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## Some Experimental Studies on the 1971 Lavas from Etna [and Discussion]

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## Some experimental studies on the 1971 lavas from Etna

BY M. J. DOWNES

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[Plates 2 and 3]

During the 1971 eruption, water and air quenched samples of lava were taken along a single flow, the one from near Rifugio Citelli to Fornazzo. The results of one atmosphere melting experiments on these samples, some of which were under controlled oxygen fugacity are discussed in relation to chemical and petrographic variations along the length of the flow as well as at its source. No significant element variation was found, particularly in respect of alkalis and water (volatilization effects). The  $\text{FeO}/\text{Fe}_2\text{O}_3$  ratio similarly lacks any significant variation except for a slight initial oxidation effect. With a liquidus of about 1200 °C, crystallization within the flow was well advanced, with over 50% of crystalline phases.

## INTRODUCTION

This paper describes some lava samples which were artificially quenched in the field, together with the results of laboratory melting experiments at one atmosphere on these samples. This study is based on one particular lava flow of the 1971 eruption of Mt Etna, the location of which

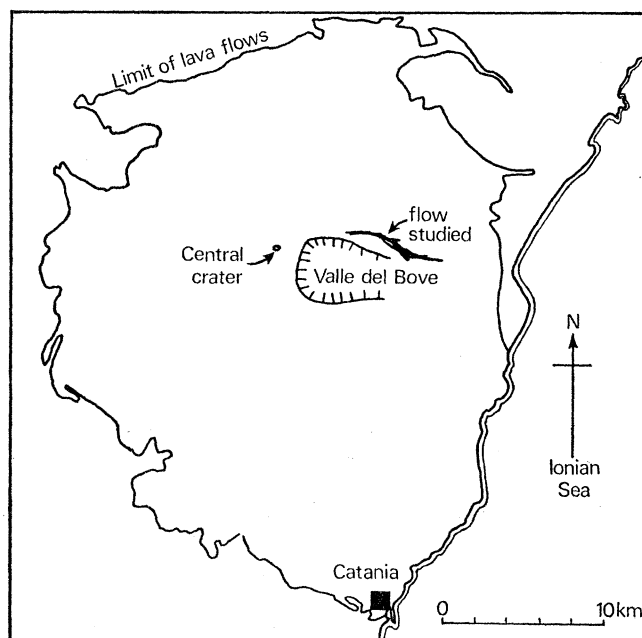


FIGURE 1. Sketch map showing the location of the flow studied in relation to the general Etna cone.

is shown in figure 1. The bocca which gave rise to the flow opened up on 11 May at a height of approximately 1800 m, less than 1 km south of the Rifugio Citelli, and the lava flowed down to the Cave Grande valley near the villages of Fornazzo and Sant'Alfio. The width of the flow varied from approximately 1 m at the bocca, to about 100 m at the flow front which was 5 to 7 km from the bocca. At the bocca, braiding of the new lava channel was common, and in the middle and lower reaches breakouts from the main channel resulted in the lateral coverage of lava to almost 1 km in width.

## SAMPLING TECHNIQUES

Samples each about 500 g were taken using a 2 m long pole with a forked attachment. Some were left to cool in air, taking about 1 h to reach 50 °C. Some were quenched by immersion in water, which was transported up to the edge of the lava flow, as there were no streams on the flanks of Etna at this time. Samples were taken along the length of the flow at about 1 km intervals, or whenever direct sampling was possible. Figure 2 shows the positions of the sampling points in relation to the whole flow. The samples (namely 204, 205, 206, 210 and 218), taken from near the bocca, where the flow is of comparatively small dimensions, are

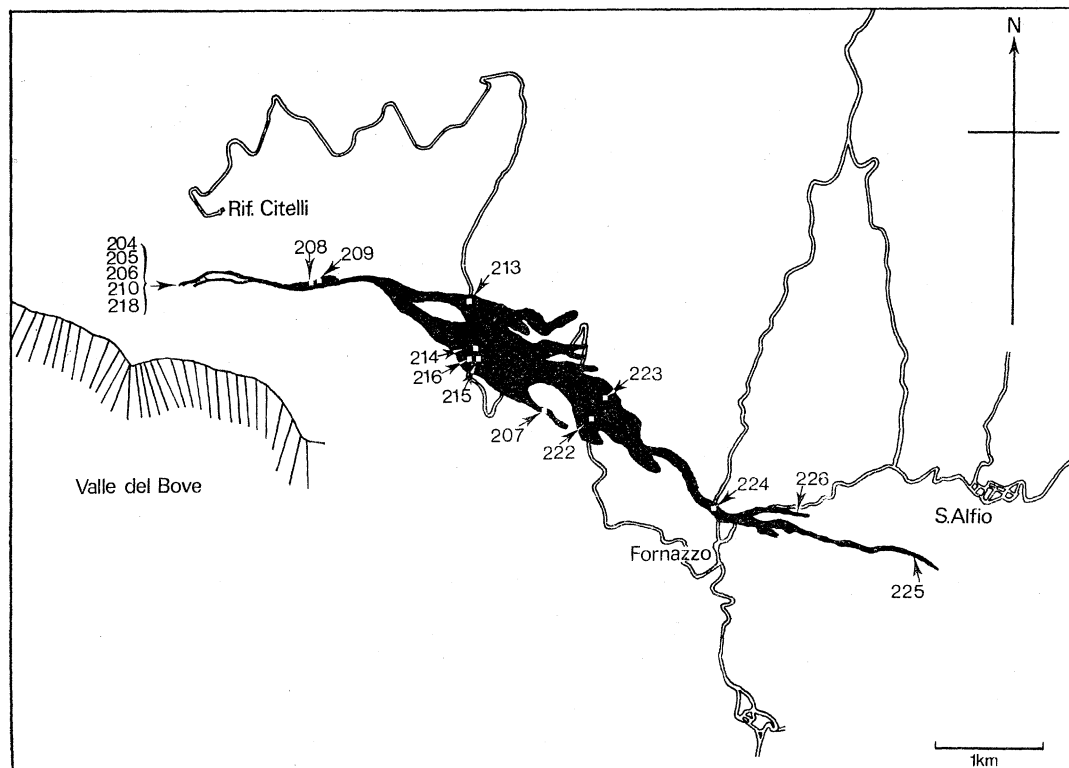


FIGURE 2. The location of samples taken from the active flow. Samples 204, 205, 206, 210, 218 were taken at different time intervals (see table 1).

representative of the hottest parts of the flow. Obtaining material from the internal parts of the flow became progressively more difficult downflow with the increasing cross-sectional area of the flow. However, down to within 1.5 km of the furthest flow-front breakouts from the main channel provided suitable sampling points (e.g. 207, 209 and 226). In the lower reaches where the fluid lava was buried beneath at least 5 m of blocky rubble it was generally not possible to take direct samples. In the case of 225 the material sampled appeared to be the sheared interior of the flow.

At the bocca samples were taken at intervals of approximately 2 days from 29 May to the end of the eruption soon after 7 June. Though only representing the very last stages of the eruption, the samples afford some comparison with the variation along the flow, since any variation resulting from the distance the lava has travelled from its source will be superimposed on to the variations of the magma being erupted. Ideally a small volume of lava should be traced and sampled, as it flows, but in practice this is difficult.

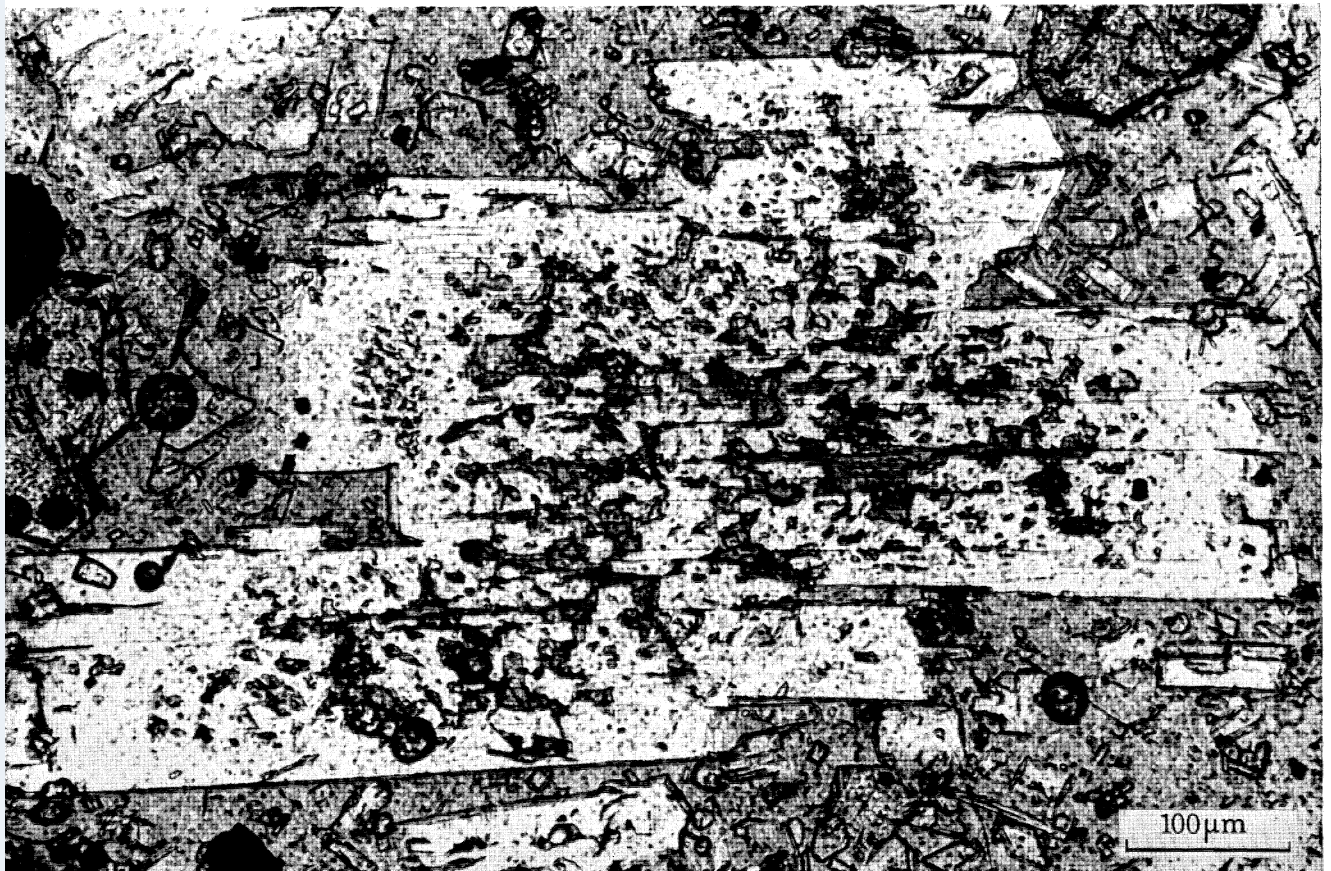


FIGURE 3. Photomicrograph of a typical plagioclase from sample 206 showing glassy inclusions.



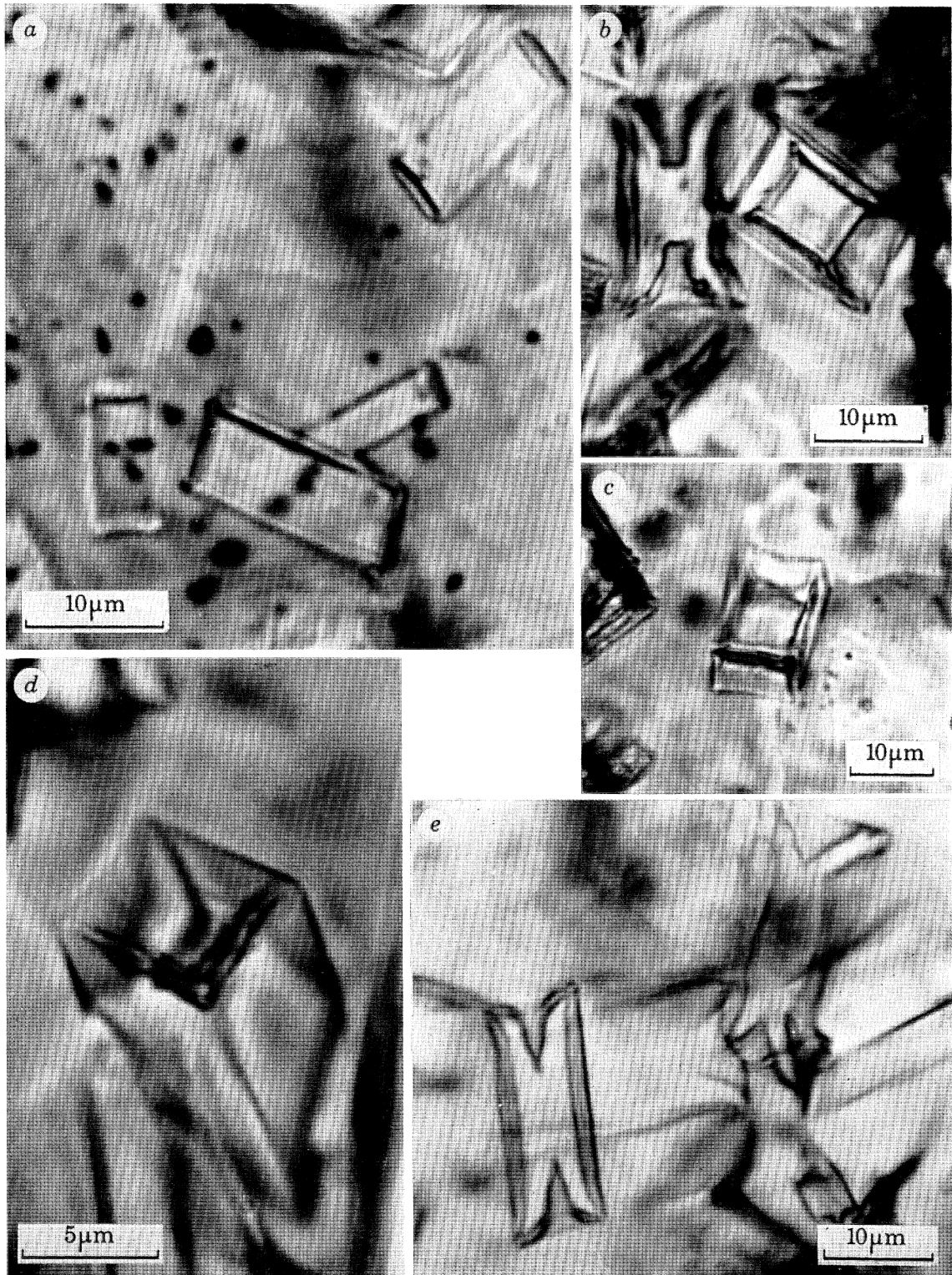


FIGURE 4. Photomicrographs of plagioclase microlites from field quenched lavas. (a) Water quenched sample. (b) Air-cooled sample showing sections perpendicular to  $c$  and  $b$  axes. (c) Air-cooled sample showing the three-dimensional aspect of the preferential edge growth, similar to a 'wash basin'. (d) Air-cooled sample showing three-dimensional aspect with an embayment on the (001) face. (e) Air-cooled sample showing sections perpendicular to  $b$  and  $a$ -axes.



## PETROGRAPHY OF THE FIELD QUENCHED SAMPLES

Quenched products from the bocca contain over 50 % crystalline phases in glass. Plagioclases vary in size almost continuously, from laths about 5 mm in length down to 10  $\mu\text{m}$ ; thus, in this case the use of the term phenocryst phase is arbitrary, and its quantity of little relation to that of the crystalline phases present. A typical mode (sample 204) is as follows:

|               | vol. % |
|---------------|--------|
| groundmass    | 56.3   |
| plagioclase   | 27.8   |
| clinopyroxene | 9.9    |
| olivine       | 4.3    |
| opaques       | 1.7    |

(The size limit, here, for phenocrysts is 2 mm.)

The variability in abundance of any one phase is discussed later in relation to glomeroporphyritic textures.

Plagioclase is the most dominant crystalline phase, the bulk of this having a composition of  $\text{An}_{60}$  (measured optically on a universal stage). In a few cases the cores of the plagioclase crystals have a composition of about  $\text{An}_{74}$ . Most plagioclases show a thin but marked rim, zoned normally from about  $\text{An}_{60}$  to  $\text{An}_{48}$ ; oscillatory zoning is present to a lesser extent. The rims are present in lavas quenched at the bocca indicating that this phenomenon is a pre-extrusion one, most probably resulting from crystallization during the final ascent of the magma. These rims are also related to morphological changes from a rounded crystal form to that of a more regular crystalline shape. The rounded form may be due to resorption, or at least disequilibrium with the melt, and the overgrowth to produce the rim may indicate a closer approach to equilibrium. In addition, interiors of plagioclases contain up to 50 % of brown, glassy inclusions of both a haphazard and a regular, subrectangular form (see figure 3, plate 2). Occasionally these glassy inclusions may be restricted to a growth band within the plagioclase. The explanation offered by Bottinga, Kudo & Weill (1966) that the inclusions are incorporated during the growth of the plagioclase is feasible in this instance: more rapid growth encasing some basaltic melt. The association of glassy inclusions, normally zoned rims and irregular (curved) growth forms, is not uncommon in plagioclases and has been attributed to incomplete resorption of early formed phenocrysts followed by a stage of crystallization of a more albitic rim (Vance 1965; Macdonald & Katsura 1965; Lowder 1970; Smith & Carmichael 1968).

Figure 4 (plate 3) shows plagioclase microlites from the field quenched samples taken at the bocca. In the water-quenched samples, microlites are regular in form (figure 4*a*), in contrast to the additional growths on the air cooled variety. Note in figure 4*d* the strong embayment on the (001) face. This and figure 4*c* show a three-dimensional aspect of the embayments, or more correctly the preferential crystal-edge growth, in particular the edges parallel to [100] and [010]. Figures 4*b* and *e* show varying sections perpendicular to  $x$ ,  $y$  and  $z$ . The latter is due to fast but not too rapid cooling, producing two effects: (i) rapid crystallization of the plagioclase, and (ii) rapid increase in viscosity of the melt. Similar crystal forms are not uncommon in experimentally quenched products, but usually with pyroxenes. It was not possible to duplicate the observed texture in plagioclases experimentally. This texture is not present in material collected farther down the flow where cooling was slower.

Augite, as in most other samples of Etna lavas, displays hour-glass structure and growth banding. It is generally associated with opaque 'microphenocrysts' and often contains

inclusions of olivine (about  $Fa_{15}$ ) microphenocrysts which are always euhedral, only occasionally showing signs of resorption. Glomeroporphyritic aggregates of augite are common, such an aggregate containing 74 % augite, 18 % Ti-magnetite and 8 % olivine. Augite microlites from air-cooled samples show a tendency to acicular growth parallel to the  $c$ -axis but from the middle of the {001} faces in contrast to the crystal edge growth of the plagioclases. The amount of extra growth during the air cooling, on both plagioclase and clinopyroxene is of the same order, namely, in both cases  $5 \mu\text{m}$  on a  $10 \mu\text{m}$  crystal, indicating that their speeds of growth are similar under these conditions. Glomeroporphyritic aggregate of plagioclase are generally rare. Such textures are probably due to synneusis (Vogt 1964; Vance 1969) particularly the association of Ti-magnetite, with augite rather than plagioclase. A tentative sequence of crystallization based on textural relationships is plagioclase–olivine–augite/Ti-magnetite. Ultramafic inclusions, as for the whole of the Etna suite, are notable by their absence.

### CHEMISTRY

A total of 17 chemical analyses have been done, five from the bocca (table 1) and twelve from along the flow (table 2). These analyses were done by X-ray fluorescence spectrometry. The chemical homogeneity is apparent in the lack of any significant single element variation, less than 1 % for any oxide. With the high viscosity of the lava flow, between  $10^{-5}$  and  $10^{-9}$  Pa s (G. P. L. Walker, personal communication), crystal sorting is unlikely to have taken place

TABLE 1. ANALYSES OF SAMPLES FROM THE BOCCA

|  | 204       | 205       | 206       | 210       | 218       |
|--|-----------|-----------|-----------|-----------|-----------|
| SiO <sub>2</sub>                           | 47.19     | 47.12     | 47.52     | 47.63     | 47.88     |
| Al <sub>2</sub> O <sub>3</sub>             | 15.76     | 15.52     | 15.80     | 15.82     | 15.90     |
| FeO  | 7.83      | 7.49      | 7.14      | 7.21      | 7.87      |
| Fe <sub>2</sub> O <sub>3</sub>             | 4.10      | 4.42      | 4.53      | 4.36      | 3.83      |
| MgO  | 4.74      | 5.08      | 4.80      | 4.93      | 4.28      |
| CaO  | 11.80     | 11.66     | 11.53     | 11.57     | 11.58     |
| Na <sub>2</sub> O                          | 3.40      | 3.57      | 3.49      | 3.25      | 3.27      |
| K <sub>2</sub> O                           | 1.72      | 1.68      | 1.71      | 1.74      | 1.73      |
| TiO <sub>2</sub>                           | 1.89      | 1.90      | 1.88      | 1.87      | 1.92      |
| MnO  | 0.21      | 0.22      | 0.21      | 0.21      | 0.21      |
| P <sub>2</sub> O <sub>5</sub>              | 0.43      | 0.43      | 0.46      | 0.45      | 0.44      |
| H <sub>2</sub> O <sup>+</sup>              | 0.36      | 0.43      | 0.33      | 0.36      | 0.34      |
| total                                      | 99.43     | 99.52     | 99.40     | 99.40     | 99.25     |
| $\frac{\text{FeO}}{\text{Fe}_2\text{O}_3}$ | 1.91      | 1.70      | 1.58      | 1.65      | 2.06      |
| date<br>sampled                            | 29. v. 71 | 31. v. 71 | 3. vi. 71 | 5. vi. 71 | 7. vi. 71 |

during the relatively short time that it flowed. Figure 5 shows some of the oxide variations at the bocca and their total variation is within that observed along the flow (figure 6), implying that the magma being erupted is of almost constant composition. The main element variations expected along the course of the flow are those of total alkalis ( $\text{Na}_2\text{O} + \text{K}_2\text{O}$ ), the oxidation state of the iron ( $\text{FeO}/\text{Fe}_2\text{O}_3$ ) and water ( $\text{H}_2\text{O}$ ). These are shown in figure 6 plotted against the distance between an individual sample location and the bocca.

Taking into account the variation at any given distance from the bocca, the  $\text{FeO}/\text{Fe}_2\text{O}_3$  ratios show an initial but slight decrease within the first 2 km, but beyond this distance they remain

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TABLE 2. ANALYSES OF SAMPLES TAKEN ALONG THE FLOW

|                                    | 208   | 209   | 213   | 214   | 215   | 216   | 207   | 222   | 223   | 224   | 226   | 225   |
|------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| SiO <sub>2</sub>                   | 47.15 | 47.41 | 47.27 | 47.48 | 47.74 | 47.42 | 47.37 | 47.74 | 47.64 | 47.16 | 47.38 | 47.64 |
| Al <sub>2</sub> O <sub>3</sub>     | 16.36 | 15.70 | 15.81 | 15.94 | 16.16 | 15.72 | 15.62 | 15.81 | 16.15 | 15.34 | 15.97 | 16.08 |
| FeO                                | 7.09  | 7.38  | 6.87  | 6.87  | 6.77  | 7.32  | 7.09  | 7.13  | 6.42  | 6.86  | 7.07  | 6.54  |
| Fe <sub>2</sub> O <sub>3</sub>     | 4.49  | 4.43  | 5.04  | 4.85  | 4.57  | 4.78  | 4.59  | 4.52  | 5.38  | 5.13  | 4.54  | 4.56  |
| MgO                                | 4.70  | 5.09  | 4.96  | 5.06  | 4.60  | 5.08  | 4.71  | 4.71  | 4.49  | 5.26  | 4.71  | 4.59  |
| CaO                                | 11.45 | 11.40 | 11.39 | 11.41 | 11.37 | 11.49 | 11.54 | 11.39 | 11.46 | 11.62 | 11.37 | 11.33 |
| Na <sub>2</sub> O                  | 3.69  | 3.37  | 3.54  | 3.27  | 3.59  | 2.95  | 3.82  | 3.42  | 3.39  | 3.49  | 3.79  | 4.11  |
| K <sub>2</sub> O                   | 1.74  | 1.73  | 1.75  | 1.71  | 1.75  | 1.75  | 1.75  | 1.75  | 1.73  | 1.71  | 1.75  | 1.74  |
| TiO <sub>2</sub>                   | 1.84  | 1.89  | 1.84  | 1.86  | 1.84  | 1.90  | 1.89  | 1.87  | 1.83  | 1.90  | 1.83  | 1.81  |
| MnO                                | 0.21  | 0.22  | 0.21  | 0.21  | 0.21  | 0.22  | 0.21  | 0.21  | 0.21  | 0.21  | 0.21  | 0.20  |
| P <sub>2</sub> O <sub>5</sub>      | 0.44  | 0.45  | 0.46  | 0.45  | 0.46  | 0.44  | 0.47  | 0.46  | 0.44  | 0.46  | 0.47  | 0.45  |
| H <sub>2</sub> O <sup>+</sup>      | 0.39  | 0.33  | 0.29  | 0.37  | 0.33  | 0.32  | 0.41  | 0.38  | 0.30  | 0.44  | 0.46  | 0.36  |
| total                              | 99.55 | 99.40 | 99.43 | 99.48 | 99.39 | 99.39 | 99.47 | 99.39 | 99.44 | 99.58 | 99.55 | 99.41 |
| FeO/Fe <sub>2</sub> O <sub>3</sub> | 1.58  | 1.67  | 1.36  | 1.42  | 1.48  | 1.53  | 1.54  | 1.58  | 1.19  | 1.34  | 1.56  | 1.43  |
| distance from the bocca (km)       | 1.2   | 1.2   | 2.5   | 2.75  | 2.75  | 2.75  | 3.5   | 3.9   | 3.9   | 5.1   | 5.9   | 7.0   |

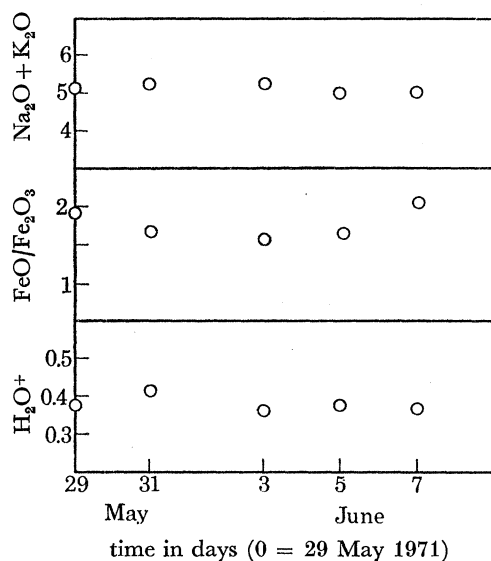


FIGURE 5. The variation with time of total alkalis, oxidation state of iron and water content, at the bocca.

almost constant. There are several factors which may explain this. Kennedy (1948) asserts, as a result of comparing the lower FeO/Fe<sub>2</sub>O<sub>3</sub> ratios found in gabbros with those in basalts, that the process of extrusion tends to reduce the state of oxidation of iron in a magma. This could equally mean, as has been suggested by Verhoogen (1962) that whereas basalts are oxidized, gabbros are even more oxidized. He states that rapid cooling inhibits stronger oxidation than that which occurs in plutonic rocks. The results from the Etna lava flow suggest a limited amount of oxidation of the magma on extrusion. The lack of continued oxidation along the flow may be in part due to the relatively high viscosity which would tend to inhibit oxidation. The formation of a hard crust sealing off the interior of the flow would have the effect of producing a closed system which would cool at constant composition and would result in a



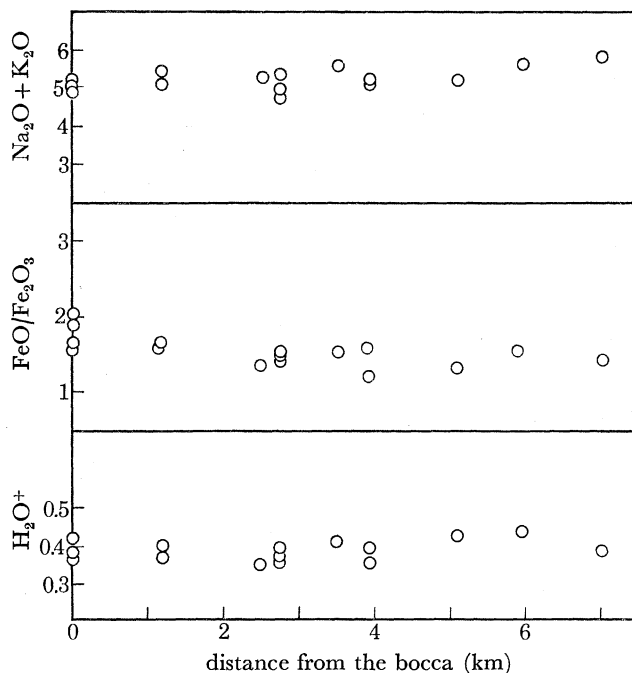


FIGURE 6. The variation of total alkalis, oxidation state of iron, and water, with distance from the bocca.

decrease in the  $pO_2$  (Hamilton & Anderson 1969). Thus the approach to this condition of a closed system may balance out the effect of oxidation from the atmosphere, giving a constant FeO/Fe<sub>2</sub>O<sub>3</sub> ratio. Air cooled samples commonly showed a rim, 1 to 2 mm in width, of darkened (brown) glass, this being the only noticeable effect of pronounced oxidation by the atmosphere. The effect of water on the lava when used as a quenching medium is confined to less than 3 mm (maximum) on the surface of the sample. Within this rim there is an abundance of skeletal phases with a dominance of opaque grains, with little or no discoloration of the glass.

The variation in alkalis (figure 6) is similarly minimal, remaining at about  $5.0\% \pm 0.2\%$ . This variation is within the same as that observed at the bocca. If loss of alkalis were to occur, there should be a decrease away from the source. However, a cooling lava flow below its liquidus is unlikely to show strong variations in alkalis unless the cooling rate is fairly slow as for example in Kilauea Iki lava lake (Richter & Moore 1966) and in thick flows (Hart, Gunn & Watkins 1971; Kuno 1965).

Water is another oxide which might be expected to decrease, but was found to remain constant at about  $0.38\% \pm 0.08\%$ .

#### MELTING EXPERIMENTS

The results of one atmosphere melting experiments performed in air on the five bocca samples show approximately the same liquidus temperatures, namely 1205 °C (the error in measurements is  $\pm 3$  °C). The temperatures of appearance of successive phases in sample 204 are:

| temperature<br>(°C) | phases                                    |
|---------------------|---|
| 1205                | magnetite                                 |
| 1198                | plagioclase                               |
| 1165                | olivine closely followed by clinopyroxene |

The appearance of magnetite as a first phase reflects the high Fe content of these lavas. By comparison to the general Etna suite, magnetite only appears as a first phase on the liquidus when the Fe content is greater than 10%; below this value plagioclase is the primary phase.

Additional runs were made at near liquidus temperatures, under differing  $pO_2$  conditions using a  $CO_2/H_2$  mixture in a gas flow apparatus and monitoring the  $pO_2$  with a solid electrolyte (Zirconia) probe. The results of these runs are given in table 3. Thus just below the plagioclase liquidus the  $pO_2$  at which magnetite reacts with the melt is about  $10^{-4}$ . The lack of magnetite as a major phenocryst phase in the lavas would thus indicate a  $pO_2$  lower than  $10^{-4}$  at low

TABLE 3. CONTROLLED  $pO_2$  RUNS

| temperature ( $^{\circ}C$ ) | $pO_2$       | phases                          |
|-----------------------------|--------------|---------------------------------|
| 1194                        | $10^{-8}$    | plagioclase + glass             |
| 1194                        | $10^{-5}$    | plagioclase + glass             |
| 1194                        | $10^{-3.75}$ | magnetite + plagioclase + glass |
| 1194                        | $10^{-0.7}$  | magnetite + plagioclase + glass |

pressures. Also the abundant featherlike Ti-magnetites at the lava-water contact of the field-quenched lavas indicate a high  $pO_2$  which is not present in the lava-air contacts. The absence of haematite and the relative abundance of magnetite in the lava samples from along the length of the flow suggests that even though the  $pO_2$  may increase with decreasing temperature, the environment remains within the magnetite buffer field with respect to haematite. From the melting relations it is clear that with a large melting interval between plagioclase and olivine, fractionation of plagioclase could take place giving a melt richer in Fe and poorer in  $SiO_2$  relative to the general Etna suite.

#### CONCLUSIONS

From quench products taken from the active bocca it is clear that crystallization is well advanced with over 50% crystalline phases and with crystal sizes ranging from about  $5\ \mu m$  to 5 mm. The order of crystallization of plagioclase-olivine-clinopyroxene and magnetite inferred from textural relations in the field quenched samples is compatible with the experimental results. Magnetite appears as a primary liquidus phase at a  $pO_2$  greater than  $10^{-4}$ , below which plagioclase is the primary phase.

The abundance of glassy inclusions in the plagioclase can be interpreted as meaning either rapid crystallization, thereby incorporating liquid inclusions, or rapid reaction with the liquid causing a resorption phenomenon.

The quenching technique enables stages of crystal growth to be observed, e.g. the rapid growth forms of plagioclase and the limitation of albitic rims on the plagioclases to pre-extrusion growth.

Along the length of the flow there is no significant variation in alkalis and water content, indicating that post-eruptive volatilization effects are minimal. The oxidation state of the iron remains fairly constant with a tendency to a decrease in the  $FeO/Fe_2O_3$  ratio down the flow near the source.

The author wishes to thank Professor W. S. MacKenzie and Dr D. L. Hamilton for critically reading the manuscript. Financial support from N.E.R.C., particularly for field work during the 1971 eruption, is gratefully acknowledged.

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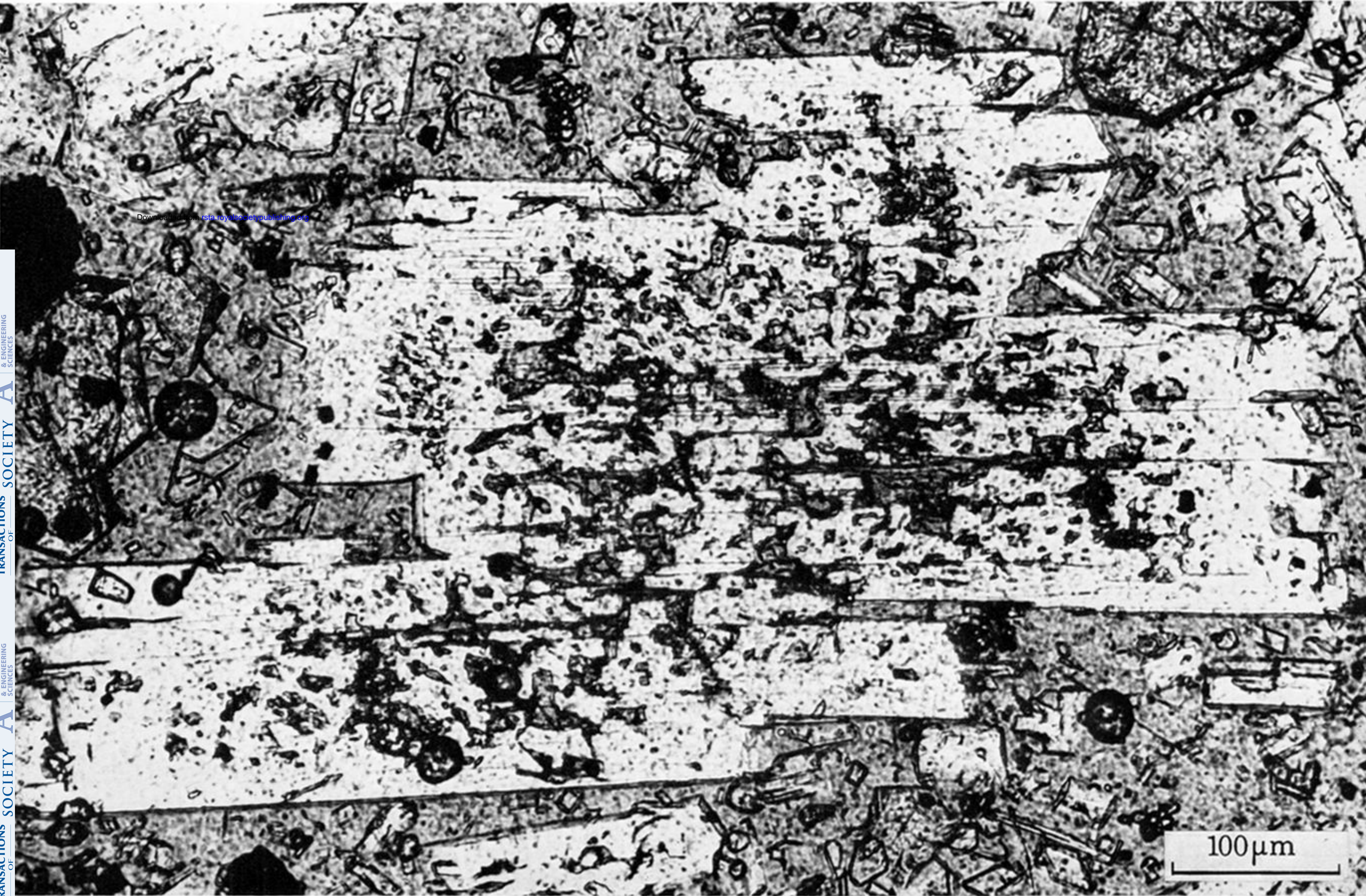
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*Discussion*

DR R. CRISTOFOLINI (University of Catania) asked if there were any data about what the temperature was when 50 % of the magma had crystallized.

M. J. DOWNES: A melting run at 1070 °C and at a  $p_{O_2}$  of  $10^{-8}$  contained approximately 50 % crystalline phases, this proportion being close to that found in the quenched lavas. It is of interest to note that temperature measurements made by Le Guern (personal communication), though made at a different time, indicate lower temperatures, namely, about 1040 °C. Apart from fluctuations in the lava temperature this could be due to the effect of a metastable supercooling of the lava, with crystallization being inhibited.

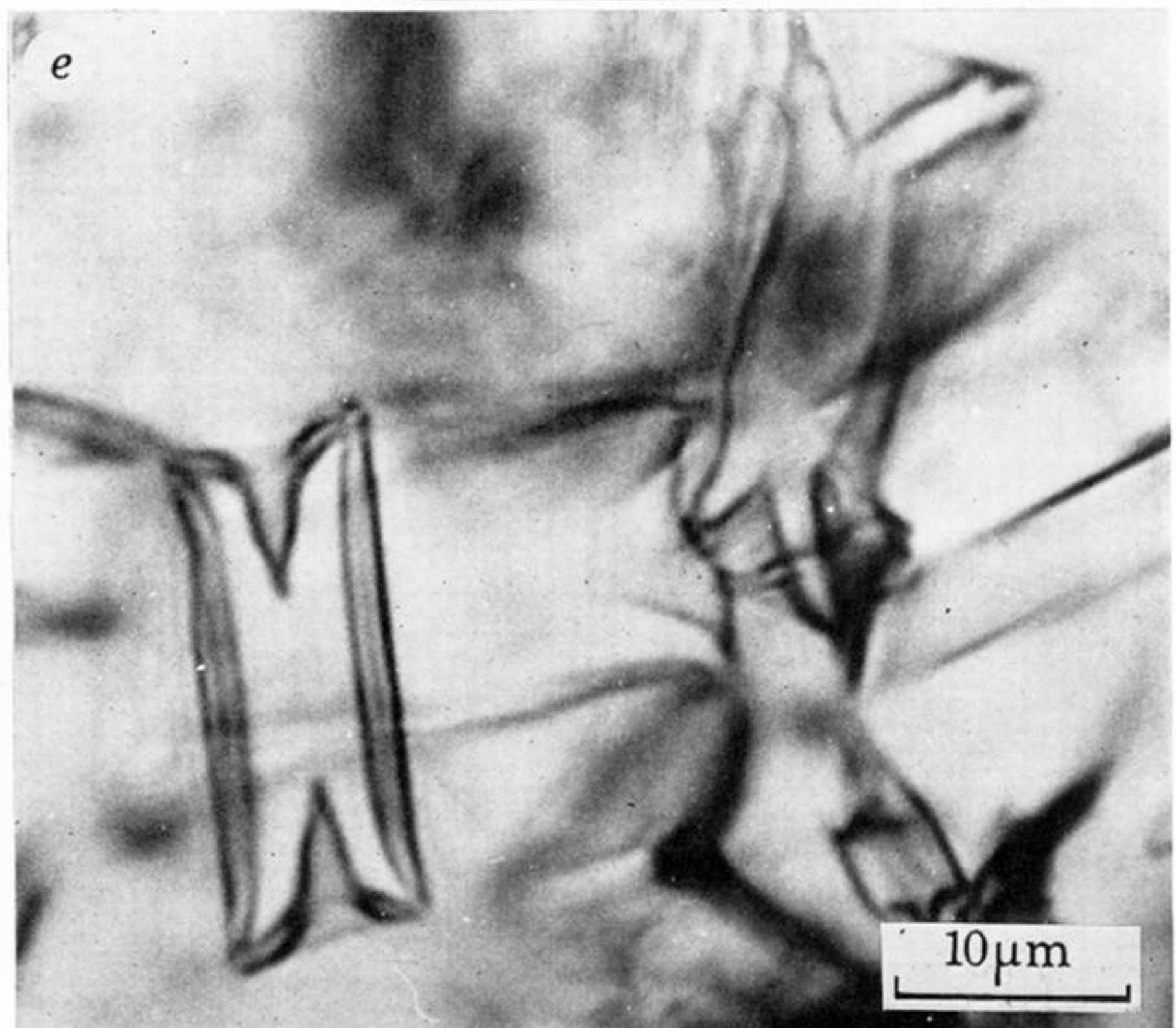
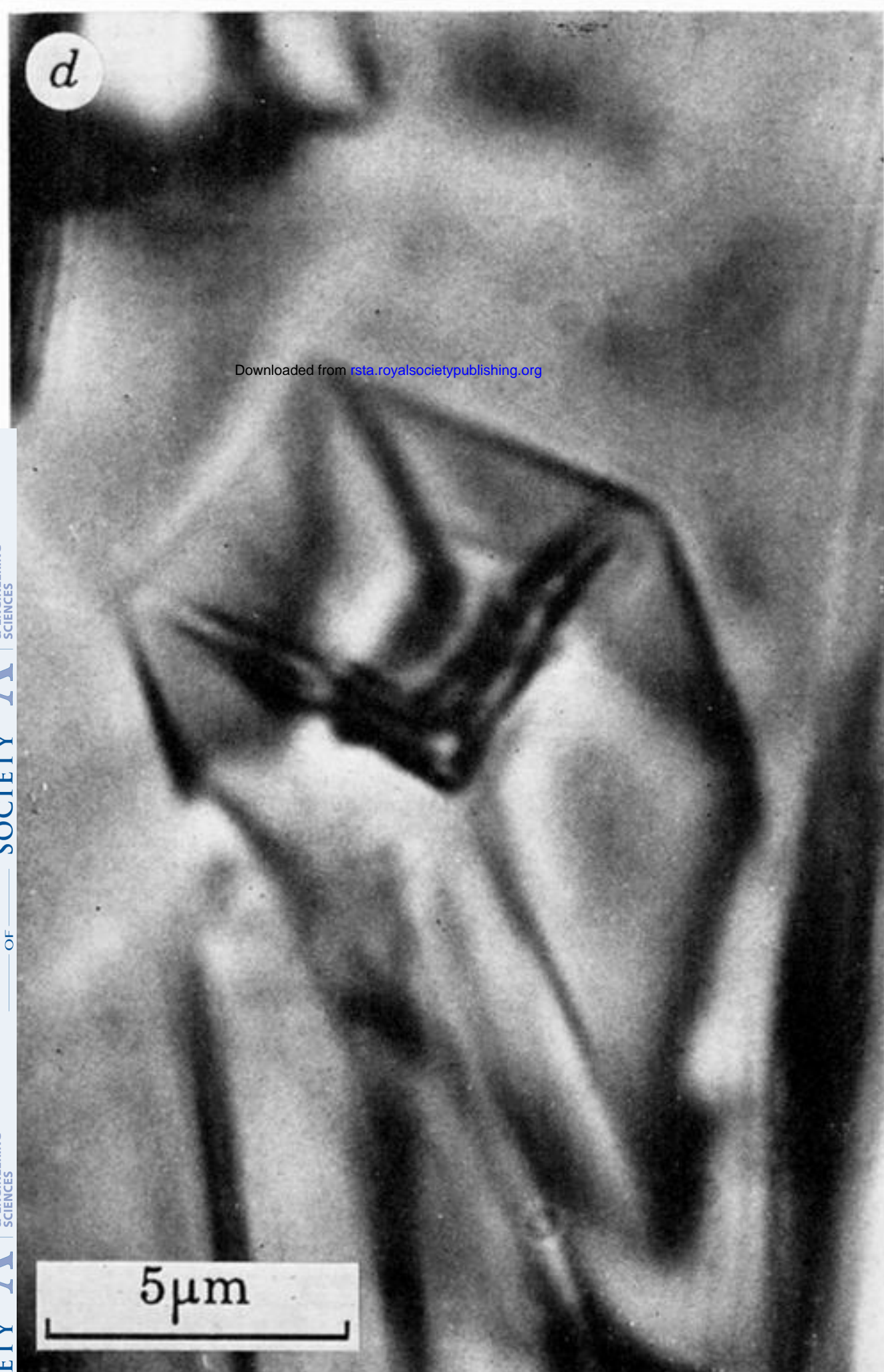
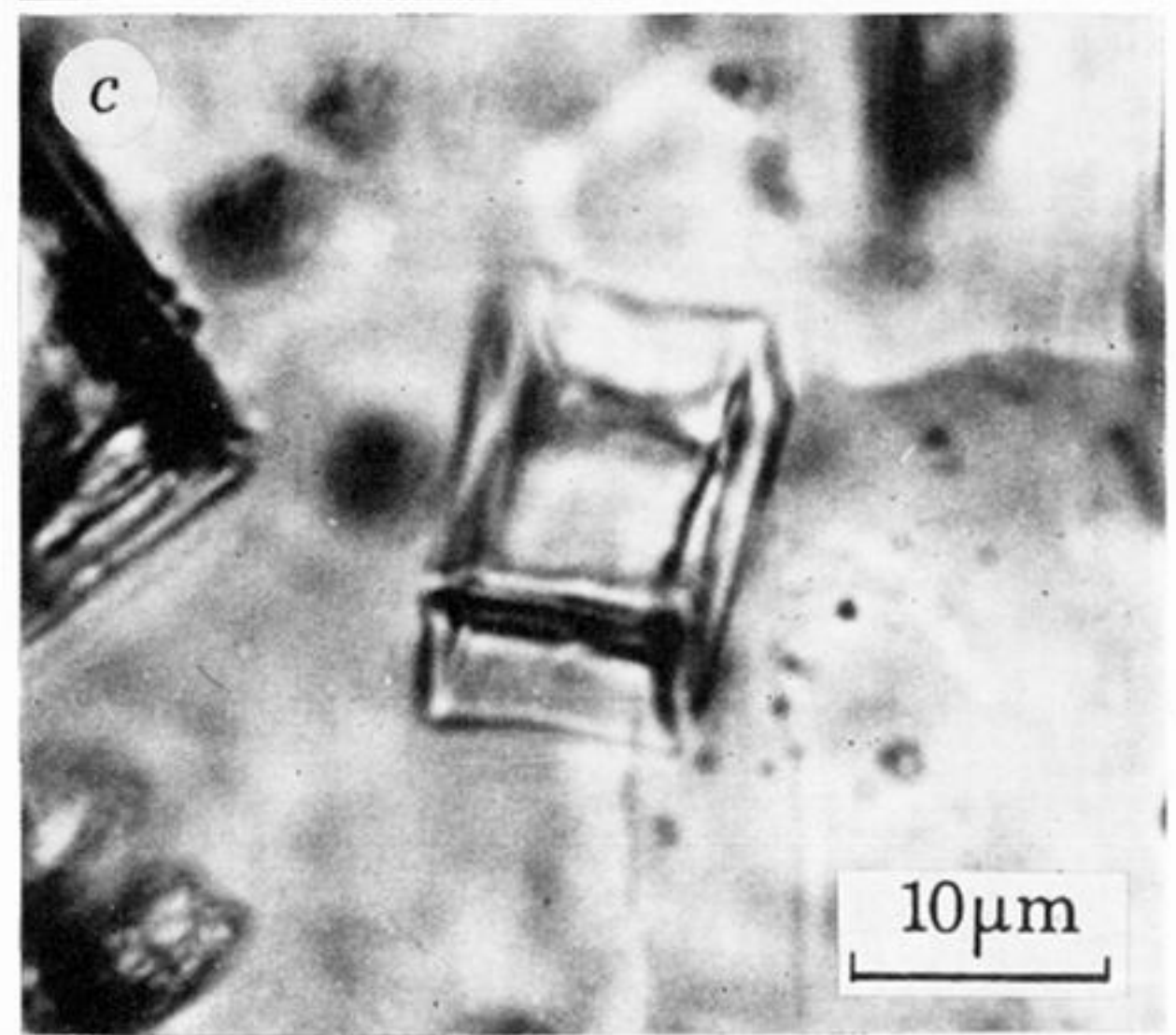
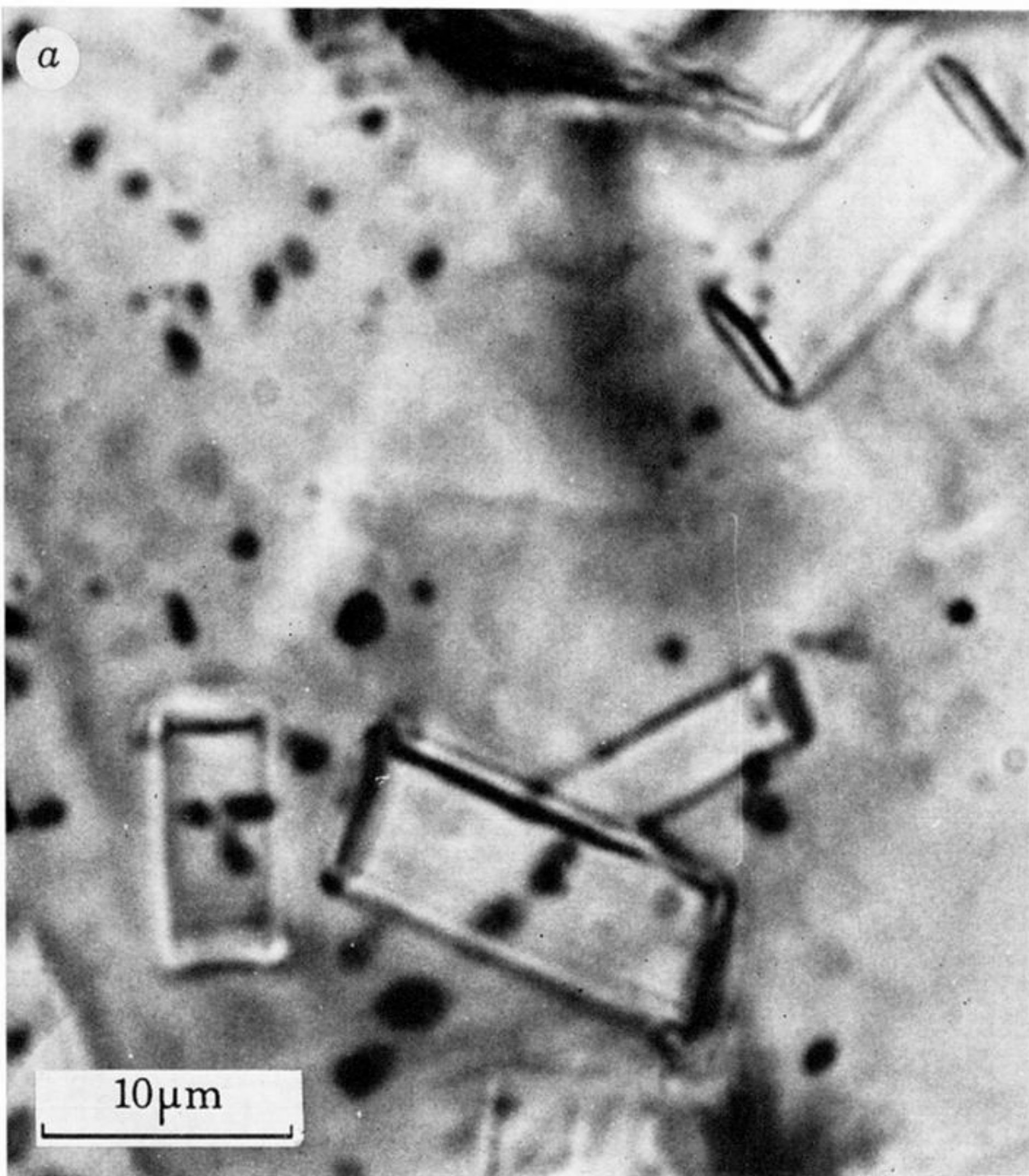




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FIGURE 3. Photomicrograph of a typical plagioclase from sample 206 showing glassy inclusions.





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FIGURE 4. Photomicrographs of plagioclase microlites from field quenched lavas. (a) Water quenched sample. (b) Air-cooled sample showing sections perpendicular to  $c$  and  $b$  axes. (c) Air-cooled sample showing the three-dimensional aspect of the preferential edge growth, similar to a 'wash basin'. (d) Air-cooled sample showing three-dimensional aspect with an embayment on the (001) face. (e) Air-cooled sample showing sections perpendicular to  $b$  and  $a$ -axes.