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TRANSLATION-GLIDING IN CRYSTALS

M. J. BUERGER, *Massachusetts Institute of Technology*

ABSTRACT

In the absence of any treatment of translation-gliding in English, this paper is presented as an introduction to forthcoming experimental and theoretical contributions to our knowledge of that subject. The fundamental concepts are discussed, and a tabulation of existing data and literature appended.

INTRODUCTION

The plastic deformation of crystals, judging by the literature, appears to be a subject of very remote interest to most crystallographers and mineralogists. The crystallographic investigations along this line have been carried on mainly by our more academic German contemporaries, especially by Mügge and Johnsen. On the other hand the metallurgists have, of late, deluged their literature with a large mass of data, accompanied by encouraging crystal structure explanations, bearing on the plastic deformation of metal crystals. While this branch of crystallographic metallurgy is still in its infancy, enough evidence has been brought forward to demonstrate that the plastic properties of metals are dependent upon, and to a remarkable degree, predictable from their respective crystal structures.

Not so much, unfortunately, can be said about our state of knowledge regarding the mechanism of plastic deformation of crystals other than metals. The investigations have been concerned mainly with mineral crystals, and most of them were on record before the advent of crystal structure analysis in 1912. These publications accordingly contain no crystal structure interpretations of the experimental observations recorded, nor have more recent papers attempted to give structure explanations of these earlier results. Except in a few cases of twin-gliding, subsequent observations have likewise been unaccompanied by discussions of structural significance.

The mineralogist may well study this field, not only to cast light upon the nature of crystal structure, but also because an understanding of the plastic flow of crystals is fundamental to an understanding of the plastic flow of rocks, and, in part, probably causally connected with recrystallization. Early concepts ascribed the changes of metamorphism to differential pressure, temperature, and recrystallization. More recently, it has been in vogue to discount these processes in favor of metasomatic exchange of fluid constituents, so much so, that the possibilities of the earlier ideas are perhaps not fully appreciated. It has been found that metals are constrained to recrystallize by reason of plastic flow and subsequent annealing, and the geologist would do well to study this question for his own peculiar applications.

Since no systematic treatment of the plastic properties of crystals has appeared in English, the present paper is presented to offer an introduction to several experimental and theoretical contributions which follow. Only that plastic mechanism to be designated as "translation-gliding" will be considered.

GENERAL FEATURES OF TRANSLATION-GLIDING¹

TWIN-GLIDING AND TRANSLATION-GLIDING. Plastic deformation mechanisms may be grouped into two major divisions, twin-gliding and translation-gliding. Twin-gliding is a clearly defined single mechanism while translation-gliding really includes several closely related phenomena. Twin-gliding involves a translatory movement of one part of a crystal in such a manner that this resulting deformed portion takes the relation of a twin to the remaining portion of the original crystal. In general, the crystallographic orientation of the twinned part has been altered in a regular manner prescribed by the corresponding twin law, and thus the slipping movement must be equally distributed in amount throughout the deformed crystal part.

Translation-gliding is a slipping process of *indefinite* magnitude which may take place between two portions of certain crystals. It differs from twin-gliding in that the magnitude of the slip may differ for various structural planes of the same attitude, and in

¹ A. Johnsen, Die Struktureigenschaften der Kristalle: *Fortschritte der Mineralogie*, etc., 3, 1913, pp. 100-110.

A. Johnsen, Schiebungen und Translationen in Kristallen: *Jahrbuch der Radioaktivität und Elektronik*, 11, 1914, pp. 248-259.

that, if the crystallographic orientations of the individual slipping blocks are altered at all, they are irrationally altered and thus do not take the relation of twins to one another. Since several distinct processes may be involved, these will be discussed under their respective titles for clearness.

PURE TRANSLATION. Pure translation is the simplest of translation-gliding processes. It involves a slip between two adjacent portions (blocks or sheets) of the crystal in such a manner that corresponding crystallographic elements remain parallel in each block (Figure 1). The planes along which the gliding takes place are designated by the symbol T , and the direction of movement by the symbol t . In all cases, both T and t are rational crystallographic elements.

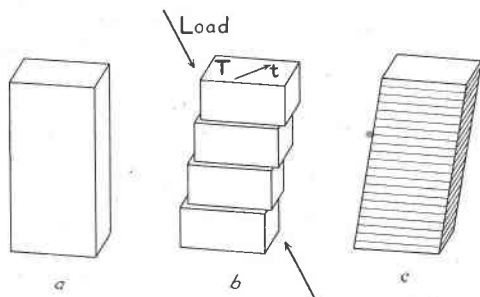


FIG. 1.

The determination of T is rather easily accomplished on a given deformed crystal; t is more difficult to obtain. To the first approximation, it may be said that translation takes place by block slipping (important exception to this is discussed elsewhere).² That is, the applied pressure forces blocks of the crystal to slip past one another without loss of continuity, the planes delimiting the blocks and along which the shear is localized being T . In general, natural crystal faces or ground-on surfaces not parallel to t will be found, after deformation, to be covered with striations marking the traces of T on those particular surfaces (Figure 1). These striations are exceedingly minute and must be searched for with high-magnification binoculars. Using a sharp (rather than diffused) light source, the steps between blocks and the blocks themselves, appear as thin striae marked by difference in intensity of illumination.

² M. J. Bueger, The Cause of Translation Striae and Strain-hardening in Crystals: *Proc. Inst. Metals Division, A. I. M. M. E.*, 1928, pp. 385-386.

Knowing its traces on the crystal surfaces, T may be identified by inspection, in simple cases, by merely noting what crystallographic face is parallel to all these traces. In more complex cases, especially in crystals of systems other than cubic, simple calculations may be necessary to establish T .

Surfaces parallel to t necessarily remain free from striations (Figure 2). This circumstance provides one of the two methods of determining t^3 (for the other method, see under Bend-gliding, p. 50); t is obviously the axis of the zone containing the plane T and those (other) faces free from striations. Thus, knowing these, t may be determined by inspection, or by the usual cross-multiplication of the symbols of the striation-free faces, one of which may be T .



FIG. 2.



FIG. 3.

It not infrequently happens that no faces of the deformed crystal are striation-free because a face parallel to t is not developed on the particular specimen in question. In experimental deformation, the remedy for this condition is to grind an artificial surface on a new crystal parallel to one of the possible translation directions or to seek a new crystal having this plane naturally developed. This direction, t , of course, will be some simple rational direction in the translation plane, so the possibilities are limited to only a few, usually two, directions. If deformation of this new specimen leaves the selected surface striation-free, the possibility chosen was the correct one.

It should be noted that, generally speaking, the plane T must be established by at least two non-parallel sets of traces. Thus, in the example shown in Figure 3, both T and t are indeterminate since the two sets of striations are parallel. In experimental work this condition may be remedied either by selecting a crystal for further testing which is rich in forms, or by grinding artificial

³ O. Mügge, Ueber Translationen und verwandte Erscheinungen in Krystallen: *Neues Jahrbuch für Min.*, 1898, I, p. 72.

facets of the desired attitude on less desirable material, such as cleavage pieces.

In isometric crystals T may also be identified by the fact that about the slip planes a slight anisotropism becomes localized.⁴ It has been assumed in certain quarters that one of the principal axes of the indicatrix of the resulting anisotropism corresponds with t , and this assumption appears very reasonable, indeed, from struc-

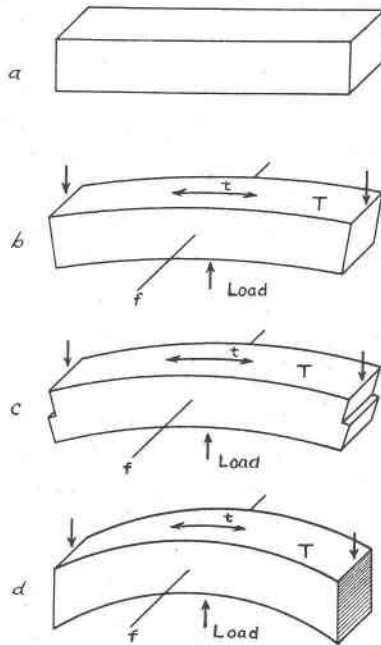


FIG. 4.

tural considerations, but this criterion for the determination of t has not always been judiciously applied. In crystal systems other than isometric the birefringence is correspondingly slightly altered along translation planes.

Crystals of high symmetry offer complications in the determination of the translation elements since frequently all crystallographically equivalent translation planes slip simultaneously, or because a plane may, when symmetrically loaded, simultaneously slip in several equivalent directions. Each crystal kind presents a problem unto itself.

⁴ See p. 51; also M. J. Buerger, *op. cit.*, p. 387 and 388.

BEND-GLIDING (*Biegegleitung*). Bend-gliding is a heterogeneous process, including at once elastic and plastic deformations. If a crystal is capable of easy translation, it may be perceptibly bent about an axis which lies in the translation plane and normal to t . The mechanism is pictured in Figure 4. Up to the limit of pure elasticity (which can not clearly be observed by simple inspection) the crystal subjected to bending stresses has its concave surface under compression and its convex surface under tension (Figure 4*b*). According to the principles of mechanics, a longitudinal shear is developed in the translation planes under these circumstances, and provided translation is sufficiently easy that it occurs before actual rupture of the crystal, the elastic strain is partially relieved, upon application of further stress, by translation along T (Figure 4*c*). The crystal thereafter remains permanently bent even though the causal external forces are removed. Examination of the crystal reveals traces of the translation planes as numerous fine striae on faces not parallel to t (Figure 4*d*).

It should be noted that each little layer bounded by translation planes is itself still under elastic strain, although the original strain between it and its neighboring layers has been relieved and reversed in direction by the plastic process, translation. Furthermore, the translatory movement is zero at some point in the bend (at the center of the idealized illustration in figure 4, *c* and *d*), and of finite value at other points, becoming cumulatively larger the greater the distance from the zero point. Thus, not only the bend-gliding as a whole, but the translation itself is heterogeneous in character. Further, a boundary of a unique sort exists between adjacent, bent translation blocks. On one side of the boundary, the face of the block under tension is stretched, on the other, the face of the layer under compression is contracted, so obviously the crystal units on either side of the operative translation planes are periodically in and out of phase or continuity with one another, even though the crystal itself remains optically clear and although the crystal faces parallel to t show no visual evidence of discontinuity. The forces residing in or about this boundary are responsible for maintaining the crystal in its bent condition.

Stibnite, cyanite and gypsum show bending to a remarkable degree. Cyanite, prepared for student use in optical crystallography by grinding through 100-mesh, may frequently be observed under the microscope to have been bent into a semicircle

in the process of crushing, while gypsum, in the form of a thin cleavage flake, may be bent into a complete cylinder.

Bend-gliding not only occurs in a directed attempt to produce it, but usually is an incidental accompaniment of attempts to produce pure translation. This results from the application of a non-uniform or eccentric load. Doubtless the peculiar boundary surface produced in bend-gliding contributes to the anisotropism of the translation planes of isometric crystals. In the experimental stretching of metal single crystal wires, bend-gliding is invariably present due to the varying rotations of the different slipping blocks.

When two flexible sheets in contact are bent about an axis so that slip occurs between them, the contraction on the concave sides of the sheets takes place in a direction normal to, and toward, the axis of bending, and the expansion of the convex sides of the sheets likewise takes place in a direction normal to, but away from, that axis. Consequently the direction of the shear between the sheets, which is the moment of their respective, adjacent contraction and expansion in the slip surface, necessarily occurs in a direction normal to that axis also. Thus if the direction of the shear is specified in a plane between two sheets, the bending axis is known to lie in that plane and at right angles to the shearing direction, or conversely, if the bending axis is known, the direction of slip is fixed.

This circumstance supplies the other method of determining t . In certain cases it is useful, but in others it may be misleading or confusing. This happens when slip may occur in several directions at once, in which case the surface of the crystal may present a confusingly warped appearance; or other planes at angles to the one under observation may also function as slip planes, in which case these may produce a meaningless apparent bending of the latter. This possibility may be disregarded if the surface under observation is definitely striation-free.

The bending axis or folding axis is designated by the symbol f . Since it perforce lies normal to t in T , it need not necessarily be a rational crystallographic direction.

TWIST-GLIDING. Certain crystals are capable of undergoing a considerable amount of plastic twisting about a torsion or twisting axis, τ . With the exception of NH_4Cl and NH_4Br , the known crystals characterized by this property are of relatively low symmetry, possibly because if the phenomenon occurs in crystals of high

symmetry its presence is masked by other plastic processes taking place simultaneously in numerous equivalent directions. NH_4Cl and NH_4Br are unique, among crystals of high symmetry, in having only three equivalent translation directions, and these at right angles, so that one translation direction can function independently of the others.

The mechanism of the process is but poorly understood. After twisting, the crystal displays the striations characteristic of translation along T parallel to t (Figure 5). The planes, T , farthest from

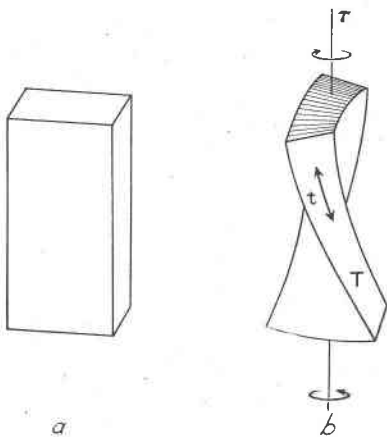


FIG. 5.

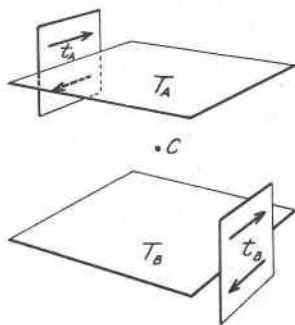


FIG. 6.

the twisting axis would normally be lengthened the most by twisting, so they apparently slip relative to those nearer the axis and in this contraction thus tend to relieve the stretching effect. Faces not in the zone τ show, after deformation, a duplex warping. Curvature about one axis is due to different requirements of slip for planes at various distances from the central slipping axis; the other curvature appears to be related to an actual distortion of the slip planes (See Figure 6).

TRANSLATION-SYMMETRY. From a gross point of view, if a crystal is capable of translation along a plane $T = (hkl)$ in a direction $t = [uvw]$, it may slip along any plane of the family of planes having the attitude with respect to the crystallographic axes indicated by (hkl) regardless of central distance. This is diagrammatically shown in figure 6, in which translation is simply represented by its essential quality, a shearing couple, the direction of the arrows

representing the differential displacement of translation thus being drawn parallel to t ; the plane of the couple is conveniently represented as normal to T , but this is not necessary for a general demonstration. If T_A slips, any other parallel plane, T_B , may do so in a corresponding manner and in the same sense. Thus, between the two sets of vectors indicative of the translation process, a center of symmetry, C , is introduced. In other words, translation processes are centro-symmetrical, considered from a point-group, symmetry viewpoint, and in finding the number of equivalent translation planes of a given crystal, its point group must be multiplied by a symmetry center. A number of the crystal classes unite through this multiplication process, reducing the 32 crystal classes to 11 centro-symmetrical groups.⁵ The 32 point groups unite to form the 11 centro-symmetrical groups as follows:

Crystal System	Centro-Symmetrical Group	Included Point Groups		
		Schoenflies' Symbol	Roger's Symmetry Formula ⁶	Roger's Number ⁶
Triclinic	S_2	C_1	No symmetry	1
		S_2	C	2
Monoclinic	C_2^h	C_2	A_2	3
		C_1^h	P	4
		C_2^h	$A_2 \cdot P \cdot C$	5
Orthorhombic	V^h	V	$3A_2$	6
		C_2^v	$A_2 \cdot 2P$	7
		V^h	$3A_2 \cdot 3P \cdot C$	8
Tetragonal	C_4^h	S^4	\overline{AP}_4	9
		V^d	A_4	10
		C_4^h	$A_4[\overline{AP}_4] \cdot P \cdot C$	13
	D_4^h	C_4	$\overline{AP}_4 \cdot 2A_2 \cdot 2P$	11
		D_4	$A_4 \cdot 4A_2$	12
		C_4^v	$A_4 \cdot 4P$	14
		D_4^h	$A_4[\overline{AP}_4] \cdot 4A_2 \cdot 5P \cdot C$	15

⁵ Theodor Liebisch, *Grundriss der Physikalischen Krystallographie, Leipzig, 1896*, pp. 180-181.

A. Johnsen, Die Struktur eigenschaften der Krystalle. *Fortschritte der Mineralogie, etc.*, **3**, 1913, p. 137.

⁶ Austin F. Rogers, A Mathematical Study of Crystal Symmetry: *Proc. Am. Acad. Arts & Sci.*, **61**, 1926, p. 200.

A Tabulation of the 32 Crystal Classes: *Am. Mineralogist*, **13**, 1928, p. 571.

Crystal System	Centro-Symmetrical Group	Included Point Groups			
		Schoenflies' Symbol	Roger's Symmetry Formula ⁶	Roger's Number ⁶	
Hexagonal	C_3^i	C_3	A_3	16	
		C_3^i	$\overline{AP}_6(C)$	17	
	D_3^d	D_3	$A_3 \cdot 3A_2$	18	
		C_3^v	$A_3 \cdot 3P$	19	
		D_3^d	$\overline{AP}_6 \cdot 3A_2 \cdot 3P(C)$	20	
	C_6^h	C_3^h	$\overline{CA}_6(P)$	21	
		C_6	A_6	23	
		C_6^h	$A_6[\overline{AP}_6][\overline{CA}_6](P)(C)$	25	
	D_6^h	D_3^h	$\overline{CA}_6(P) \cdot 3A_2 \cdot 3P$	22	
		D_6	$A_6 \cdot 6A_2$	24	
		C_6^v	$A_6 \cdot 6P$	26	
		D_6^h	$A_6[\overline{AP}_6][\overline{CA}_6](P) \cdot 6A_2 \cdot 6P(C)$	27	
	Isometric	T^h	T	$4A_3 \cdot 3A_2$	28
			T^h	$4\overline{AP}_6 \cdot 3A_2 \cdot 3P \cdot (C)$	30
		O^h	O	$3A_4 \cdot 4A_3 \cdot 6A_2$	29
T^d			$3\overline{AP}_4 \cdot 4A_3 \cdot 6P$	31	
O^h			$3A_4[3\overline{AP}_4] \cdot 4\overline{AP}_6 \cdot 6A_2 \cdot 9P \cdot (C)$	32	

ONE-SIDED GLIDING. A curious consequence of symmetry is that, unless one of the proper elements is present in a special space relation to T and t , the translation itself may be one-sided. The only symmetry element necessarily involved in translation is a center, and conversely if the process of translation is operated upon by a symmetry center, only translation in its original sense results. Thus, in Figure 6, the translation couple in T_A is clockwise, and the symmetry center, C , reproduces it correspondingly clockwise in T_B .

Under each of certain conditions of specific, possible space relationship between the translation elements and the symmetry elements of the point-group of a crystal, the translation direction automatically loses the general characteristic of rotational sense, and becomes "two-sided." The possible relations which give rise to "two-sidedness" are:

- (a)⁸ An even-fold symmetry axis parallel to t (Fig. 7).
- (b)⁷ A symmetry plane normal to t (Fig. 8).
- (c)⁷ An even-fold symmetry axis normal to T (Fig. 9).
- (d) A symmetry plane parallel to T (Fig. 10).

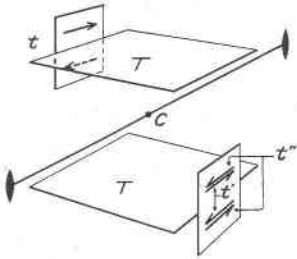


FIG. 7.

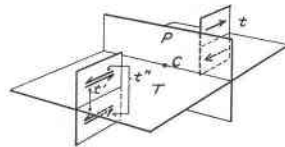


FIG. 8.

In each of the figures, the symmetry center, C , reproduces the initial couple, t , in its original sense, t' , while the other symmetry element simultaneously reproduces it in the opposite sense, t'' . This new, double couple generated by symmetry therefore, lacks a rotational sense, and consequently translation must take place with equivalent ease in either direction. In order to avoid confusion, the indicated symmetry operations in the illustrations have not been completed.

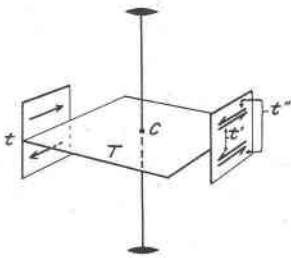


FIG. 9.

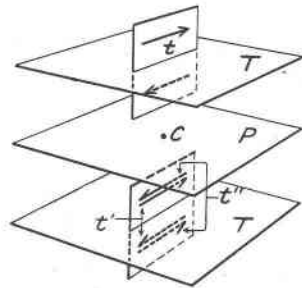


FIG. 10.

⁷ After his experimental discovery of one-sided translation-gliding in $\text{BaBr}_2 \cdot 2\text{H}_2\text{O}$ these two relationships were implicitly set forth by O. Mügge, Ueber Translationen und verwandte Erscheinungen in Krystallen: *Neues Jahrbuch*, 1898, I, pp. 112-113.

⁸ This relationship, in addition to those of Mügge, was recognized by A. Johnsen, Schiebungen und Translationen in Krystallen: *Jahrbuch der Radioaktivität und Elektronik*, 11, 1914, p. 256.

Due to the centro-symmetrical character of translation-gliding, the translation-gliding group, a , is identical with b , and similarly c is identical with d , as indicated by the brackets. The accompanying figures have been particularized for simplicity; if these are redrawn in a general fashion (using a general position for both translation plane and translation direction, and employing a random angle between the plane of the translation couple and the translation plane) it will be evident that the bracketed relations involve each other. Thus, whether Mügge was aware of the fact or not, his conditions for two-sided gliding⁹ embrace all possible ones.

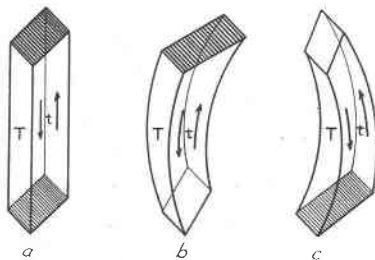


FIG. 11.

One-sided translation-gliding is most easily observed in bend-gliding, especially in monoclinic crystals lacking the above mentioned two-sided translation conditions. For example, with $T = (100)$, $t = [001]$, $f = [010]$ as shown in Figure 11, if the crystal is bent convex forward, the translation couple sense being counterclockwise as seen in the figure, striae appear only at the top (Fig. 11*b*). If it is bent concave forward, striae appear only at the bottom (Fig. 11*c*). Both $\text{BaBr}_2 \cdot 2\text{H}_2\text{O}$ and low- KClO_3 offer excellent illustrations of one-sided gliding. In both examples, a family of planes in the b -axis zone may be readily sheared counterclockwise as viewed from the positive end of the b -axis, but translation-gliding is impossible in the reverse sense. On the other hand, cyanite and $\text{KMnCl}_3 \cdot 2\text{H}_2\text{O}$, crystals whose triclinic symmetry, in the strictest sense, require non-equivalence of translation senses, apparently glide with equal ease in both senses. Doubtless even here there is a real difference in gliding ease which is only inapprecia-

⁹ Mügge, as well as Johnsen, actually stated conditions under which one-sided gliding was to be expected. They implied, of course, two-sided gliding under conditions which were excluded for one-sided gliding.

ble because of the lack of sensitivity of the methods of investigation.

TRANSLATION-GLIDING CRITERIA. Since both translation-gliding and twin-gliding processes give rise to striations which may resemble one another very closely on superficial examination, methods other than simple inspection must usually be resorted to in order to distinguish between these two types of gliding. All such methods are based upon the general principle that twin-gliding changes the orientation of the parts of the crystal affected according to a definite twin-law, while translation-gliding either does not change the orientation of the affected part, or, in the case of bend-gliding, changes them continuously and irrationally.

Probably the simplest means of distinguishing these processes is by etching. Having determined the plane and direction of gliding, the crystal is ground and polished parallel to any random or predetermined face and etched with some suitable reagent. Twinning then becomes apparent as a grating or plaid etch pattern, showing up twinned and original portions of the crystal in contrast because their different orientations on the polished face react with different degrees of rapidity to the etchant. As a rule, the slower the action of the etchant (by dilution, for example) the greater the contrast between the twins. Since translation-gliding does not change the orientation of adjacent slip blocks, etching produces a uniform etch on a crystal deformed by this mechanism.

A somewhat more elaborate criterion may be had by goniometric measurement. The angle between the sides of the grooves, which give the visible appearance of striations due to difference in intensity of light reflected by them to the eye, is characteristic of the twin law, and the sides of the grooves are facets which yield reflections as good as the original faces, except as their decreased size effects the image. Translation, on the other hand, proceeds with a different intensity along the various possible T planes of a family, thus changing any originally smooth face (except one parallel to t) to a minutely undulating one, with the result that the reflection from this face is broken up, or drawn out over a range.

Twin-gliding in anisotropic crystals may often be established by the change in optical orientation of the resulting twin lamellae, but this criterion, while definite, should be used with caution because of possible confusion with the slight change in anisotropism which appears along translation planes in translation-gliding.

If the gliding plane is parallel to a symmetry plane, twin-gliding may be disregarded as a possibility and the deformation ascribed to translation-gliding.

Such criteria are not always necessary. It may be perfectly obvious that twin-gliding has taken place when a large secondary twin is produced (e.g. in calcite), but in general, translation-gliding which always produces small striations, can not be regarded as established until it has been proven that the striations are not the result of polysynthetic twin-gliding on a very minute scale.

EXPERIMENTAL METHODS FOR INVESTIGATION OF TRANSLATION-GLIDING

The softer and more plastic crystals usually require no special apparatus for the investigation of their gliding elements. This very susceptibility to deformation, however, sometimes causes great difficulty, since a very soft crystal will mold itself about and take an accurate impression of any instrument used to apply the deforming force. Thus, at least two opposite surfaces of the crystal will fail to reveal the attitude of the striations resulting from the gliding, because they are casts of the surfaces of the instrument and the substratum. In a later paper on the deformation of some of the alkali halides and related crystals, the writer will indicate several methods of investigating these softer substances.

On the other hand, hard crystals invariably cleave, part, or shatter if they are simply pressed, as in a vise. This difficulty can be easily overcome by embedding the crystal in some plastic medium. As the crystal is deformed, its deformation is resisted by the enclosing substance, which thus affords a pressure to counteract incipient parting. One of the simplest methods of attaining this end is that due to Kick; this has been fully described in an earlier communication.¹⁰ The crystal is embedded in alum or some other plastic substance which has been introduced into a copper tube in a molten condition, and pressure is then applied axially to the tube and its contents.

Kick's method has several drawbacks: the bulging of the tube causes a certain unevenness of the forces acting on the crystal because the bulge is rarely symmetrical; the ductility of the

¹⁰ M. J. Buerger, The Plastic Deformation of Ore Minerals, I, *American Mineralogist*, 13, 1928, pp. 4-5.

copper prevents the application of very high retaining pressures; the experimental difficulties attending the emplacement of the crystal in the molten medium prevent fixing its orientation with desirable exactness; and finally, critical work with small crystals is practically impossible.

An apparatus ascribed to Tresca,¹¹ and used almost exclusively by Johnsen,¹² and later workers, is much more suitable for gliding investigations. A diagram of the writer's modified apparatus of this general design is shown in Figure 12. It consists essentially of a stout steel cylinder containing a one centimeter bore. One

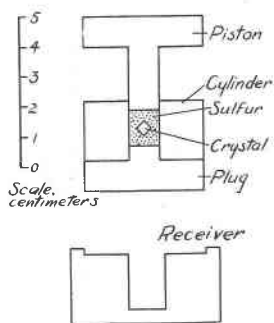


FIG. 12.

end of the bore is closed with a plug, and into the other is fitted a piston. Filling of the apparatus preparatory to deformation is accomplished as follows: precipitated sulfur¹³ is packed into the plugged cylinder, and given an initial compacting by means of the piston, until it fills about half the bore. A shallow pit is scraped in the top of the compressed sulfur and a little new sulfur dusted therein to make a somewhat yielding base for the crystal. The crystal may then be lowered into the bore of the cylinder with a pair of forceps, set in approximate orientation on the sulfur base and centered. Final adjustments of orientation and centering can be accomplished while viewing the setting with the aid of a pair of binoculars sighted directly down the bore. When the crystal is satisfactorily set, more sulfur is dusted into the bore until full and

¹¹ *Comptes Rend.*, 70, 1870, p. 288.

¹² A. Johnsen, Einfache Schiebung an Lithiumsulfat-Monohydrat: *Neues Jahrb., B. B.*, 39, 1914, p. 508.

¹³ Sodium nitrate, later removable by solution in water, as well as the ether-soluble mercuric chloride, have also been used for this purpose.

carefully compressed with the piston. The last operation is repeated until just enough of the bore is unoccupied by the sulfur to allow the piston to be seated properly for starting the compression.

The compression, in the case of a relatively soft crystal, may be carried on in a large vise, but ordinarily a hand-driven testing machine with a capacity of some 50,000 pounds is desirable for deforming the harder crystals. After sufficient pressure has been applied, the plug is removed from the cylinder¹⁴ and then replaced by the slug receiver. The apparatus is then again placed in the press, and the piston expels the hardened sulfur plug with its contained crystal. The latter may be removed for examination by solution of the enclosing sulfur in carbon disulfide.

With the aid of this apparatus crystals as small as a millimeter along an edge may be easily investigated, and no renewal of apparatus is necessary for successive tests.

THE CRITICAL DATA OF TRANSLATION-GLIDING

The accompanying table briefly lists the available critical data of translation-gliding. Only the information relating to crystals other than metals¹⁵ have been included, and the writer hopes the list will be found to be reasonably complete. The classification adapted is, to some extent, arbitrary; it follows that of centrosymmetrical symmetry groups. For certain purposes it may appear desirable to regroup the data from a point of view of structural similarity but in the present state of knowledge this type of classification could not be carried to completion.

The information for minerals followed by an asterisk has been deduced from observations of natural occurrences and not from experiments.

¹⁴ This must be done with the aid of a vise and wrench. For this purpose it is desirable to have both plug and cylinder fitted with square flanges.

¹⁵ A short resumé of our knowledge of translation-gliding in metals will be found in the publication: *Cohesion and Related Problems*, a general discussion held by the Faraday Society, November, 1927, especially the article by M. Polanyi: *Deformation, Rupture, and Hardening of Crystals*, p. 76.

CENTRO-SYMMETRICAL GROUP	CRYSTAL	NUMBER OF EQUIVALENT ELEMENTS		FUNDAMENTAL ELEMENTS		TRANSLATION SENSE IF ANY	OBSERVER	REFERENCE			
		<i>t</i>	<i>T</i>	<i>t</i>	<i>T</i>						
S_2 (triclinic)	Cyanite $KMnCl_3 \cdot 2H_2O$ Aminoguanidine nitrate $CH_6N_4 \cdot HNO_3$	1	1	[001]	(100)	?	Mügge	<i>Neues Jahrbuch</i> , 1898, I, 81-82.			
		1	1	[101]	(010)		"	"	1892, II, 95-102.		
		1	1	[001]	(010)		"	"	<i>Zeit. Krist.</i> , 71, 1929, 70-73.		
C_2 (monoclinic)	Low- $KClO_3$	1	1	[100]	(001)	} Counter-clockwise from +b } Counter-clockwise from +b	Fischer	<i>Neues Jahrbuch</i> , B. B., 32, 1911, 37.			
	$BaBr_2 \cdot 2H_2O$	1	1	[001]	(100)		Mügge	"	1889, I, 145-160.		
	Orpiment	1	1	[001]	(010)		"	"	"	1898, I, 111-114.	
	Vivianite	1	1	[001]	(010)		"	"	"	"	1898, I, 81.
	Erythrite	1	1	[001]	(010)		"	"	"	"	1898, I, 98.
	Sulfonal	1	1	[010]	(100)		"	"	"	"	1898, I, 98-99.
	$(C_2H_6) \cdot (SO_2)_2C(CH_3)_2$	1	1	[010]	(100)		"	Siefert	<i>Centralblatt. f. Min.</i> , 1920, 101.		
	Lorandite	1	1	[010]	(101)		"	Mügge	<i>Neues Jahrbuch</i> , 1898, I, 99.		
	Miargyrite*	1	1	[010]	(100)		"	"	"	"	1898, I, 100-101
	Gypsum	1	1	[001]	(010)		"	"	"	"	1898, I, 90-96.
	Calcium butyrate	1	1	Ca.[301]	(010)		"	"	<i>Zeit. Krist.</i> , 71, 1929, 75.		
	$Ca(C_4H_7O_2)_2$	1?	1?	[010]?	(001)?		"	"	"	"	71, 1929, 76.
	Barium butyrate	1?	1?	[010]?	(001)?		"	"	"	"	
$Ba(C_4H_7O_2)_2$	1?	1?	[100]?	(001)?	"	"	"	"			
Pyroxene*	1?	1?	[001]?	(100)?	"	"	"	"			
Mica	1	1	[100]	(001)	"	"	"	"			
Leadhillite	2	1	[110]	(001)	"	"	"	"			
Wolframite*	?	1	?	(001)	"	"	"	"			
		?	?	?	(100)	"	"	"			
		?	?	?	(010)	"	"	"			

* Inferred from observation of natural occurrences; not experimental data.

CENTRO-SYMMETRICAL GROUP	CRYSTAL	NUMBER OF EQUIVALENT ELEMENTS		FUNDAMENTAL ELEMENTS		TRANSLATION SENSE IF ANY	OBSERVER	REFERENCE
		<i>t</i>	<i>T</i>		<i>T</i>			
C ₂ ^s (Monoclinic continued)	Li ₂ SO ₄ ·H ₂ O	{ ?	1?	?	(100)?	}	Johnsen	Neues Jahrbuch, B.B., 39, 1914, 515-516.
		{ ?	1?	?	(301)?			
		{ ?	2?	?	(121)?			
		{ ?	1?	[101]?	(101)?			
		{ ?	1?	?	(301)?			
P ^s (orthorhombic)	Stibnite Bismuthinite Guanajuatite Manganite Aragonite Columbite* Barite Diammine zinc chloride (NH ₃) ₂ ZnCl ₂ Anhydrite Sulfur Bronzite* Strontium butyrate Sr (C ₄ H ₇ O ₂) ₂ Epsomite	1	1	[001]	(010)	}	Mügge " " Veit Mügge " Veit Mügge Mügge Veit Mügge Veit Mügge " "	Neues Jahrbuch, 1898, I, 77-79 " " 1898, I, 81. " " 1898, I, 81. Centralblatt. f. Min., 1922, 2. Neues Jahrbuch, B.B., 45, 1922, 131-133. " " 1898, I, 147-150. " " 1898, I, 151-152. " " B.B., 45, 1922, 128-131. Zeit. Krist., 71, 1929, 64-68. " " 1898, I, 73-77. " " B.B., 45, 1922, 133-135. " " 1920, 26-28. " " 1898, I, 114-118. Zeit. Krist., 71, 1929, 77. Centralblatt. f. Min., 1915, 33-36.
		1	1	[001]	(010)			
		1	1	[001]	(010)			
		1	1	[001]	(010)			
		1	1	[001]	(010)			
		1	1	[100]	(010)			
		2	1	[101]	(010)			
		1	1	[100]	(001)			
		2	2	[011]	(011)			
		1	2	[001]	(110)			
		1	2	[100]	(011)			
		1	1	[010]	(001)			
		1?	2	[100]?	(012)			
		2?	4	[110]?	(111)			
		1?	1?	[001]?	(010)?			
1?	1?	[010]?	(001)?					
1?	1?	[100]?	(001)?					
?	?	[110]?	(110)?					
?	?	[101]?	(100)?					
?	?	[011]?	(011)?					
?	?	[101]?	(101)?					
?	?	[102]?	(201)?					

* Inferred from observation of natural occurrences; not experimental data.

CENTRO-SYMMETRICAL GROUP	CRYSTAL	NUMBER OF EQUIVALENT ELEMENTS		FUNDAMENTAL ELEMENTS		TRANSLATION SENSE IF ANY	OBSERVER	REFERENCE
		<i>t</i>	<i>T</i>	<i>t</i>	<i>T</i>			
C_4^h (tetragonal)	Phosgenite	1	2	[001]	(110)		Taricco	<i>Atti. del Reale Acad. de Lincei</i> , 19, 1910, 278-284.
	Chalcopyrite	?	4	?	(111)	?	Mügge Mügge Buerger	<i>Neues Jahrbuch</i> , 1914, I, 43-48. " " 1920, 30-31. <i>Am. Mineralogist</i> , 13, 1928, 41-46.
C_3^h (hexagonal)	Dolomite	3	1	[01.0]	(00.1)		Johnsen	<i>Neues Jahrbuch</i> , 1902, II, 139-144.
D_3^h (hexagonal)	Magnesite	3	1	[01.0]	(00.1)		Johnsen	<i>Neues Jahrbuch</i> , 1902, II, 142.
	Siderite	3	1	[01.0]	(00.1)		"	" " " " " "
	Rhodochrosite	3	1	[01.0]	(00.1)		Veit	" " " " B.B., 45, 1922, 128
	Smithsonite	3	1	[01.0]	(00.1)		"	" " " " " "
	Calcite	3?	3?	[12.1]	(01.2)		Mügge	" " " " 1898, I, 119-123.
					\Leftrightarrow [110] Miller			
D_6^h (hexagonal)	Graphite	3	1	[21.0]	(00.1)		Mügge	" " " " 1898, I, 108-110.
	Brucite	3	1	?	(00.1)		Mügge	" " " " 1884, I, 57. " " " " 1898, I, 110-111.
D_6^h (hexagonal)	Ice	?	1	?	(00.1)		McConnel	<i>Proc. Roy. Soc.</i> { 48, 1890, 259-260. 49, 1891, 323-343.
	Molybdenite	3	1	[21.0]	(00.1)		Mügge	<i>Neues Jahrbuch</i> , 1895, II, 211-228. " " " " 1898, I, 110.

CENTRO-SYMMETRICAL GROUP	CRYSTAL	NUMBER OF EQUIVALENT ELEMENTS		FUNDAMENTAL ELEMENTS		TRANSLATION SENSE IF ANY	OBSERVER	REFERENCE
		t	T	t	T			
O ^h (isometric)	Salamoniac	3	6	[001]	(110)		Johnsen	<i>Neues Jahrbuch</i> , 1902, II, 149-153.
	Low-NH ₄ Br	3	6	[001]	(110)		"	" " " " " "
	NaF†	3	6	[001]	(110)		Johnsen	" " 1902, II, 148-149.
	Fluorite	6	3	[110]	(001)		Veit	" " B.B., 45, 1922, 122-125.
Galena		6	3	[110]	(001)		Mügge	" " 1898, I, 123-138.
				3	3	[100]		
Halit†		6	6	[110]	(110)		Taricco	<i>Atti. della Reale Acad. de Lincei</i> , 19, 1910, 508-511.
Sylvit†	KBr†	6	6	[110]	(110)		Reusch	<i>Ann. der Physik und Chemie</i> , 132, 1867, 443-444, and 449-450.
				6	6	[110]		
KI†		6	6	[110]	(110)		Johnsen	" " 1902, II, 146.
				6	6	[110]		
RbCl	Periclase	6	6	[110]	(110)		Johnsen	<i>Zeit. Krist.</i> , 52, 1912-13, 275-276.
				6	6	[110]		
High-NH ₄ I		6	6	[110]	(110)		Johnsen	<i>Zeit. Krist.</i> , 52, 1912-13, 275-276.
				6	6	[110]		
Sphalerite		?	4‡	?	(111)?		Veit	" " 1920, 29-30.
							Buerger	" " B.B., 45, 1922, 125-128.
								<i>Am. Mineralogist</i> , 13, 1928, 35-41.

‡ Incomplete or erroneous; new data to be published shortly.