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ON THE INTERACTION OF PRISMATIC AND GLISSILE DISLOCATIONS

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ABSTRACT

A transmission electron microscopy study of the interaction between a prismatic dislocation loop and a straight dislocation moving in its glide plane in MgO is reported. The interactions are discussed in terms of Kroupa's theoretical estimates of interaction parameters.

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I. INTRODUCTION

When crystals are quenched from high temperature or irradiated, a large supersaturation of point defects is introduced. On subsequent annealing these interstitials or vacancies cluster to form dislocation loops. In some materials, particularly ionic solids, plastic deformation introduces damage mostly in the form of vacancy and interstitial dipoles.[1] On heating to high temperatures, these dipoles break up into prismatic dislocation loops by pipe diffusion.[2] On further heating single dislocations through their long range elastic interaction with dislocation loops of suitable stress field start moving. Theoretical studies of various interactions between prismatic dislocation loops and straight dislocations have been made by Kroupa[3] and Saada and Washburn.[4] Hirsch and Silcox[5] observed in the electron microscope interactions between moving dislocations and loops in aluminum and with stacking fault tetrahedra in gold. Strudel and Washburn[6] reported some of the interactions between imperfect loops and dislocations in aluminum. However, direct electron microscopic evidence of the above interactions in ionic solids is still lacking. In the present report, the interactions between a prismatic dislocation loop and a straight dislocation in MgO are studied by repeatedly photographing the same area in the microscope after different annealing treatments done outside the electron microscope.

II. EXPERIMENTAL

Single crystals of magnesium oxide in the form of {001} thin slices (1 × 1 × 0.05 cm) were deformed plastically (bending) until they were full of slip bands. Details of the deformation are described elsewhere.[3] Initial thinning of these samples was done by chemical polishing in an orthophosphoric acid bath at about 150°C. Electron microscope samples were obtained using a jet polishing technique on these samples.[7]

Electron microscope samples were heated outside the microscope and the same area was photographed repeatedly under identical diffraction conditions. A Siemens 100 keV electron microscope was used. For the details of the contamination-free annealing techniques, see Ref. 8.

III. RESULTS

Figures 1 through 3 show interactions where the dislocation loop and the dislocation are on perpendicular planes and have the same b-vector. Figure 1 represents the same area after different annealing treatments done outside the electron microscope: A → B, 20 min at 1250°C; B → C, 20 min at 1250°C; C → D, 20 min at 1250°C; D → E, 49 min at 1100°C; E → F, 45 min at 1100°C; F → G, 45 min at 1100°C; G → H, 21 min at 1200°C; H → I, 34 min at 1200°C.
The interaction of a mixed dislocation at 3 with a prismatic dislocation loop at 4 of the same Burgers vector b = 1/2[101], is shown in Figs. 1-A through H. During annealing the dislocation through its long-range interaction moves and joins the loop in Fig. 1-F. Notice the reaction at the point of contact. The sudden change in the width of the dislocation is because of high screw component of the dislocation. The image width of the pure edge dislocation is about twice that of a screw dislocation in this orientation in MgO (Narayan, unpublished). As annealing is continued further, the annihilation of the dislocation loop occurs by pipe diffusion and prismatic slip. Notice the prismatic slip in the part of the dislocation loop which is near the surface of the foil (Fig. 1-G). On further heating (Fig. 1-H) the dislocation loop is completely annihilated both by pipe diffusion and prismatic slip. During annealing from Fig. 1-G to 1-H, the dislocation interacts with the loop 5 and annihilates it. The severe bending of the dislocation is because of localized interaction between the loop and the dislocation.[3] The dislocation also starts interacting with the loop 7 and on further heating it annihilates the loop

mainly by pipe diffusion (Fig. 1-I). Notice again the severe distortions of the dislocation due to localized interaction. A similar interaction is shown in Fig. 2-A through E. The annealing treatments in Fig. 2 were as follows: A → B, 49 min at 1100°C; B → C, 45 min at 1100°C, C → D, 45 min at 1100°C + 21 min at 1200°C; D → E, 34 min at 1200°C + 39 min at 1237°C. A mixed dislocation with a high screw component at 1 (b = 1/2[101]) interacts with the prismatic loop at 2 of the same b-vector. In this case the dislocation loop was very near to the surface. Therefore, the loop was annihilated primarily by prismatic slip rather than pipe diffusion. When the same dislocation interacts with the loop at 3 which is near the center of the foil, the annihilation of the loop occurs primarily by pipe diffusion. Severe bending of the dislocation due to localized interaction with the loop is apparent (see Fig. 2-C). In Fig. 3 at 1, almost a pure screw dislocation interacts with the prismatic dislocation loop which is very near to the surface and annihilation of the loop occurs primarily by prismatic slip. For Fig. 3A, the picture with g = [$\bar{2}$00] is also given which shows the interaction more clearly. A probable mechanism of this type of annihilation is proposed below. Annealing treatments in Fig. 3 are: A → B, 26 min at 1250°C; B → C, 40 min at 1250°C.

Figure 4 shows the interaction where the dislocation loop and the dislocation lie on the same plane and have same b-vector. The annealing treatments in Fig. 4 were as follows: A → B, 10 min at 1367°C + 15 min at 1116°C; B → C, 30 min at 1116°C + 26 min at 1280°C + 40 min at 1280°C. The dislocation loop and the dislocation both have the b-vector, 1/2[101], and are of pure edge character. They therefore have a strong interaction.[3]

Here the loop is primarily annihilated by pipe diffusion during annealing (see Fig. 4-C). The prismatic slip is almost absent because the dislocation, being at 90° to the glide cylinder of the prismatic loop, prevents gliding of the loop through its line tension force. The loop is like a wire ring fastened by strings of wires which prevent it from falling down.

IV. DISCUSSION

When the dislocation is normal to the plane of the loop of radius R, the forces on elements of dislocation vary as $1/r^3$ for $r \geq 2R$, where r is the separation between the loop and the dislocation. These forces depend both on b^{OG} (glide component of the Burgers vector of the dislocation loop) and b^{OP} (edge component of the Burgers vector of the dislocation loop). The total force of interaction obeys the inverse-square force law, i.e.,

$$F_r = F_m \frac{R^2}{r^2} \quad \text{for} \quad r \geq R \quad ,$$

$$= - F_m \quad \text{for} \quad r \leq R \quad ,$$

where F_m is the maximum force of interaction and is given by $f_1(\theta)\mu b^{OG} b/2$ for a screw dislocation and by $f_2(\theta)\mu\nu b^{OP} b/(1-\nu)$ for an edge dislocation. The function $f(\theta)$ represents the angular dependence of the interaction force, b is the Burgers vector of the dislocation, μ is the shear modulus of elasticity and ν the Poisson's ratio. The total interaction energy at distances $r \geq 2R$ varies as $1/r$ and for $r = R$ it is proportional to the radius of the loop R.

Thus, although the forces on elements of the prismatic edge loop ($b^{OG} = 0$) and pure screw dislocation due to mutual interaction are non-zero, the integral of forces (the total force of interaction between the loop and the dislocation) is zero. Since dislocations in Figs. 1 through 3 have a slight edge component which can interact with the loop and because the interaction between the loop and the dislocation is of localized nature, an instability is set up and the dislocation starts bending locally. As

the bending continues, the edge component of the dislocation increases locally and the interaction increases. This results in severe local bending of the dislocation (see particularly Figs. 1-G and 2-D).

When the dislocation loop is very close to the surface (Figs. 2 and 3), after the dislocation of the same Burgers vector has touched the loop, the subsequent annihilation occurs primarily due to prismatic slip by the following mechanism. The dislocation is divided into two segments at the point of contact by a process similar to that in Fig. 1-F. This results in two high energy constrictions. Both segments try to acquire lower energy configuration, i.e., become straight by removal of constrictions. The segment closer to the surface aided by surface image forces starts slipping out to the surface. This continues until the whole loop has slipped out.

When the dislocation loop and the dislocation are on the same plane corresponding to the geometry in Fig. 4, the total interaction energy E_{int} is given by[3]:

$$E_{int} = - \mu b^{OP} \frac{b}{(1-\nu)} r[1 - \sqrt{(1 - R^2/r^2)}] \quad \text{for} \quad r \geq R \quad ,$$

$$E_{int} = - \mu b^{OP} \frac{b}{(1-\nu)} r \qquad \text{for } r \leq R \quad ,$$

where r is the separation between the loop and the dislocation, and R being the radius of the loop. This predicts relatively strong interaction between the loop and the dislocation, which is shown in Fig. 4.

CONCLUSION

These observations provide direct evidence of various dislocation interactions. Both prismatic slip and pipe diffusion are the important mechanisms of dislocation loop annihilation. The former is important when the loop is near the surface and the latter when the loop is near the center of the foil. These loop-dislocation interactions may lead to dislocation channelling in irradiated ionic crystals.

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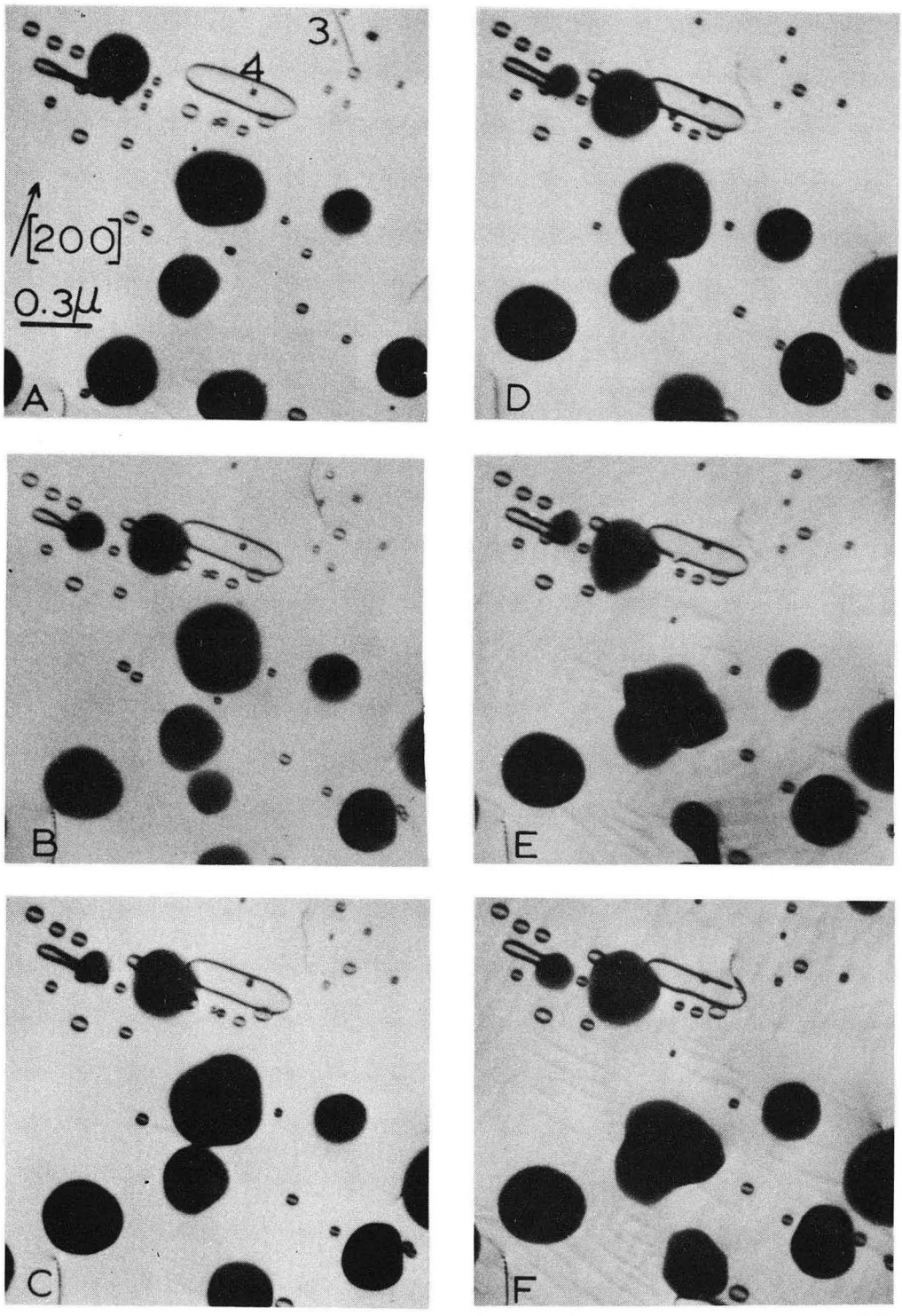
FIGURE CAPTIONS

Fig. 1 The interaction between a prismatic dislocation loop and the mixed dislocation of the same Burgers vector but on perpendicular planes. Notice the interaction at the point of contact in Fig. 1-F and annihilation of the loop partly by prismatic slip and partly by pipe diffusion (Figs. 1-G and 1-H). The bending in the dislocation (Fig. 1-H) is due to localized interaction between the loop and the dislocation.

Fig. 2 The interaction between loop 2 (near the surface) and dislocation 1 and annihilation of the loop primarily by prismatic slip. Loop 3 is annihilated primarily by pipe diffusion. The severe distortion in the dislocation is due to localized interaction.

Fig. 3 The interaction between the loop and almost a pure screw dislocation and annihilation of the loop by prismatic slip.

Fig. 4 The interaction between a prismatic dislocation loop and an edge dislocation with the same b = 1/2[101] and on the same plane. Notice the absence of prismatic slip in the dislocation loop.



XBB 733-1506

Fig. 1(A)-(F)

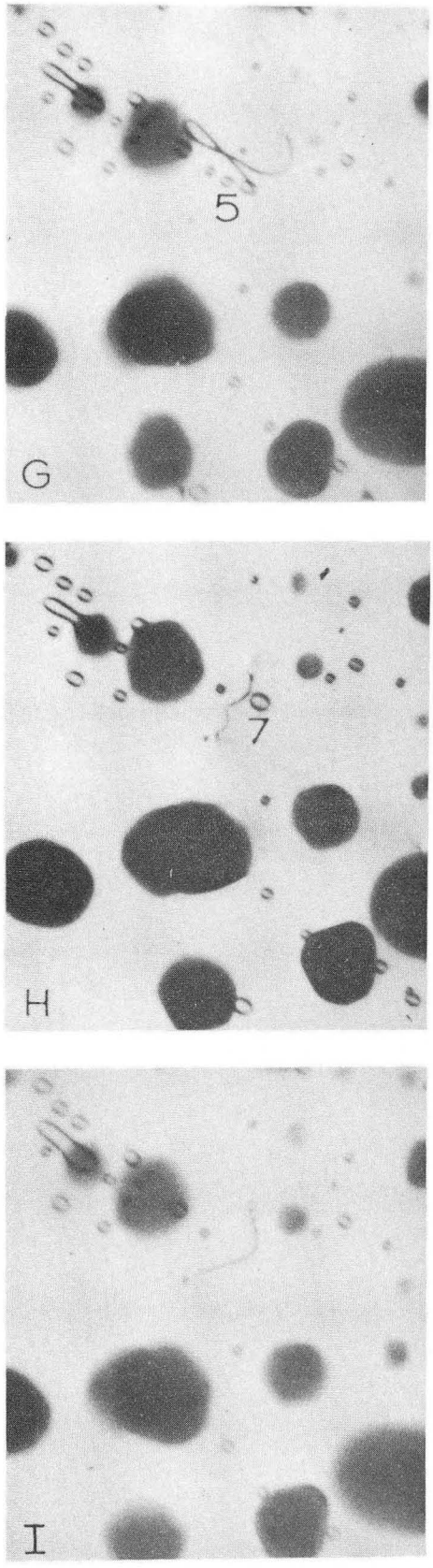


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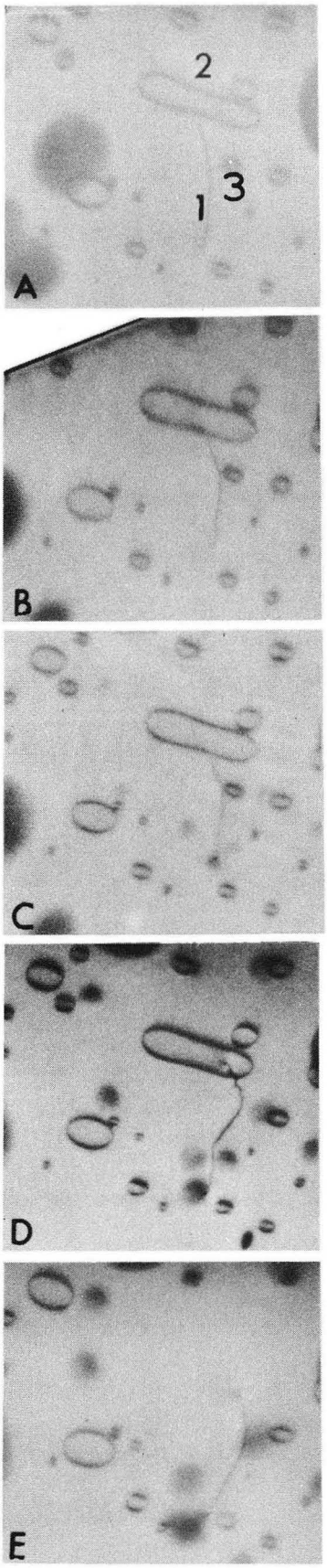
Fig. 1(G)-(I)



0.5 μ

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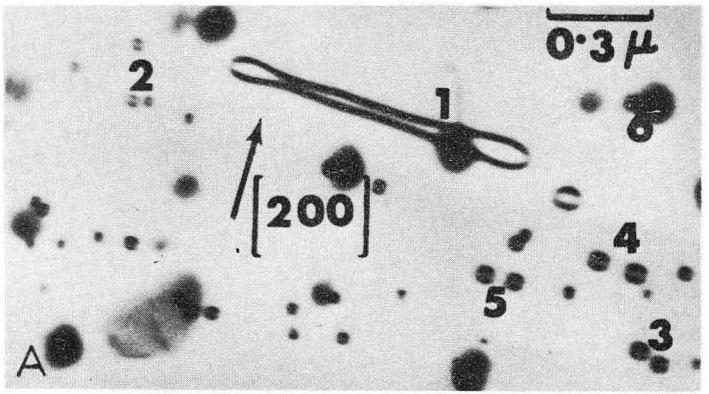
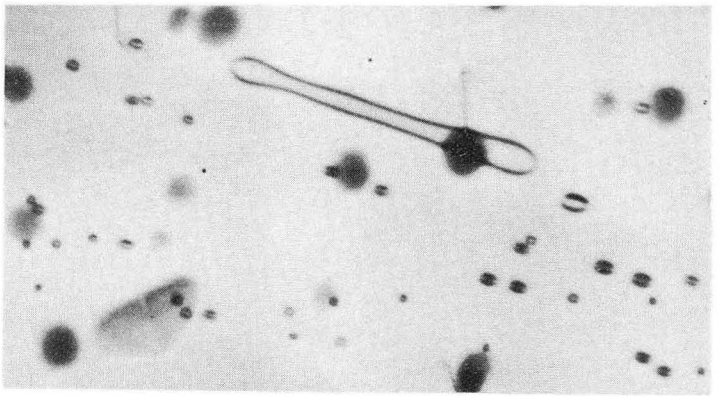
Fig. 2.





g - ve

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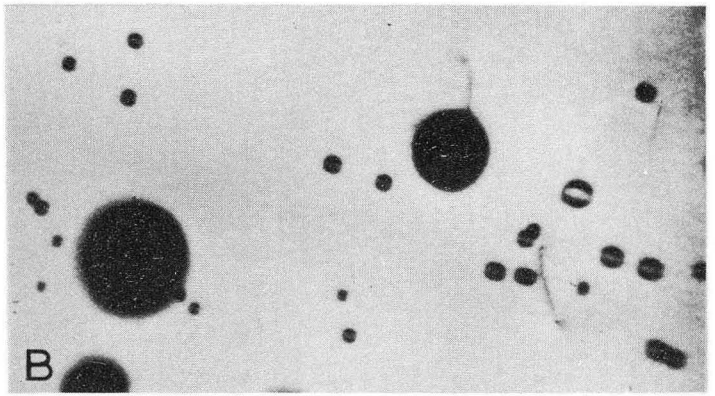


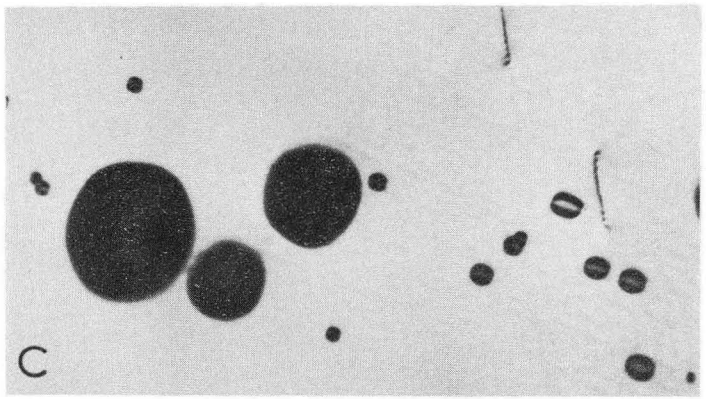
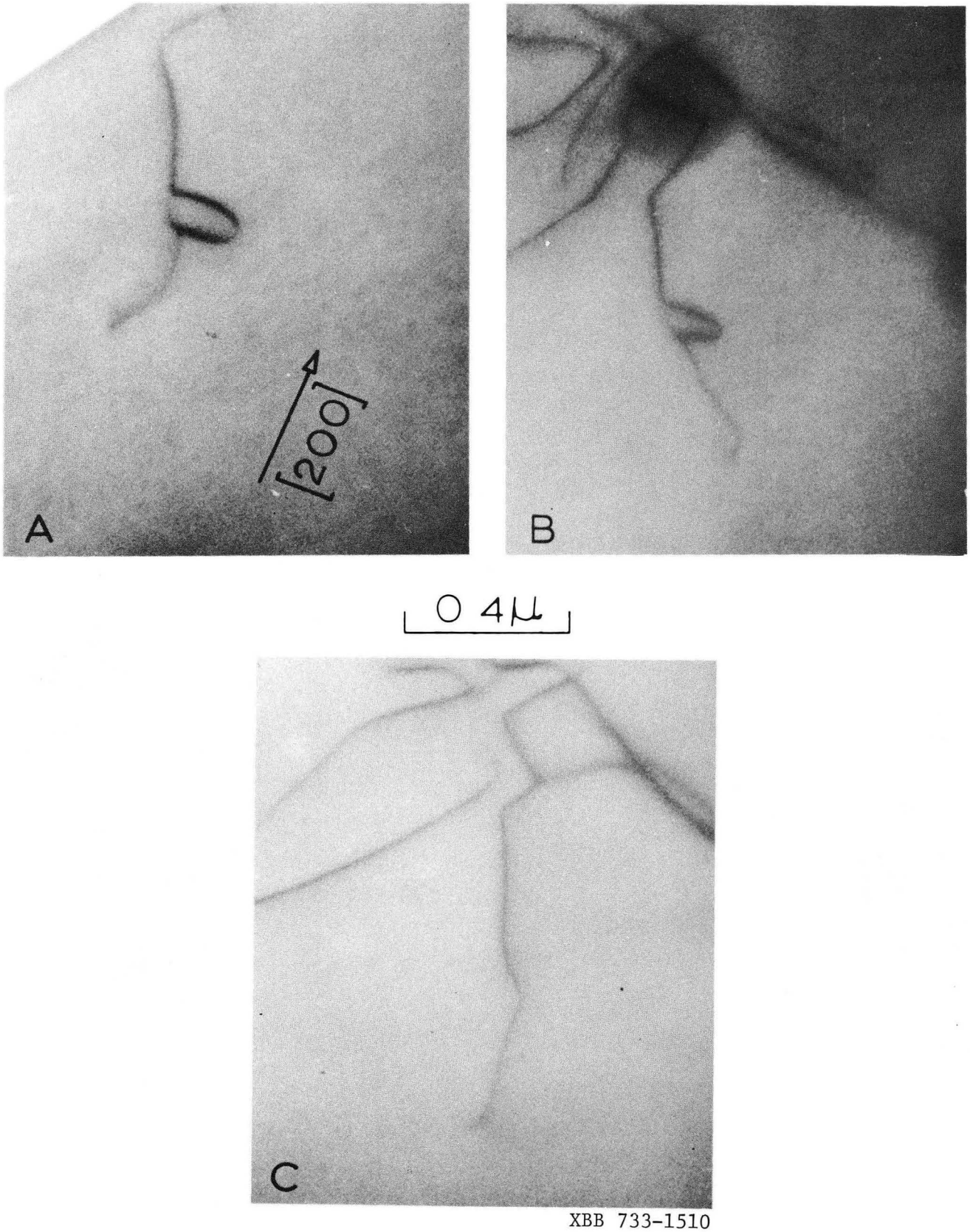


Fig. 3.



XBB 733-1510

Fig. 4.

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