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The General Principles of Scanning Electron Microscopy

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The general principles of scanning electron microscopy

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[Plate 6]

Introduction

In the transmission electron microscope, as shown in figure 1 (Nixon 1962), the electron gun at the top illuminates the specimen with the beam angle controlled by the condenser lens. The lenses below the specimen are used to magnify the image of the specimen which is viewed on the final screen at many thousand times magnification. If a second electron gun is placed below the fluorescent screen at the bottom of the column and the electron beam is projected upwards

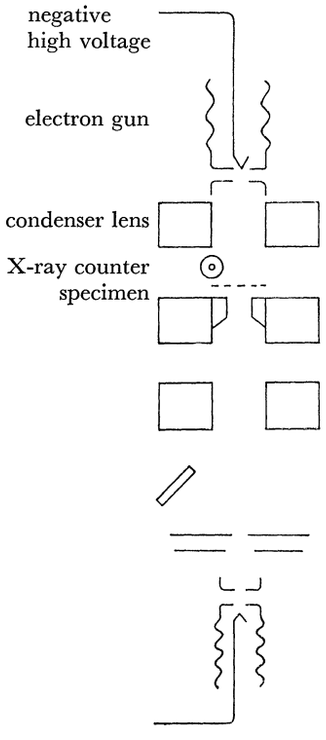

Figure 1. An electron optical column combining normal transmission electron microscopy using the electron gun at the top of the column with an electron probe in the specimen plane using the same lenses but with an additional electron gun at the bottom of the column (Nixon 1962).

through the same lenses this second electron source will be reduced in size by the same amount that the specimen image is magnified. This effect can be observed with both electron guns on at the same time and demonstrates the reversibility of rays through electron lens systems. In this way the resolved point in the specimen image on the fluorescent screen or on the photographic plate is equal to the focused electron probe in the plane of the specimen.

In order to obtain a two-dimensional image it is then necessary to move the probe over the specimen and collect the transmitted or reflected electrons as a time varying signal. This

similarity between the two types of instruments is useful in understanding both the probe-forming system and in the image formation when the scanning microscope is used in transmission. The scanning microscope alone needs only one electron gun, quite often placed at the top of the column as in conventional transmission electron microscopy, plus ancillary electronics as discussed in the next section.

The basic instrument

The schematic diagram in figure 2 shows the fundamental components of the scanning electron microscope. The electron gun (hot cathode, combined thermal and field emission, pure field emission, borides or oxides, pulsed, pointed or flat or curved) forms a source of

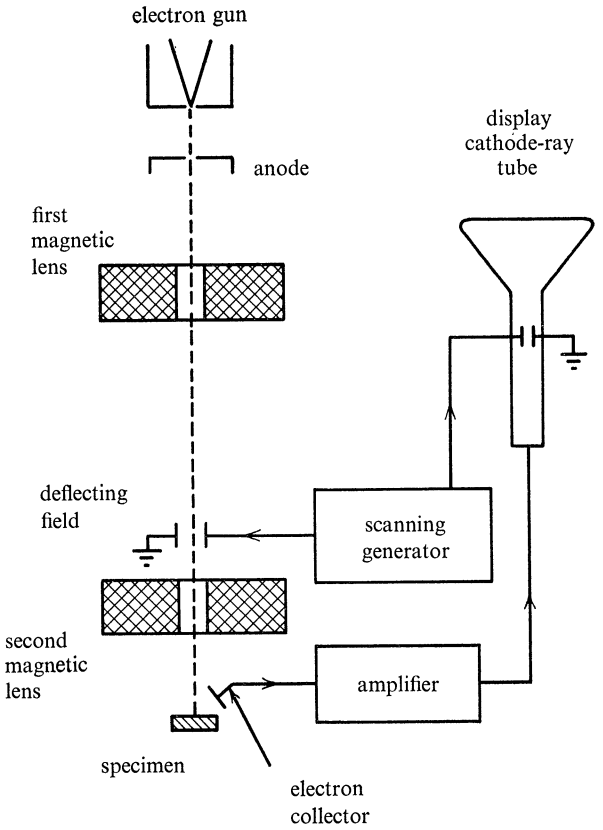

Figure 2. The reduced form of the scanning electron microscope. Many variants are possible on this basic theme such as different lenses, guns, deflecting fields, detectors, amplifiers and display schemes, but all of these items must be present in one form or another.

electrons which are accelerated towards the anode which is held at earth potential relative to the few volts, few kilovolts or tens of kilovolts on the gun cathode and control grid(s). These electrons pass through one or more electron lenses (magnetic, electrostatic, crossed field, multi-pole, mini, maxi, superconducting) and the image of the electron source is formed in the plane of the specimen, after successive reductions, with a diameter of a few tenths to a few tens of nanometres. At some points along the path the electron beam is deflected (1, 2, 3, ..., n times) by fields controlled by the scanning generator. As a result the beam is moved over the surface of the specimen in a predetermined form such as a square television type raster, a circle, a

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spiral, a stepwise incremental scan following a digital input, or some other control. These primary electrons produce secondary electrons at the specimen surface and are detected by an electron collector. Other events lead to the emission of light, X-rays, infrared, ultraviolet, and semi-conductor effects within the specimen. The collector may be adjusted to deal with all the other signals as well, either in turn or simultaneously.

The specimen may be moved mechanically through the x, y, and z directions, rotated, tilted with respect to several axes, heated, cooled, stretched, strained, probed, or otherwise experimented on within the microscope.

The amplifier enhances the collected signal and may also alter the contrast, differentiate, integrate, or otherwise process the information coming from the specimen as the electron beam is scanned over the surface. The scanning generator is also linked to the display cathode-ray tube, so that the electron beam in this tube is also being scanned in the same way as the main beam in the main electron optical column. However, the scanning power supplied to the main column may be attenuated at will while the display tube is scanned over a constant area. As a result, any reduction of the scanned area on the specimen leads to an increase in the viewed magnification which is given by the ratio of the tube screen face (constant) to the specimen scanned area (variable). Other readouts are possible such as storage tubes, facsimile printers, computer interfaces for direct analysis, tape recordings, cine film, electrograph, closed circuit television, etc.

The advantages of the scanning electron microscope evolve from the fact that the surface of a solid specimen is available for experimentation, including simple observation, at a resolution much better than that of the optical microscope and with a depth of field that is orders of magnitude greater. The charge on the electron means that electrostatic and magnetic fields may be visualized directly with ease. The lack of a direct analogue with conventional transmission electron microscopes or optical microscopes has led to new applications not previously possible. The insertion of the specimen into a vacuum is done rapidly with an airlock, and the whole column is kept at high or ultra-high vacuum while this is accomplished. Live material has been studied under special circumstances in these conditions.

Electron-optical operation

The fundamental electron-optical equations for electron probe-forming systems have been presented by many authors and were known to the early workers in Germany and the United States. Magnetic lens performance for electron probes was discussed by Nixon (1952) and reviewed in Cosslett & Nixon (1960). The scanning electron microscope was dealt with in detail by Smith (1956), and Mulvey (1967) has given an up-to-date summary of electron microbeams in this context. The basic equations show that the electron probe size is given by

$$d_{\min} = \approx C_s^{\frac{1}{4}} \lambda^{\frac{3}{4}}, \tag{1}$$

where C_s is the spherical aberration coefficient of the final lens used and λ is the electron wavelength. This result is found by combining the need for a large aperture for resolution with a small aperture to reduce the effect of lens aberrations. At 25 kV and with an immersion lens of $C_s = 0.4$ mm, the electron probe would be 0.8 nm. For large specimens outside the lens, and therefore $C_s = 10$ mm, the probe would be 1.5 nm. The fourth root of the coefficient means that the electron probe size hardly doubles when the coefficient varies by a factor of 15.

Similarly, any attempt at correcting the spherical aberration must do so by a large amount or the effect on probe size will be negligible.

The several lenses must reduce the size of the electron source to less than that given by the above equation, and in high resolution instruments three or more lenses are found. The electron source size of a few tenths of a millimetre must be reduced 10000 times for a probe of a few hundredths of a micrometre. With a long working distance for the final lens the total reduction is shared equally among all lenses. The final electron probe is assumed to be shielded from all unwanted magnetic and electrostatic fields either constant or varying, from outside or inside

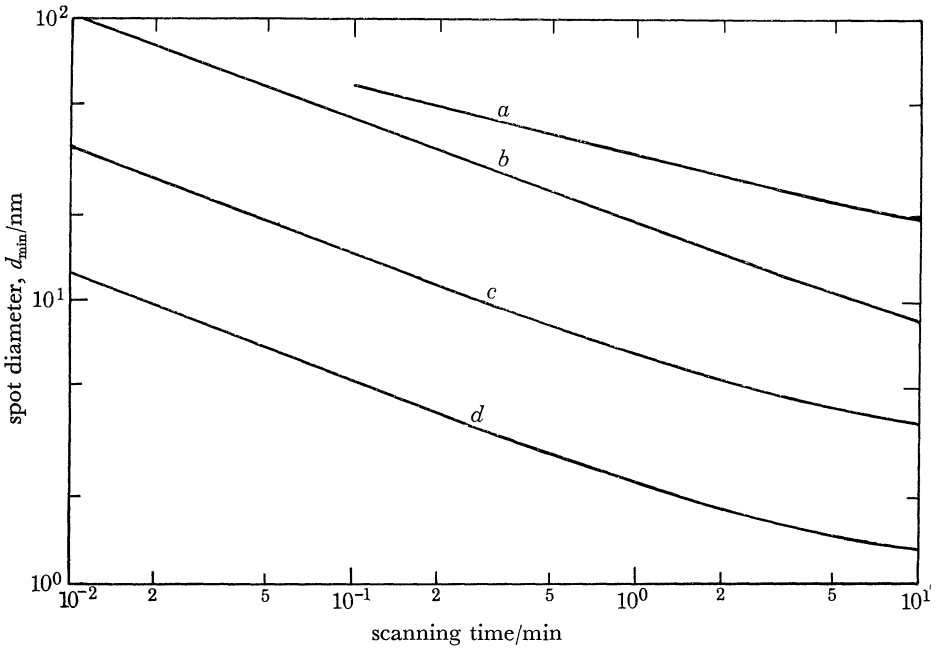


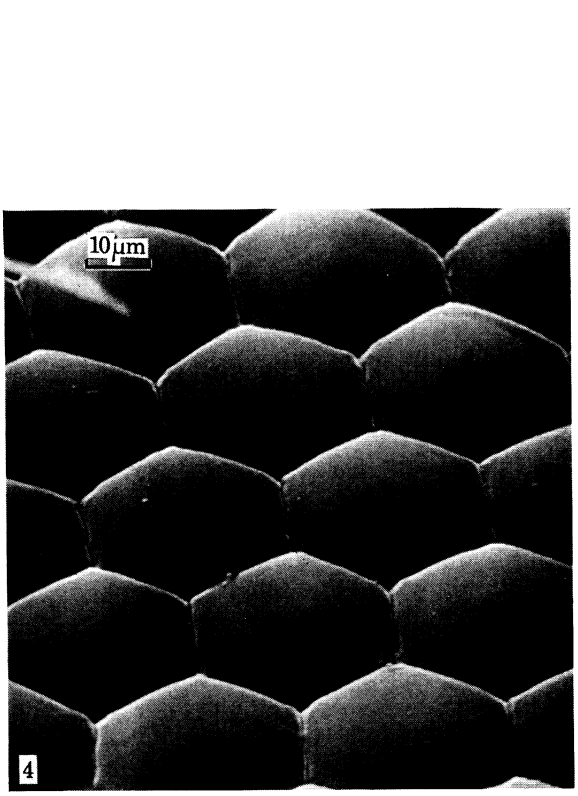
FIGURE 3. Electron probe diameter against scanning time for (*a*) a lens of C_s of 11 cm and astigmatism of 3 μm; (*b*) a lens of C_s of 11 cm and corrected astigmatism; (*c*) predicted performance in reflexion for a lens of C_s of 3 cm and at 15 kV; (*d*) predicted performance in transmission for a lens of C_s of 3 mm and at 50 kV (Smith 1956, p. 37).

the column and the specimen itself is stationary to within the resolution sought without the harmful effects of mechanical or thermal changes. The power supplies for the lenses and the electron gun must also be stable to at least one part in 100000 or better for high resolution results.

This fine electron probe must contain enough electrons to be able to form a relatively noise-free picture in a reasonable scanning time. The same lens equations may be re-written to show that

$$i \propto V d^{\frac{8}{3}} C_s^{-\frac{2}{3}}, \tag{2}$$

where i is the current in the probe of size d at a voltage V. In the scanning electron microscope this current might be about 10^{-11} A or 10^8 electrons per second. If the electron probe is to sweep out a 1000 by 1000 line picture or 10^6 picture points, the time of scan can be estimated. The statistical variation or 'noise' due to a finite number of electrons arriving for one picture point limits the speed of scan if a noisy picture is to be avoided. Noise is evident at 10^4 electrons per picture point and not observed at 10^6 electrons per picture point. If we choose the compromise at 10^5 and the current as 10^8 electrons per second then we may scan 10^3 picture points



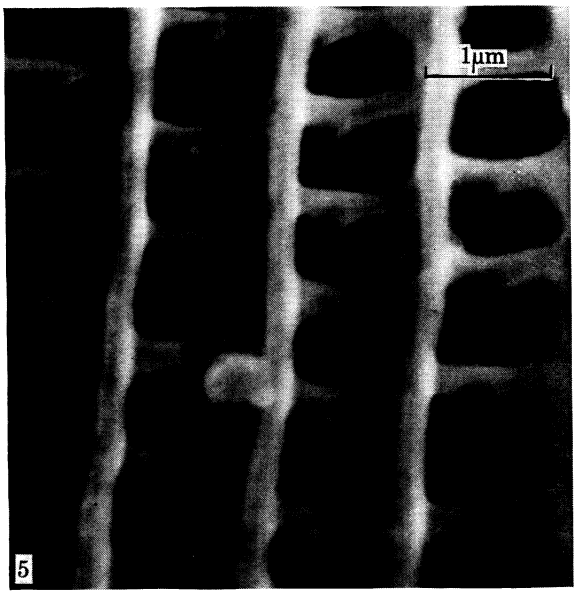


FIGURE 4. The eye facets of a wasp. The bright edges of the facets show the direction of the electron collector.

FIGURE 5. The natural diffraction grating of the wing of a butterfly giving rise to the iridescent colours from white light. The spacing of the bars is about 1 μm or twice the wavelength of blue-green light and so such a picture could not be obtained with a light microscope.

FIGURE 6. The surface of a marine coral. The rough surface is seen all in focus at low magnification in (*a*). The central region is then enlarged further in (*b*) and a rough surface is seen again but now on a smaller scale.

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per second or 1000 s per full frame scan. These long times are used in practice for recording; and faster scanning at 1 to 5 s per frame with a long persistence viewing screen gives an acceptable result for searching the specimen area. Faster scans of the t.v. type are also of use for rapid focusing and adjustments or for fast changes in the specimen. These scanning times may be traded for reduced resolution, i.e. a larger electron probe diameter. This has been calculated by Smith (1956) and the result is shown in figure 3.

The predicted performance shown in *c* was reached by Pease & Nixon (1965) and that of the transmission scanning electron microscope shown in *d* by Crewe (1968) using a field-emission source and one lens. If the minimum frame time of about half a second is taken for curve *c*, a spot size of some 30 nm is possible as a goal for fast frame scanning.

The above emphasis on resolution reflects the unfavourable comparison with the transmission electron microscope when only a single figure for performance, resolution, is used. This approach has prevented the spread of scanning electron microscopy until recently when two other aspects, depth of field and contrast, were widely understood. Indeed the whole subject of microscopy should be treated as a problem in communications and a particular system will have a contrast transfer function to describe its performance.

Depth of field

The very small angular aperture of the electron probe forming system permits a large depth of field all in focus at once. At a resolution of 1 μm the optical microscope will have a depth of field of the same order, about 1 μm. The scanning microscope will have a depth of field of up to 7000 μm at this resolution. As a result very rough surfaces such as pollen grains, microfossils, bone and tooth surfaces may be seen in focus across the whole specimen. At higher magnification, where a resolution of 10 nm or better from solid surfaces has been reached, the depth of field is still some hundred times greater than the value for the point to point resolution.

Contrast

The third feature of the scanning electron microscope, in addition to high resolution and great depth of field with respect to the optical microscope for solid specimens, is contrast. Scanning micrographs of solids inclined at an angle to the electron beam appear as if the eye were placed along the electron beam axis and illumination fell on the specimen from the electron collector placed to one side. This enhances the three-dimensional effect seen even when looking at one micrograph alone. The specimen may be tilted with respect to the beam, or vice versa, and two micrographs recorded that will combine to give a stereographic pair. The third dimension can be measured with accuracy by using photogrammetric techniques from aerial photography (Boyde 1970).

Results

These features of scanning electron micrographs are shown in figure 4, plate 6, of the eye of a wasp, and figure 5, plate 6, of the wing of a butterfly. A full description of the use of the scanning electron microscope in the study of insects with interpretation of the diffraction grating structures seen in figure 5 has been given by Hinton (1969). The rough surface features

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of coral seen at two different magnifications in figure 6*a* and *b*, plate 6, show the depth of field available.

Some of this material has appeared in 'Introduction to scanning electron microscopy', by W. C. Nixon, *2nd Annual Scanning Electron Microscope Symposium* (Illinois Institute of Technology Research Institute), Chicago, 1969. Mr L. R. Peters produced the micrographs in this paper and has given excellent assistance in this subject for many years.

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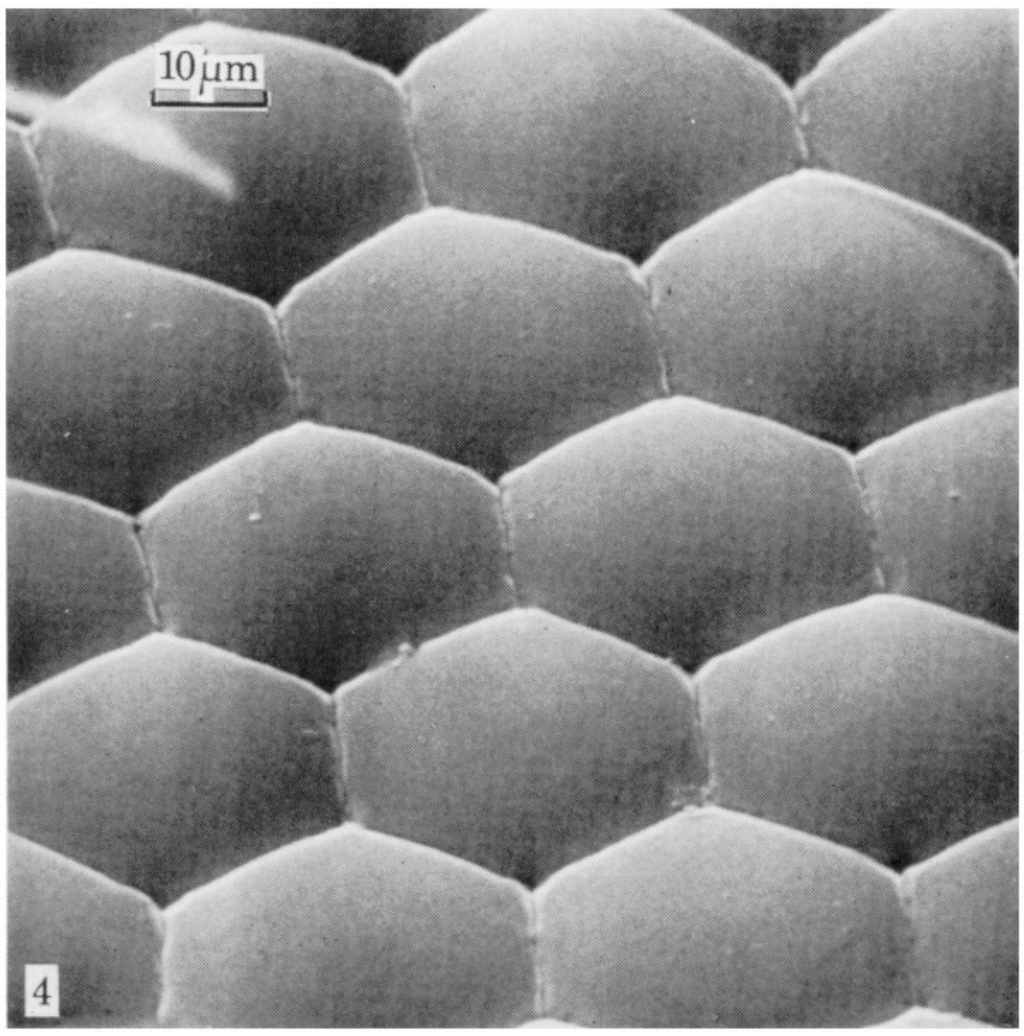

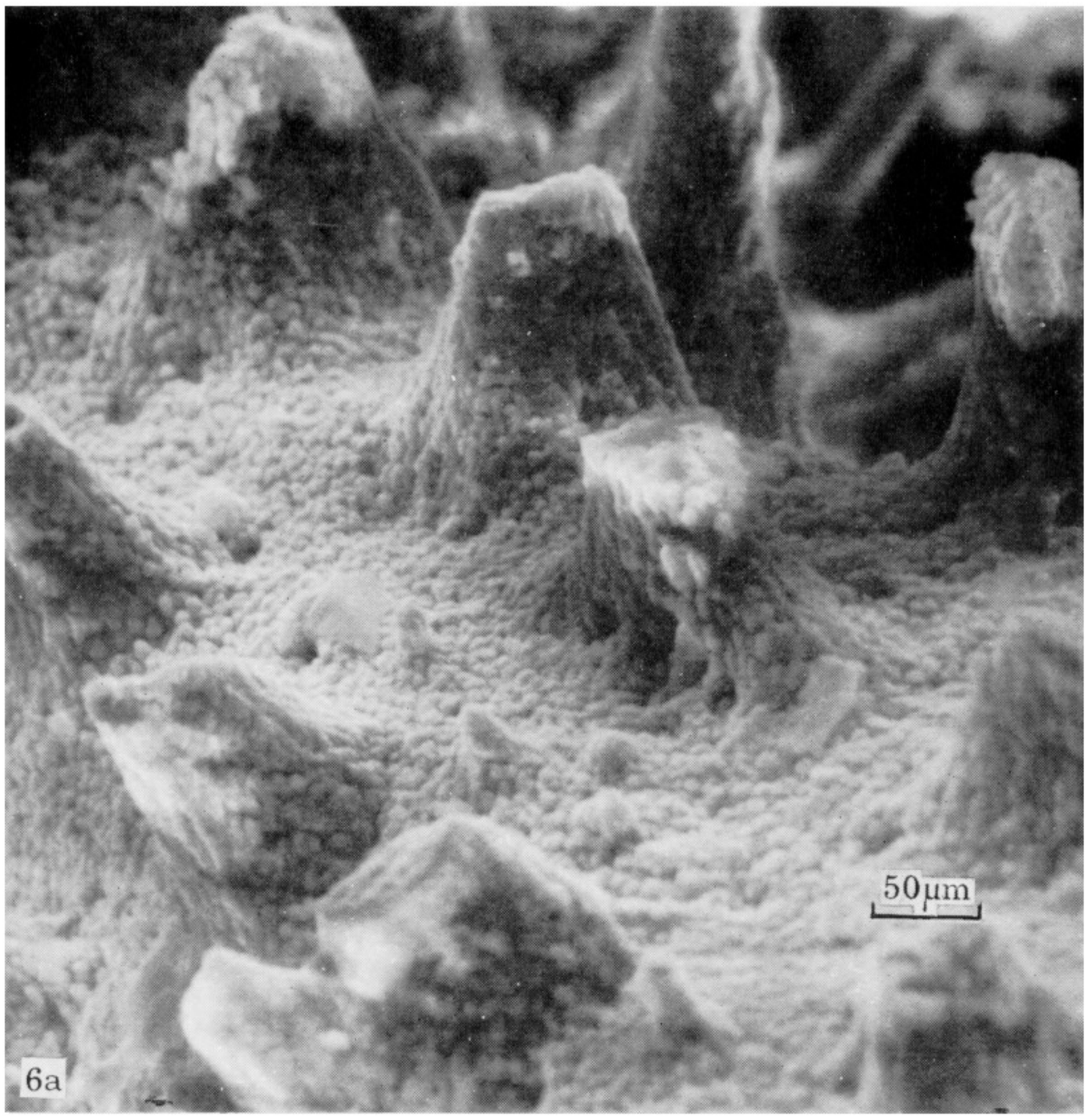

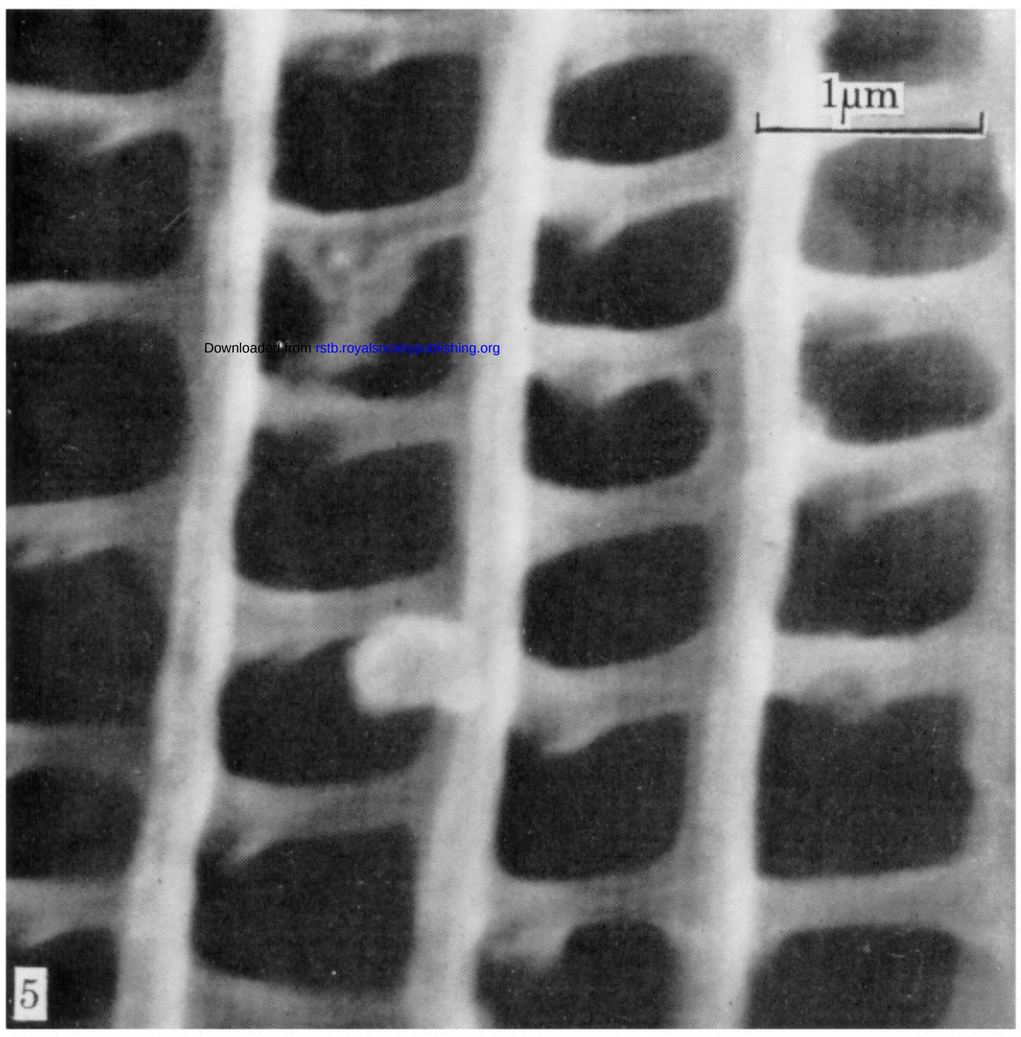

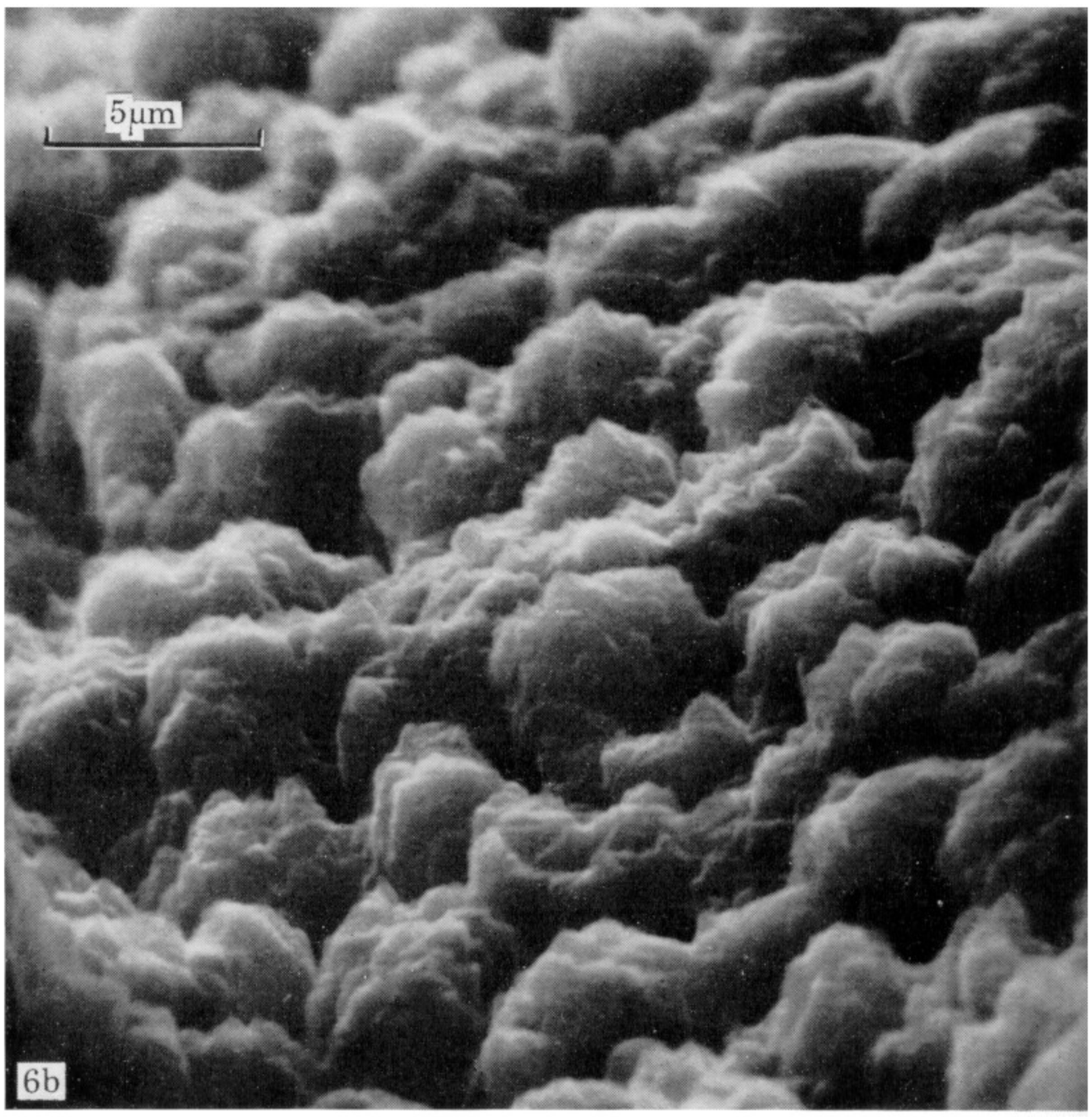

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