning is by far the most important, occurring about twice as often as ξ-twinning. This latter law comes next in importance.

Of those laws whose existence is rendered probable by a low 'index' and low 'obliquity' (compare G. Friedel, loc. cit.) those in the zone $[(10\bar{1}0), (10\bar{1}1)]$ seem much more capable of existence than those in the zone $[(11\bar{2}1), (11\bar{2}2)]$. It is interesting to find three of the new laws among those rendered probable by their low 'index' and 'obliquity'; twinning on $(30\bar{3}2)$, $(20\bar{2}1)$, and $(21\bar{3}1)$ being among the first that might be expected, according to G. Friedel. The Zinnwald law seems of easy formation, but it will need a more satisfactory definition to render it acceptable.

The small number of specimens found of twinning on $(21\bar{3}3)$ shows that this is a much rarer law than the others. (Since writing the description of the law, however, I found another, very large and sharp, but less symmetric, specimen amongst the ξ-twin lot of my Esterel material.) The same might be suggested for the Sardinian law, but the nearness of other laws possibly interferes with its more frequent formation.

The main conclusion I have arrived at, after examination of this material, however, is that more useful progress can be obtained by systematic study of even second-rate material, if it be abundant, than by the description of a few exceptionally good specimens, that may turn out later to be but chance conjunctions. The cases on which the idea of 'hetero-twinning' is based are somewhat of that nature. G. Friedel has pointed out that the normal interpretation of Breithaupt's law or the Zwickau law is quite sufficient, without any new theory. The same applies to Paul and Goldschmidt's[1] description of a 'hetero-twin' of orthoclase. From their description of it, I have no doubt that it is caused by the simultaneous presence of two laws, the Carlsbad and Baveno laws, which, as I have shown in the Esterel andesines, lead to groups in which the middle member, that acts as link for the other two, is often quite invisible. The same groupings have been observed at Four-la-Brouque in Auvergne[2] and at Zarzalejo near Madrid,[3] but these have been described in rather indefinite terms. I have myself collected such twinned crystals of orthoclase at Zarzalejo that are quite comparable to the 'Carlsbad-Baveno' combination found in the Esterel andesines. And it is shown in the present paper that combined law groups also occur in quartz, such as might give rise to ideas of 'hetero-grouping'. It is doubtful whether the Zinnwald grouping is due to such a double law, although there is a possibility of this. A combination of the Esterel law and the Sardinian law would, for instance, give a group of three crystals in which the c-axes of the outer two crystals would be at 38° 44′.

[1] F. Paul and V. Goldschmidt, Orthoklas-Heterozwilling. Zeits. Kryst. Min., 1909, vol. 46, p. 471.

[2] A. Lacroix, Min. de France, 1896, vol. 2, p. 89; 1910, vol. 4, p. 815.

[3] L. Fernández Navarro, Bol. R. Soc. Española Hist. Nat., 1919, vol. 19, p. 137. [Min. Abstr., vol. 1, p. 13.]

No visible trace of this association can be observed, however, on the numerous specimens found; and the fact that no specimen of the Sardinian law was noticed amongst the Cornish crystals is, also, against such an explanation. A measurement of the extinction-angles in a section through one of these groups might give information on this point, but the three-fold grouping may only exist at one small point in the interior of the crystal. The section might, very possibly, not be cut so as to include this point, and the result would still be indefinite. The suggestion made by Prof. G. Friedel, that X-rays could be used to elucidate the true nature of this group, seems to me the most likely to lead to positive results. Such 'hetero-twins' as are assimilable to parallel growths of two different substances in definite orientations would still be possible, but this condition would at once imply coincidence of the intimate particles at the contact, and we are brought back to the existence of a twinning plane or axis.

Addenda: Since the above was written a paper by J. Bindrich,[1] on porphyry-quartz twins, has been brought to my notice. This paper raises several points that can usefully be discussed here. Beside Esterel and Verespatak twinning, he observed two examples of the Sardinian law and gives confirmatory measurements of them. This law not having been observed in Cornwall, it is interesting to find it confirmed in other porphyry-quartzes. Bindrich has, however, overlooked the fact that an example of the Sardinian law, from the Esterel, was described in this Magazine in 1922. He also observed two examples of the Zinnwald grouping, giving Jenzsch's rather misleading definition of 'twinning on $(11\bar{2}0)$'. He observed no other laws, although he mentions in a final paragraph a number of cases of supposed 'hetero-twins'. Some of these may possibly be found to follow one or other of the laws mentioned in this paper.

Another point seems to need discussion. He divides his Esterel-law specimens into groups, according to the direction of the contact surface. In these porphyry-quartzes it is unwise to lay stress on the direction of this surface. The change in orientation of the intimate particles, that gives rise to a twin, took place at one small point, during the growth of the crystal. After that, each portion of the twin may be looked upon as growing independently of the other. The contact-surface depends, then, entirely on a number of external influences and does not represent the true composition-plane of the twin at its point of inception. One of the

[1] J. Bindrich, Centralblatt Min., Abt. A, 1925, 203–210. [Min. Abstr., vol. 3, p. 378.]

results of this independent growth of the parts is that the individual portions can be readily separated from each other. In the Esterel twins that have thus become separated, the contact, where it is truly plane, is always parallel to $(10\bar{1}1)$. Designation of types on this basis leads to much complication and confusion. This is another reason that makes it preferable to separate twinning of β-quartz from that of α-quartz, otherwise we have such designations as 'the Esterel type of the Reichenstein-Griesernthal law' and have to further define which of the two latter divisions it belongs to, &c.

An attempt is therefore made here to simplify matters by treating both varieties of quartz quite independently and reserving for porphyry-quartz special names for each law. The other laws having been generally identified with the locality where they were first observed, I would suggest the following designations for all twin-laws so far observed in β-quartz. (Only twin-planes are mentioned and not axes, the former being sufficient, in all the cases mentioned, to define the law.)

Laws of twinning for β-quartz.

Angle between the c-axes.	Twin-plane.	Name of law.	Remarks.
84° 34′	$(11\bar{2}2)$	'Verespatak' law	Rather than the 'Verespatak' type of the Gardette or Japanese law.
76 26	$(10\bar{1}1)$	'Esterel' law	The first description published was that of the Esterel specimen.
115 10 (64 50)	$(10\bar{1}2)$	'Sardinian' law	This name is retained, having already been used in former papers. The original specimen may have been of α-quartz, but its true twin nature, even, is doubtful.
55 24	$(30\bar{3}2)$	'Belowda Beacon' law	First identified from Belowda Beacon and confirmed from the Esterel and Wheal Coates.
42 58	$(20\bar{2}1)$	'Cornish' law	Found both at Belowda Beacon and Wheal Coates.
33 8	$(21\bar{3}1)$	'Wheal Coates' law	So far, not observed elsewhere in good specimens.
83 30	$(21\bar{3}3)$	'Pierre Levée law	First observed on a specimen from the Esterel, near 'Pierre Levée'. The best example is from there.

I am still leaving aside the Zinnwald grouping until a satisfactory definition can be given for it. As previously stated, the angle between the c-axes is 38° 13′, half that for Esterel twinning. The rather doubtful existence of Wedding's supposed law on $(30\bar{3}1)$ makes it advisable not to include it here; if it were found really to exist, it might be termed the 'St. Agnes' law. It is very probable that this list will be added to in the future, several laws being still possible, e.g. Breithaupt's law (Zwickau law).

In conclusion, I wish to express my best thanks to Sir John Flett, without whose help it would have been quite impossible for me to obtain the material to start this work. He collected, himself, valuable material and interested others in searching for still better. To Mr. William Boxhall I am indebted for the material from the china-clay pit near Belowda Beacon, and to Prof. H. L. Bowman for very kindly giving me detailed information for finding the Wheal Coates material. I would also like to mention Prof. G. Friedel, who has done so much to clear the question of twinning in quartz; and also to thank him for the kindly personal advice which he has given to me when any special difficulty arose.

EXPLANATION OF THE PLATES VIII AND IX.

Plate VIII:

A. β-Quartz twins from Belowda Beacon china-clay pit, Cornwall (enlarged 1·4 diam.).

Nos. 1 and 2. 'Esterel' twinning; very symmetric in no. 1; somewhat less, owing to parallel growth, in no. 2.

3. Repeated 'Esterel' twin; the three *c*-axes in one plane. I–II, II–III are Esterel twinned; I–III simulate twinning on $(30\bar{3}1)$.
4. 'Verespatak' twinning; twin-plane $(11\bar{2}2)$.
5. The same, less symmetrically developed.
6. The same, seen from below. (Compare no. 25, pl. IX.)

B. β-Quartz twins from Wheal Coates, Cornwall (enlarged 2·3 diam.).

7. Esterel twin of symmetrical development.
8. The same; one crystal complicated by parallel growth.
9. 'Verespatak' twin.
10. The same, seen from below. (Compare no. 25, pl. IX.)
11. Triplet of two 'Esterel' twins (I–II and II–III Esterel twins).
12. Triplet of an 'Esterel' twin (I–III) and a 'Verespatak' twin (I–II).
13. Triplet of two 'Verespatak' twins (I–III and II–III).
14. Two 'Esterel' twins, simulating a twin on $(30\bar{3}1)$. I–II and I–III are Esterel-twinned; II–III simulate a twin on $(30\bar{3}1)$.

Plate IX: Rarer twin-laws of β-Quartz (enlarged 2·5 diam.).

Except nos. 17 and 26 from the Esterel Mts., France, these are all from Wheal Coates, Cornwall.

Nos. 15–17. *'Belowda Beacon' law*; twin-plane $(30\bar{3}2)$. No. 15 is at the same time Esterel-twinned, the small crystal below being Esterel-twinned with the left-hand one of the main group. No. 17, from the Esterel Mts., is a twin on the 'Belowda Beacon' law given here for comparison.

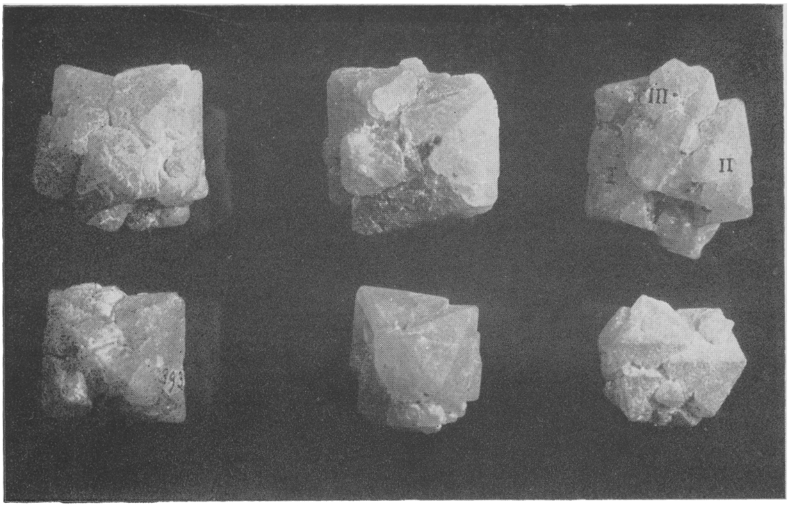
18. Twin on *'Cornish' law*; twin-plane $(20\bar{2}1)$.

19 and 20. *'Zinnwald law'* (?). The angle is very close to that of the previous law. They can hardly be distinguished from each other except by careful measurements.

21–23. *'Wheal Coates' law*; twin-plane $(21\bar{3}1)$ and $(12\bar{3}1)$. No. 22 is set up with the twin-plane vertical and normal to the plate; nos. 21 and 23 are set up with one crystal upright. It will be seen that the second crystals in 21 and 23 are orientated symmetrically with respect to each other; the twin-plane in the first being $(21\bar{3}1)$, and in the second $(12\bar{3}1)$.

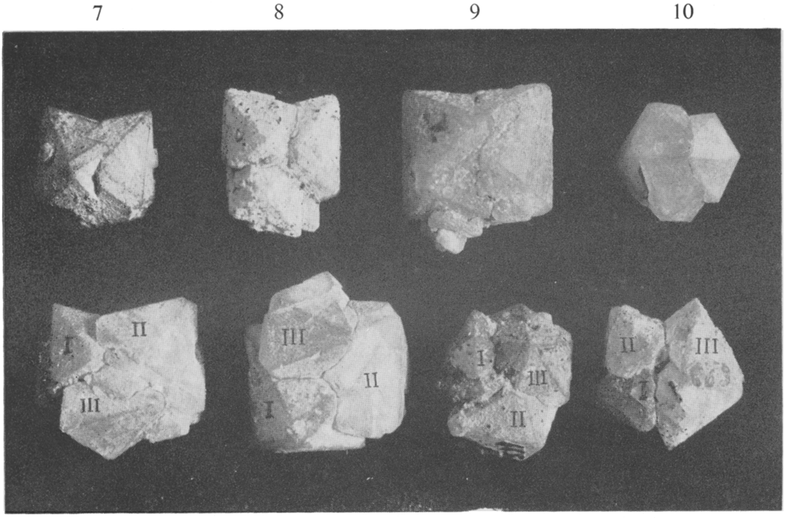
24–26. *'Pierre Levée' law*; twin-plane $(21\bar{3}3)$. All three specimens are symmetrically developed. No. 25 is seen from below, for comparison with the two ξ-twins nos. 6 and 10 of pl. VIII. In this law, the edges between the pair of faces that meet at the junction of the two crystals meet at a fairly wide angle, while in ξ-twinning they run from one crystal to the other in a straight line.

1 2 3



4 5 6

7 8 9 10



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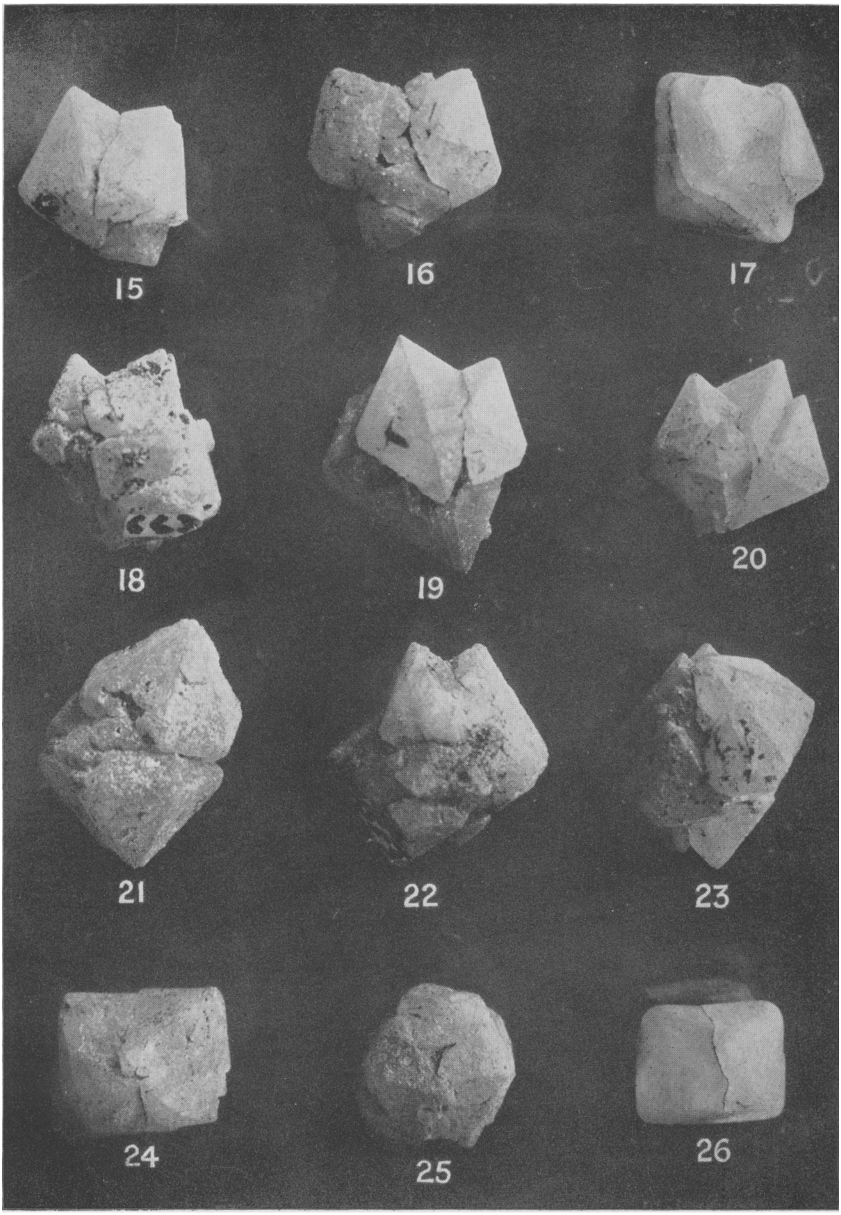

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