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Movement of screw dislocations in hematite.

(With Plates I and II.)

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Summary. The surface structure of the basal pinacoid of crystals of hematite has been studied by phase contrast microscopy, yielding evidence of the movement of dislocations after the cessation of growth. Steps due to such movement are initiated from the centre of growth spirals, and cross the growth fronts without interrupting the growth layers. Viewed from the dislocation the step has the higher side on the left for right-handed spirals and vice versa. In the majority of cases the step is straight, but rarely it is curved or kinked. It is proposed to call such steps 'dislocation scarps'.

The number and length of dislocation scarps vary considerably in crystals from different localities. These variations probably reflect differences in the stress history of the crystals.

IT has been theoretically predicted that dislocations can move under stress, and this has been confirmed by observations on several crystals. Among the earliest to provide evidence of the movement of dislocations during growth were Forty and Frank,[2] Anderson and Dawson,[3] and Amelinckx,[4] on several different substances. In such

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[1] Now returned to the Geological Survey of Japan.

[2] A. J. Forty and F. C. Frank, Proc. Roy. Soc. Lond., vol. 217, ser. A, 1953, p. 262.

[3] N. G. Anderson and I. M. Dawson, Proc. Roy. Soc. Lond., vol. 218, ser. A, 1953, p. 255.

[4] S. Amelinckx, Natuurw. Tijdschr., 1954, vol. 36, p. 3. [M.A. 13–450.]

cases the growth fronts are kinked where they meet the step formed by the movement of the dislocation.

Experimental movement of dislocations has been carried out by several workers. For instance, Johnston and Gilman[1] demonstrated the movement of dislocations in lithium fluoride by subjecting crystals to applied stress for short periods and etching after each application of stress, when etch pits showed the positions of the dislocations. They showed that there was a minimum resolved shear stress below which none of the dislocations moved, while an increase of approximately 30 % caused all of them to move. They measured velocities of dislocations from 10^{-7} cm/sec to 10^{5} cm/sec [*sic*] with increasing stress. Thus it has been proved that dislocations can move either during or after the growth of a crystal.

One of the authors[2] has reported an example of the movement of screw dislocations in hematite after the cessation of growth. A study of several hundred crystals from nine localities has provided much additional evidence of the movement of dislocations after growth. The frequency with which dislocations had moved and the distances they had traversed vary from one locality to another. It is suggested that this may be connected with the stress history of the crystals after growth.

Distinction between types of step associated with dislocations.

It is necessary to distinguish between three types of step, on the surface of crystals, that may be connected with screw dislocations: the initial slip-step that gives rise to a screw dislocation; the step caused by movement of a screw dislocation after the growth of a crystal; and the step produced by movement of a screw dislocation during the growth of a crystal.

The first type of step is distinguished from the other two by the absence of any growth features associated with it; there will be neither spirals, modified spirals, nor simple closed circuits of layers. In the second case, of movement after the cessation of growth, a spiral or other growth features should be centred on the point at which the dislocation met the crystal face prior to its movement. When a dislocation moves, without dissociation, it leaves a step on the surface of the crystal equal in height to the displacement vector (Burgers vector) of the dislocation (it is convenient to refer to the step caused by the movement of a screw dislocation as a 'dislocation scarp', or simply 'scarp' where this is

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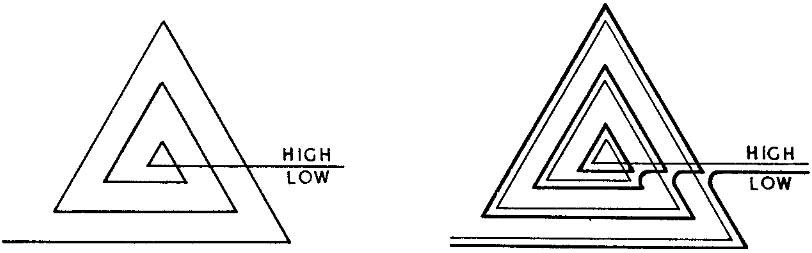
[1] W. G. Johnston and J. J. Gilman, Journal of Applied Physics, 1959, vol. 30, p. 129.

[2] I. Sunagawa, Amer. Min., 1960, vol. 45, p. 566.

unambiguous). The scarp begins at the centre of the growth spiral and may extend to the edge of the face, but often ends on the face. In the latter case a screw dislocation is present at the point of termination, but no growth spirals are developed. When the scarp is viewed from the centre of the spiral the high side is on the left in right-handed spirals and vice versa. This is the converse of case one, the type of step that could initiate a growth spiral. Apart from the small scarp which is formed, the movement of a dislocation in case two has no effect on the pattern of the growth layers, which cross the scarp without any re-entrant angle or deviation (fig. 1).



Figs. 1 and 2. Fig. 1 (left): Growth spiral in which dislocation moved after growth had ceased. Growth layers not interrupted by dislocation scarp. Fig. 2 (right): Growth spiral in which dislocation has moved during growth of crystal. A little further growth has taken place, causing the formation of closed loops with kinks.

In the third case the dislocation moves before the crystal has ceased to grow. Immediately after the movement of the dislocation the crystal might still appear as in fig. 1, having a spiral with a scarp running from its centre. The high side of the scarp in left- or right-handed spirals should be in the same sense as in case two. Fig. 2 represents the growth spiral of fig. 1 after a short period of further growth, during which the features are appreciably modified. It can be seen that one turn of the spiral is joined to an adjacent turn by the dislocation scarp, to form closed circuits with a marked kink. If the dislocation moved to another point, on the same face, a new growth spiral should form there, which would partly or completely destroy the dislocation scarp.

Observations.

Several hundred crystals of hematite have been examined from the following localities:

> Ayumikotan, Gihofuji, Sasazawa, and Saganoshima, all in Japan; Vesuvius; Stromboli; the Azores; Ascension Island; and Concord Valley, Grenada, British West Indies.

In the observations to be presented on hematite the dislocation scarps are associated with growth features. In no case has it been possible to prove with certainty that the growth pattern has been interrupted by the dislocation scarps. On a few crystals there are areas in which growth layers and dislocation scarps are very closely spaced, making interpretation difficult or impossible. If such regions are neglected none of the crystals studied shows interruption of growth patterns by dislocation scarps, and it must be concluded that in all these cases the dislocations moved after the cessation of growth. On all specimens so far examined, apart from some rare exceptions to be mentioned later, the dislocations have moved in straight lines parallel to the *a*-axes of the crystals. On some crystals different dislocations have moved in at least four directions, by displacement in a positive or negative sense along one or more of the *a*-axes.

It has not been possible to measure the height of the dislocation scarps, as most of them are probably only a few Ångstroms high. In many cases, however, it has been possible to measure the thickness of the layers emanating from the screw dislocations, when the spacing of the layers is sufficiently close. On the phase-contrast photomicrographs the visibility of each dislocation scarp seems to be the same as that of the spiral growth layers from the same dislocation. Thus the Burgers vector of the dislocation seems to be the same during growth and movement.

Evidence has been found of the movement of dislocations after the cessation of growth for isolated dislocations and for rows and closely spaced groups of dislocations.

The simplest case is illustrated in pl. I, fig. A. A left-handed triangular growth spiral is developed, with its edges parallel to the *a*-axes of the crystal. From the point at which the dislocation emerged at the centre of the spiral a straight line runs parallel to one side of the spiral. Looking from the centre of the spiral this line represents a step that is high on the right-hand side, and is the trace of the movement of the dislocation (all the photomicrographs in this paper were taken by positive phase-contrast microscopy, in which a white line marks the high side of any step). It can be seen that there is no interruption of the spiral pattern. If growth had continued after movement of the dislocation the pattern would have been interrupted by kinks, as in fig. 2, and a new spiral should start from the dislocation which now emerges at the end of the dislocation scarp. Such points can be seen in pl. I, figs. B, C, and D, but no growth spirals are developed about them.

The dislocations of dominated spirals have also been found to move.

In pl. I, fig. B a dominated spiral (lower left) is growing on the flanks of a larger dominant spiral. The dominated spiral only makes about half a turn before its growth front coalesces with a layer of the dominant spiral, both of which were found to be 7 Å high. Both dislocations have moved, and their scarps can be seen crossing the growth layers of the dominant spiral without interrupting the growth layers.

Pl. I, fig. C represents a more complicated area. There are several triangular spirals with short dislocation scarps, representing the movement of dislocations after growth had ceased. Scarps may be seen running in three directions, parallel to the edges of the growth layers. The characteristics are similar to those of pl. I, fig. A, but the density of dislocations is greater. Another example of moderate complexity is shown in pl. I, fig. D. Over thirty right-handed spirals originate from dislocations situated along a narrow band. The dislocations moved in one direction, forming a number of closely-spaced parallel scarps.

In all the examples described so far the dislocation scarps have been associated with obvious spirals. On many crystals there are less obvious spiral patterns arising from groups of dislocations that appear to be associated with misfit boundaries and other lattice defects. The movement of dislocations has often been observed in such cases, as shown in pl. II, fig. A. Two dislocation scarps run in different directions from a group of dislocations. These two scarps are of different heights. Since the growth layers are bunched into thick layers, it is not possible to determine the displacement of the dislocations nor to relate the height of the scarps to it.

On all the crystals to be described the dislocations moved in straight lines, with the exception of one very unusual crystal (pl. II, fig. B). The locality of origin of this crystal is unknown, but its microscopic characteristics closely resemble those of crystals from Ascension Island. Many of the dislocation scarps on this crystal are straight, but some are curved or kinked. Two dislocation scarps, starting from a pair of co-operating right-handed spirals, are straight for most of their length, but turn through an angle of about 10° shortly before they terminate on the crystal face. On the same crystal is a group of closely spaced right-handed spirals. The dislocation scarps associated with them start approximately normal to a prism edge and turn through an arc of about 30° to attain their usual direction parallel to one of the a-axes. Throughout this turn, and in the subsequent straight section, these scarps are strictly parallel in nearly every case. A few scarps, however, deviate slightly and seem to coalesce with neighbouring ones, apparently producing a greater displacement of the scarp. If these scarps have not coalesced they are too close to resolve. There is no doubt that these curved lines represent the movement of dislocations, since it can be seen that many of them start from the centres of growth spirals (some of these are out of the field of pl. II, fig. B). This also shows two left-handed spirals with dislocation scarps crossing the curved group of scarps.

The surface structure of crystals from Vesuvius is much more complicated than on most of the crystals examined from other localities. On the former most of the surface is covered by irregular thick growth-layers on which are superimposed a network of lines in three directions, parallel to the *a*-axes of the crystals. On the less complex parts of the surface it is possible to see that some of the lines of the network start from the centres of growth spirals, suggesting that they are dislocation scarps (pl. II, fig. C). On the crystal represented on this plate the layers are extremely thin and the turns of the spiral are very closely spaced, so that in the plate the spiral growth pyramids appear as very small light equilateral triangles. On crystals from this locality with more complex surface structures (a higher density of dislocations and many long scarps) there are many lines that cannot be shown to start from dislocations. Such lines, however, have the same appearance and characteristics as dislocation scarps in the simpler areas of these crystals, and it seems justifiable to identify them as such (pl. II, fig. D).

Complex patterns of growth features and dislocation scarps similar to those in pl. II, fig. D have been found on small areas of a few crystals from the island of Saganoshima and from Ascension Island. On such crystals the scarps may be as closely spaced as on crystals from Vesuvius but they are appreciably shorter. On these crystals the rest of the surface is far less complex, and may indeed be practically devoid of visible structure over relatively large areas. Some crystals from these localities may show no movement of their dislocations. If, however, any dislocations on these crystals show signs of movement then all of them are affected.

Three photomicrographs have been included of crystals that probably come from Ascension Island, because of the clarity with which they illustrate some features of the movement of dislocations. No crystals of which the locality is uncertain have been considered when deducing the stress history.

Stress history.

Crystals from Vesuvius, Ascension, and Saganoshima show evidence of the movement of dislocations. Crystals from Stromboli and the

Azores have suffered natural etching that may have obliterated any sign of the movement of dislocations. No evidence of such movement was found on crystals that were studied from Ayumikotan, Gihofuji, Sasazawa, and Concord Valley.

It is tentatively suggested that the movement of dislocations after growth has been caused by applied stress, which could have been produced by volcanic explosions or tectonic activity. A brief description of the conditions at each volcanic centre will be given to provide the evidence on which this conclusion is based. Stromboli and the Azores will be omitted from this discussion as the evidence is inconclusive. No dislocation scarps have been observed on crystals from the first four localities mentioned below, but they are present on some crystals from the next two and on all those examined from the last locality.

At Ayumikotan the rocks are mostly andesites and there is a little pyroclastic activity, but there is no trace of violent explosions. At Gihofuji there has been a fairly quiet outpouring of andesites. At Sasazawa there are rhyolites which are covered by andesites of the adjacent Kenashi volcano; the latter was moderately explosive, but no eruptions of extreme violence are recorded. At these three localities the crystals studied occurred at some distance from the eruptive centres: On Grenada there are andesitic and basaltic lavas with some tuffs, but the vulcanism does not appear to have been very violent. The small island of Saganoshima has two volcanic cones built of pyroclastic material with a few thin flows of trachybasalt; one of the cones is cut by a fault, which has left only half of the cone visible; the crystals studied were found close to the volcanic vents. On Ascension Island there are basalts, as well as some trachytic flows and tuffs; Daly[1] describes Green Mountain as a large basaltic cone that has been truncated by a major explosion; in the caldera thus formed a trachytic dome arose, and the eastern part of this dome, and some of the associated flows, were blown away by a second explosion, leaving a caldera nearly a mile long and 1000 yds wide. Of the Weather Post trachytic dome Daly records that there were three major explosions, after solidification, which formed calderas. The sporadic paroxysmal outbursts of Vesuvius are of such classical character that no detailed description is needed.

It will be seen from this account that dislocations do not seem to have moved after growth at those localities in which there has been fairly quiet vulcanism, or even where there has been a moderate development of pyroclastic rocks. At the other three localities, at which there is

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[1] R. A. Daly, Geol. Mag., 1922, vol. 59, p. 146.

either a fairly large fault or the vulcanism is much more violent, dislocations have moved after growth of the crystals had ceased. Although no precise correlation is possible, there seems to be a satisfactory qualitative association of the movement of dislocations with violent vulcanism or strong tectonic shock.

When crystals from Vesuvius, Ascension, and Saganoshima were compared it was found that those from Vesuvius had long dislocation scarps forming a network across the surface. Some crystals from Ascension and Saganoshima showed no movement of their dislocations, while others showed that all their dislocations had moved and over small areas of the crystals the pattern of dislocation scarps could have a complexity comparable with crystals from Vesuvius. On crystals from Vesuvius, however, all the dislocations had moved and produced long scarps. This suggests that they have suffered greater external stress than crystals from the other two localities, which seems to be in accord with the geological evidence.

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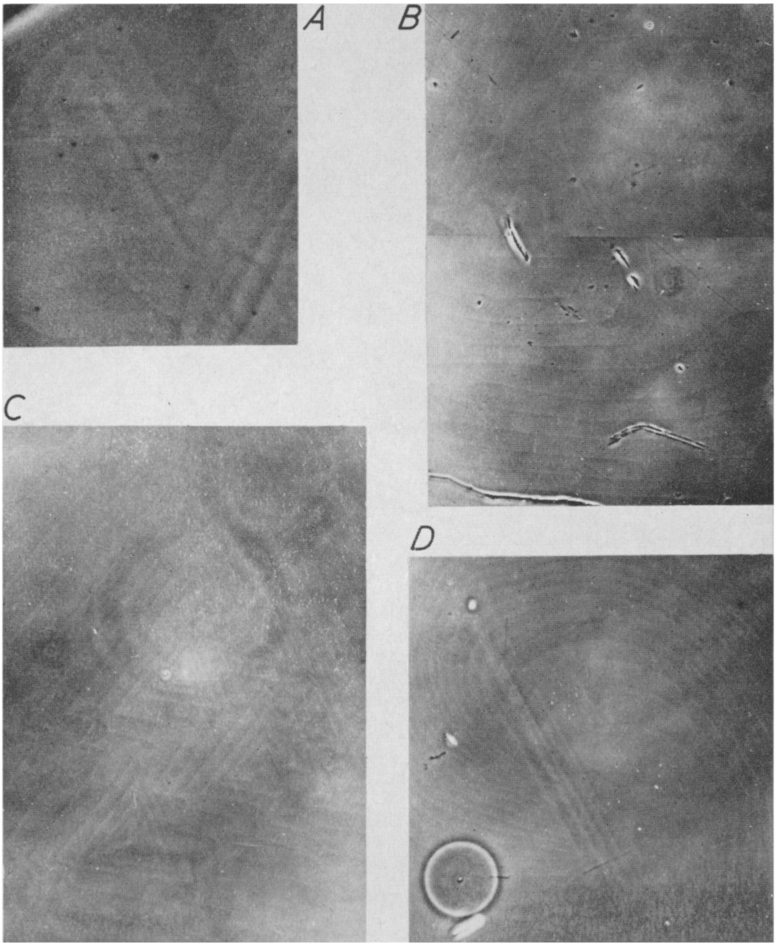
EXPLANATION OF PLATES I AND II.

PLATE I.

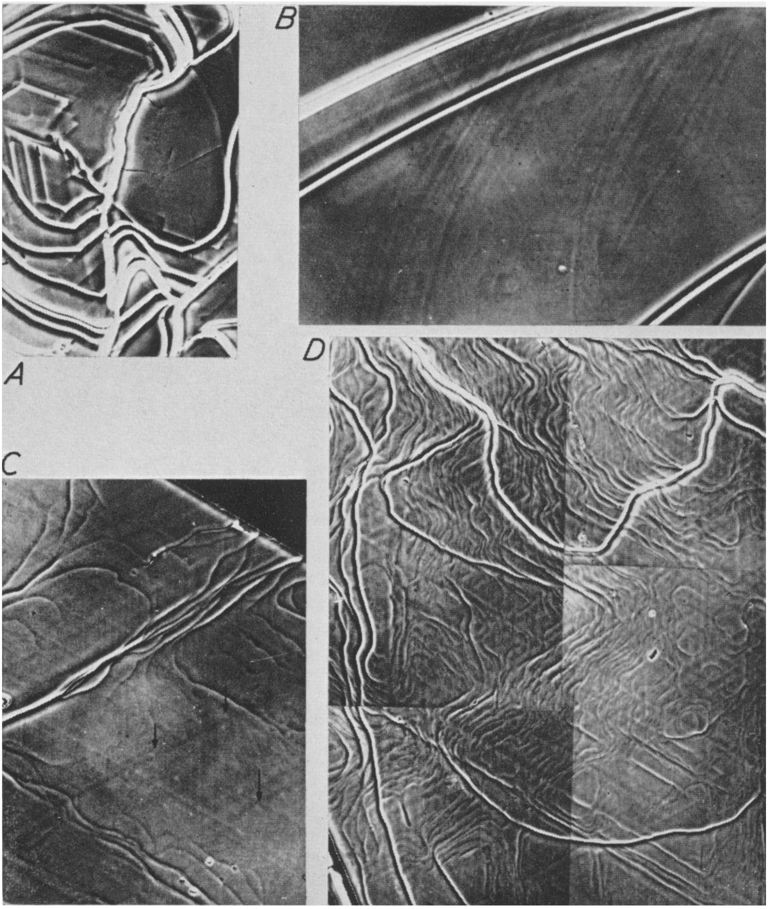
A. Left-handed spiral with dislocation scarp. Probably Ascension Island. × 260.
B. Dominant right-handed growth spiral and dominated spiral. Both have associated dislocation scarps. Both spirals have layers 7 Å thick. Saganoshima, Japan. × 90.
C. Short dislocation scarps run in three directions from different growth spirals in a closely-spaced group. Layers probably 4·6 Å thick. Ascension Island. × 115.
D. Almost linear group of over 30 right-handed dislocations. They moved in the same direction, producing closely spaced dislocation scarps. Probably Ascension Island. × 115.

PLATE II.

A. Group of dislocations with poorly developed spirals having thick, bunched layers. Two dislocation scarps run from the group in different directions. Saganoshima, Japan. × 115.
B. Closely-spaced group of right-handed spirals with curved dislocation scarps, some of which appear to coalesce. Dislocation scarps from two left-handed spirals cross the main group. Probably Ascension Island. × 110.
C. Small light triangles are growth spirals with very thin, closely-spaced layers. These bunch into thick irregular layers. Many dislocation scarps cross the field. Some terminate on spirals (arrowed). Vesuvius. × 100.
D. Similar to fig. C, but more complex. Dislocation scarps run in three directions at 60°. Vesuvius. × 80.



A. F. Seager and I. Sunagawa: Movement of Screw Dislocations in Hematite



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