Optical Diffraction Analysis of Petrographic Thin Sections

A microscope with mercury vapor illumination can be used to analyze thin sections via optical diffraction.

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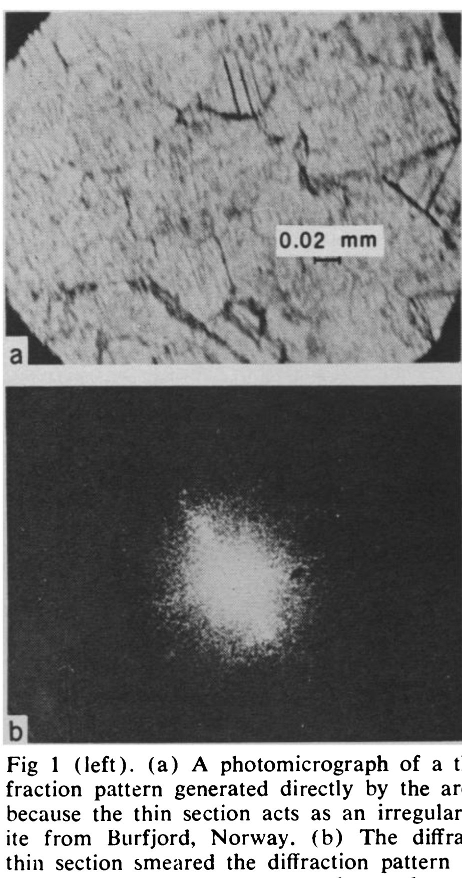
We believe that optical diffraction analysis (ODA) with a practical relatively inexpensive system can be widely applied to the analysis of petrographic, metallurgical, or biological thin sections. With the ODA technique one analyzes a two-dimensional display of spatial information by diffracting light through the display. This article describes an optical system that was used for the ODA of petrographic thin sections. The system can be applied to the study of the initiation and propagation of microfractures, the determination of overall microfabric orientations, the analysis of particle size distributions, and the determination of grain size orientations in thin sections. With the method described here one can avoid tedious measurements of microfracture orientations and grain (or cell) boundaries and quickly obtain average spacings and elongation ratios. It is also feasible to use this technique to analyze reduced photographic transparencies of maps, aerial photographs, line drawings, hand samples, and other two-dimensional displays of information, such as biological slides (*1*).

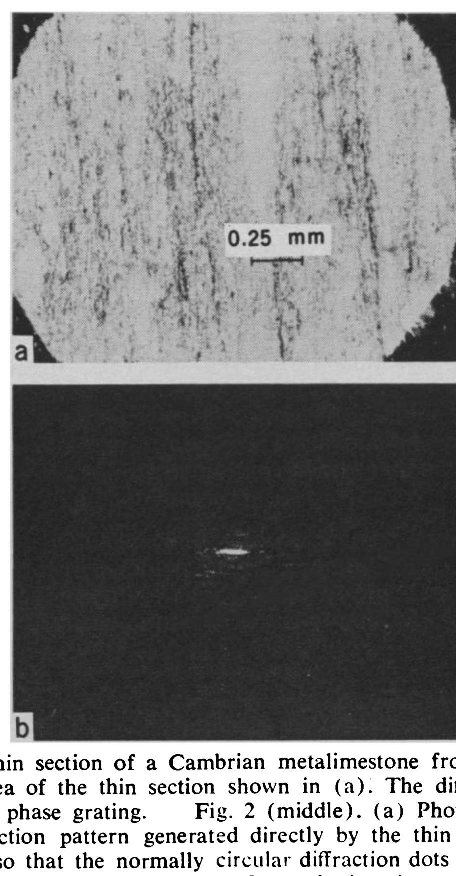
One of the reasons ODA has not been applied more extensively is the large initial cost of the hardware needed to generate high-quality diffraction patterns. In the ODA system described here a standard petrographic microscope and commercially available accessories are used. Such a microscope system requires less care and maintenance than a conventional ODA system because the microscope's optics are, for the most part, enclosed.

Theoretical Discussion

The basic principles of ODA have been presented by many authors (*2*). Detailed treatments are given in (*3*) and (*4*).

The general equation describing complex modulated plane light waves





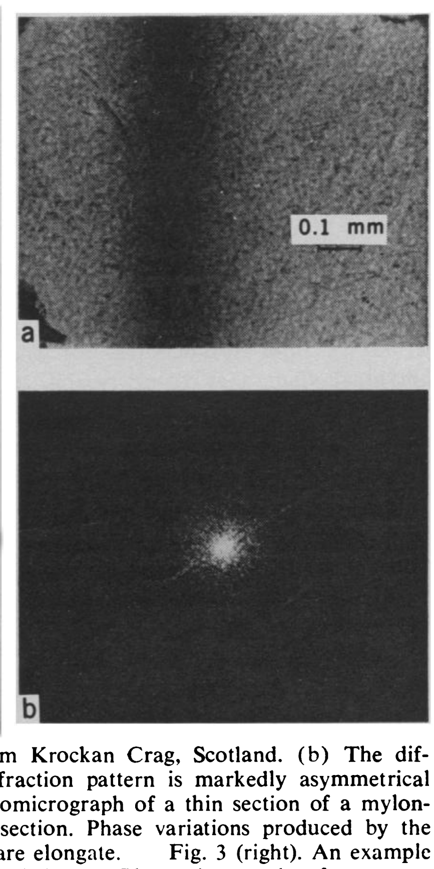


Fig 1 (left). (a) A photomicrograph of a thin section of a Cambrian metalimestone from Krockan Crag, Scotland. (b) The diffraction pattern generated directly by the area of the thin section shown in (a). The diffraction pattern is markedly asymmetrical because the thin section acts as an irregular phase grating. Fig. 2 (middle). (a) Photomicrograph of a thin section of a mylonite from Burfjord, Norway. (b) The diffraction pattern generated directly by the thin section. Phase variations produced by the thin section smeared the diffraction pattern so that the normally circular diffraction dots are elongate. Fig. 3 (right). An example of misleading data generated when only part of the microscope's field of view is recorded. (a) Photomicrograph of a quartz grain in a thin section of Rainbow granite from Morton, Minnesota. The vertical shadow is a defect that showed up in our early work and disappeared before it could be explained. (b) The diffraction pattern recorded directly with the microscope. The strong lineation trending northeast-southwest in the diffraction pattern was generated by diffracting elements outside the field of view recorded in the photomicrograph.

normally incident on a plane (x,y) and focused through a lens of focal length g into the far focal plane of the lens $F(\omega_x,\omega_y)$ is (*5*)

$$F(\omega_x,\omega_y) = \frac{\lambda}{2\pi} E_{max} e^{-i\omega t} \times \iint_{-\infty}^{\infty} \mathcal{J}(x,y) e^{-i(\omega_x x + \omega_y y)} \, dx dy$$

where ω_x and ω_y are spatial frequencies expressed in radians per unit length, λ is the wavelength of the light waves, E_{max} is the peak amplitude of the incident light waves, ω is the radian temporal frequency of the incident light, and t represents time. The thin section is described by the complex function $\mathcal{J}(x,y)$.

This equation indicates that the image of the modulating function $\mathcal{J}(x,y)$ in the front focal plane of the lens and the image in the far focal plane $F(\omega_x,\omega_y)$ are reciprocally related: each is the Fourier transform of the other. Because ω_x and ω_y are spatial frequency variables, we may refer to the far focal plane as the (spatial) frequency plane.

The output from the ODA system is the light intensity distribution in the frequency plane. This diffraction pattern is a diagram of the spacings and orientations of the elements in the input. A line connecting the dots generated by a linear element in the input is rotated 90° with respect to the diffracting element. The radial separation of the nth order diffraction dots from the zero order dot is inversely proportional to the spacings of the corresponding diffracting elements in the input.

Model Analysis

The analysis presented here is based on two assumptions: (i) the thin section is properly made for typical petrographic use and (ii) the thin section is illuminated by coherent monochromatic plane waves with wave fronts parallel to the optical flats bounding the slice and normal to the optic axis. Because of the thinness of the specimens (0.03 millimeter) and the shallow depth of field of the high-power lenses, we can assume that the diffracting elements in the thin section are planar (*6*, p. 308).

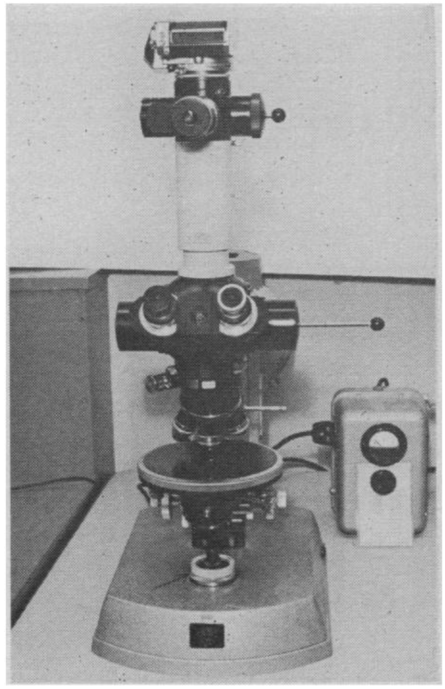


Fig. 4. Microscope arrangement used to generate and photographically record diffraction patterns generated directly by petrographic thin sections. The arrow indicates the position of the filter assembly that yields quasi-monochromatic, partially coherent light from a mercury vapor source.

We considered two major models: model A, diffraction by a single crystal; and model B, diffraction by more than one crystal with similar or dissimilar optical properties. We also considered three variations of model B based on the location at which amplitude modulation occurs within the thin section: (i) at the surface through which light enters the section, (ii) at the surface through which light emerges from the section, and (iii) in the thin layer between the entry and exit surfaces.

Analysis of model A indicated that blurring of the diffraction pattern caused by birefringence is negligible. The general analysis of model B showed that most thin sections act as irregular phase gratings which generate asymmetric diffraction patterns. Because a change in the index of refraction within a thin section causes a change in the optical path length through the section, a thin section can be represented by a composite of single-element rectangular laminar phase gratings. A single element of such a phase grating generates an asymmetric diffraction pattern (*6*, p. 231) (Fig. 1). The asymmetries observed in this study cannot be attributed to misalignments or optical flaws in the microscope system and can be used for quality control purposes when producing diffraction patterns.

Analysis of model B also indicated that the components of a diffraction pattern can shift relative to each other because of phase variations generated by the thin section. The magnitude of the shift is proportional to the focal length of the lens, the differences in the refractive indices of the minerals in the thin section, and the spatial frequency (the inverse of the spacing) of the diffracting elements. This shift appears as a smearing of the diffraction dots including distortion of the normally circular central spot as shown in Fig. 2.

The areas of thin sections that generate smeared diffraction patterns are typically either fine-grained and mineralogically heterogeneous or largely glassy. If the power of the objectives is increased, the heterogeneity is effectively reduced. With the proper choice of objective a clean diffraction pattern (such as that shown in Fig. 3b) can be

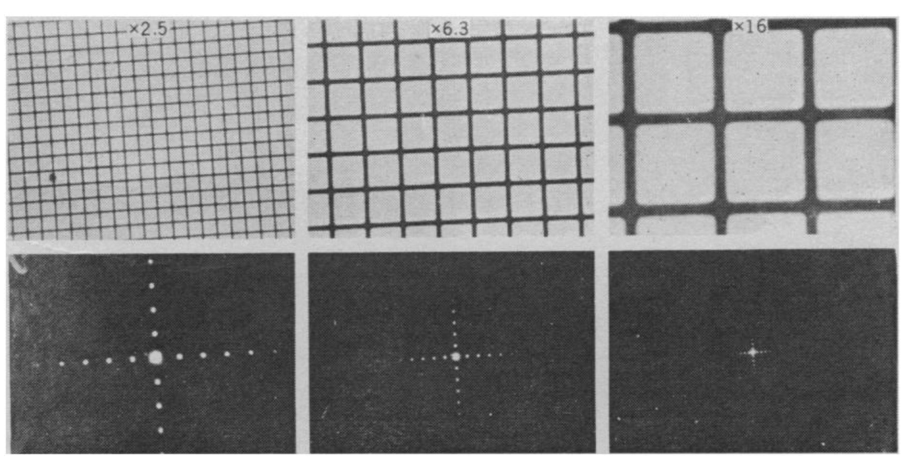


Fig. 5. Photomicrographs (top) and diffraction patterns (bottom) used to calibrate the microscope system for ×2.5, ×6.3, and ×16 objectives. The actual spacing of grid elements is 10 lines per millimeter.

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generated from any portion of an input not containing significant glassy components.

The models considered here are very simple relative to real thin sections. Where the boundaries between grains are not normal to the plane of the section, the resulting wedges shift the spectrum generated at that grain boundary. The magnitude of the shift depends on the angle between the grain boundary and the plane of the thin section. The direction of displacement is a function of the relative indices of refraction at the grain boundary. Other complexities are introduced by nonplanar grain boundaries and light rays passing through many grains with different indices of refraction. As the number of grains in the field of view increases, the complexity of the grain-to-grain relationships also increases. Experimental evidence supports the inference that any irregularities in the transforms generated by grain-to-grain relationships increase as the grain size decreases.

Diffracting elements in a thin section can be combined with each other in a variety of ways. If the combinations are additive (that is, if there are no opaque elements), the spectra generated are added in the diffraction plane. This is the result of a basic property of the Fourier transform relationship: the Fourier transform of the sum of a countable number of functions is equal to the sum of the Fourier transforms of the individual functions. However, because we can sense only light intensity (light amplitude squared), we detect either the square of the sum of the Fourier transforms if coherent light is used or the sum of the squares of the transforms if incoherent light is used.

All of the considerations discussed here are also valid for arbitrary plane structures. According to Fourier theory, any plane structure can be considered a superposition of crossed gratings.

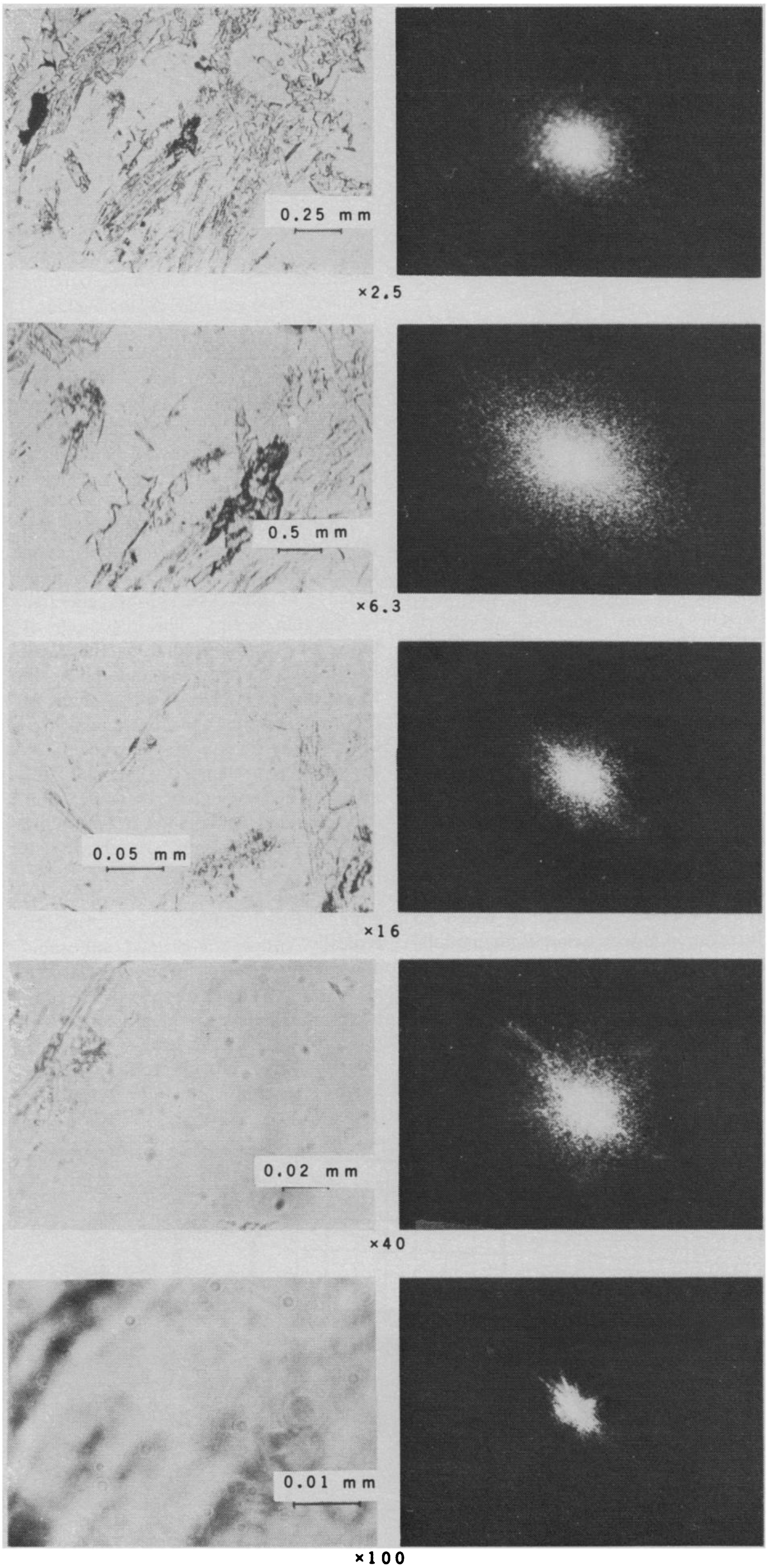

Fig. 6. Photomicrographs (left) and diffraction patterns (right) recorded with increasing objective powers. The pinhole size used to produce the diffraction patterns was the same for all powers of the objective. The increase in the number of high-frequency dots in the ×6.3 diffraction pattern may be caused by the resolution of diffracting elements that could not be resolved by the ×2.5 objective. The introduction of an auxiliary condenser lens caused an apparent increase in the size of the ×40 and ×100 diffraction patterns.

Equipment

An Optovar-equipped Zeiss standard universal microscope was used to generate transforms directly from thin sections. Other less expensive microscopes gave good results, but we preferred the Zeiss microscope because it presented few alignment problems. The transforms and photomicrographs were recorded with a 35-millimeter single-lens reflex camera attached to the microscope with a straight monocular tube, a KPL ×8 eyepiece, a Basic Body II with focusing eyepiece and mounted objective lens, and a camera adapter ring (Fig. 4).

The thin sections were illuminated with filtered mercury vapor light from a Zeiss multipurpose illuminator. The filter, which consisted of a combination of an interference filter (5.1 centimeters in diameter, 5461 angstroms) with 100-angstrom bandpass and a spatial filter (25-micrometer circular pinhole) placed on top of it, yields a quasi-monochromatic light source with a moderate degree of spatial coherence. Results obtained with this light source are comparable to those obtained from coherent, monochromatic illumination of photographic reproductions of thin sections and, in fact, yield more information. A laser light source was not used because a high degree of coherence results in an unacceptable amount of noise. A discussion of coherent versus incoherent illumination can be found in (*7*).

Procedures

A comparison of the diffraction patterns is facilitated if all such outputs are produced with standardized optical-mechanical arrangements. Because the position of the condenser affects the scale and quality of the diffraction patterns, the microscope was always adjusted for Köhler illumination (*8*). After adjusting the condenser for the objective being used, one inserts the filter assembly into the light beam by placing the combination wavelength–spatial filter on top of the field diaphragm assembly. The Bertrand lens is then inserted and focused so that the diffraction pattern is sharp as judged by the shape of the central spot. After focusing, the diffraction pattern should be centered on the ocular by a slight movement of the filter assembly. The diffraction pattern can then be viewed through the focusing eyepiece which must be precisely focused. After one has made these adjustments, the diffraction pattern is finely focused and a picture is taken according to predetermined exposure times. This photographic step in not necessarily linear. An interpretation of the intensities in photographically recorded diffraction patterns in light of this nonlinearity is beyond the scope of this article.

A photomicrograph of the input generating the diffraction pattern can be recorded after the filter assembly and Bertrand lens have been removed. Because the 35-millimeter camera records only the central area of the microscope field, there are always some diffracting elements not recorded on the photomicrographs. In Fig. 3b the strong lineation trending northeast-southwest was generated by diffracting elements outside the field of view of the camera recording the photomicrograph (Fig. 3a). We circumvented this problem by recording the diffraction patterns at one magnification and the photomicrographs at a lower magnification with no alteration of the condenser or diaphragm adjustments.

Calibration

The microscope system must be calibrated for objectives of different power. Figure 5 shows diffraction patterns generated by a 10-line-per-millimeter grid. We recorded diffraction patterns using three different objective powers. Measurements taken from these and other diffraction patterns generated for calibration purposes show a linear relationship between spatial frequencies in the inputs and the corresponding radial coordinates in the diffraction patterns. With care, inaccuracies resulting from asymmetry and smearing can be reduced to acceptable levels.

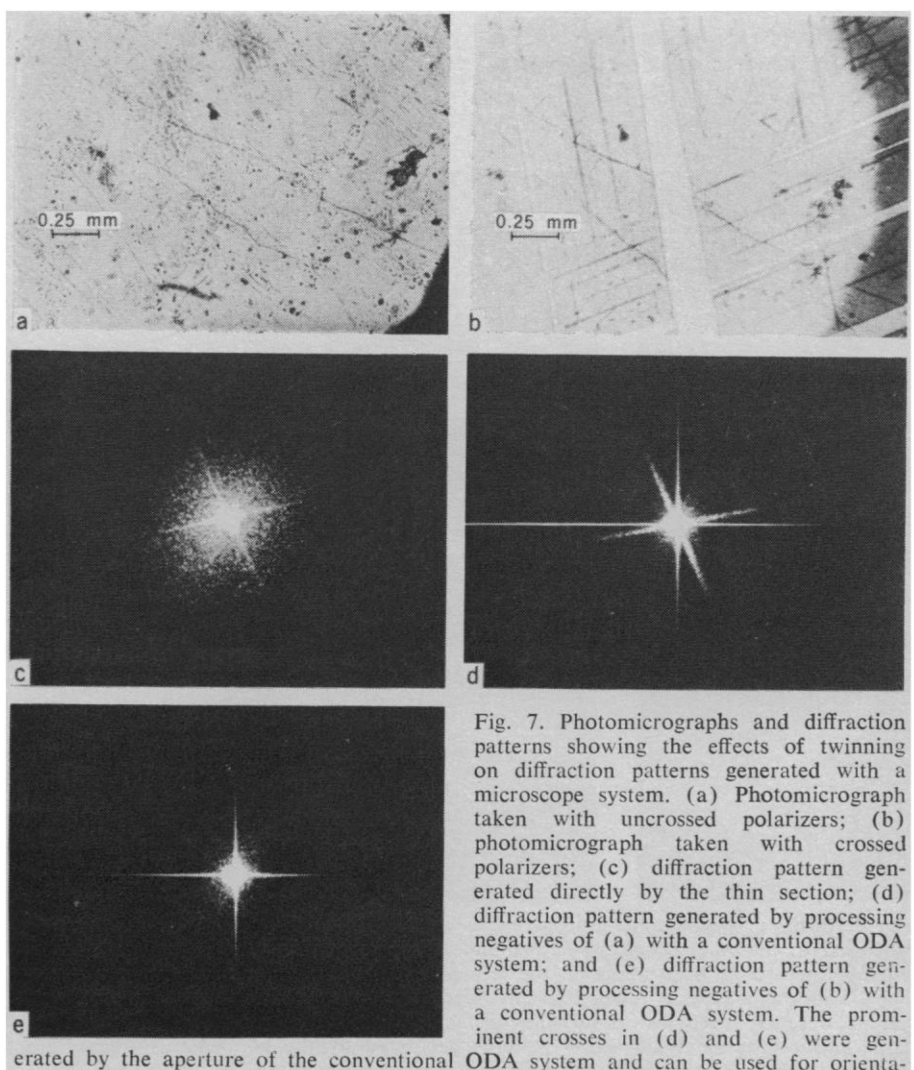

Fig. 7. Photomicrographs and diffraction patterns showing the effects of twinning on diffraction patterns generated with a microscope system. (a) Photomicrograph taken with uncrossed polarizers; (b) photomicrograph taken with crossed polarizers; (c) diffraction pattern generated directly by the thin section; (d) diffraction pattern generated by processing negatives of (a) with a conventional ODA system; and (e) diffraction pattern generated by processing negatives of (b) with a conventional ODA system. The prominent crosses in (d) and (e) were generated by the aperture of the conventional ODA system and can be used for orientation purposes. Note that (c) resembles (e) more than (d).

Objective Power Variations

The effects of varying the power of the objective used to generate the diffraction patterns were studied in different ways. Figure 6 shows the results of a set of experiments in which the pinhole size was kept constant and exposure times were varied. Generally, all these experiments indicated the same effects of changing objective power: a change from the $\times 2.5$ to the $\times 6.3$ objective increases the number of diffraction data at all radial coordinates in the diffraction pattern. Stepwise from $\times 6.3$ to $\times 100$ the diffraction patterns become progressively smaller and sharper with the number of high-frequency components rapidly decreasing. At the higher magnifications smearing effects are less prominent because of an effective decrease in heterogeneity, and the smaller field of view provides a more subdued diffraction pattern consisting mainly of dots generated by elements with relatively low spatial frequencies.

The increase in the number of higher-frequency diffraction dots in the diffraction patterns generated with the $\times 6.3$ objective is real. The increase may be due to elements in the input that are of too high a spatial frequency to be resolved with the $\times 2.5$ objective.

Effects of Twinning

Regular twinning in mineralogical thin sections should act as a phase grating of the multiple-element type. The diffraction patterns generated by regular twinning should, therefore, display the usual Fourier transform properties pertaining to symmetry, radial coordinates, and orthogonality.

In order to test the validity of this statement, photomicrographs of twinned specimens were recorded, one with crossed polarizers and one with uncrossed polarizers. The diffraction pattern generated with the microscope from each thin section directly was also recorded. The two photomicrographs were processed on a conventional ODA system. Some of the results are illustrated in Fig. 7.

In every case the diffraction pattern generated directly by the thin section resembles the diffraction pattern generated by the photomicrograph taken with crossed polarizers more closely than the diffraction pattern generated by the photomicrograph taken with uncrossed polarizers. In Fig. 7c the diffraction pattern generated directly by the thin section is somewhat asymmetrical and the twinning exhibited in the print of the corresponding photomicrograph (Fig. 7b) taken with crossed polarizers is not regular.

Descriptions of other results generated directly by petrographic thin sections can be found in (*5*).

Photographic Inputs

Figure 8 shows some results obtained when photographs were used as inputs to the microscope system. The diffraction patterns generated by the high-contrast inputs to the microscope system are almost identical to the diffraction patterns generated by the same input when processed in the conventional system. The diffraction patterns generated by the continuous-tone input to the microscope system are sensitive to the graininess of the photographic emulsion.

Conclusions and Suggestions

Diffraction patterns that are highly reproducible, of useful quality, and consistent with the input generating them can be easily obtained with a microscope system. The input can be either a reduced photograph or a thin section. With two exceptions, the relationships between a thin section and its diffraction pattern produced by a petrographic microscope are the same as the relationships between a photographic input and its diffraction pattern produced by a conventional ODA system. The exceptions are that the diffraction patterns generated directly by the thin sections may be asymmetrical or, if the thin section is sufficiently heterogeneous, may be smeared.

The microscope system is generally more useful than a conventional ODA system for the analysis of microfabric in thin sections. One can readily use the microscope system to analyze elements of widely varying spatial frequency simply by changing the objec-

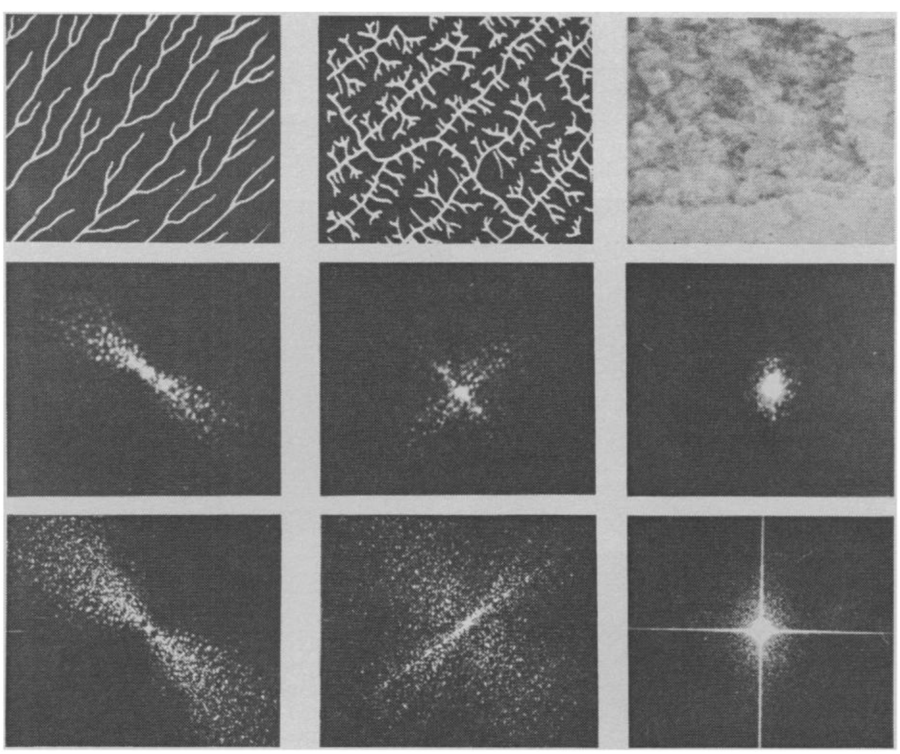

Fig. 8. Positive photographic transparencies of the illustrations in the top row were processed in the microscope system (middle row) and in a conventional ODA system (bottom row). Illustrations in the left column and the middle column were produced with high-contrast inputs (strictly black and white). Illustrations in the right column were produced with a variable-tone input (some gray component). The microscope and conventional diffraction patterns generated by the high-contrast inputs are almost identical. The microscope diffraction pattern generated by the variable-tone input reflects, for the most part, the grain of the film.

tives. The diffraction patterns can be magnified by changing to a higher-power ocular.

In most cases the microscope-generated diffraction pattern transmits the useful spatial information in the thin section more completely than the conventionally produced diffraction pattern; the photographic inputs for the conventionally produced diffraction pattern emphasize lower-frequency spatial information. This property, combined with the microscope system's better response to twinning, makes the microscope more sensitive to commonly used microfabric elements.

For the analysis of thin sections, a conventional ODA system is superior to the microscope system in only three cases. First, if one wants to analyze the entire thin section at one time, a conventional system must be used with a photographic input of the thin section. Second, if the thin section is extremely heterogeneous (crystallographically or mineralogically), the microscope-generated diffraction pattern may exhibit gross smearing even with the highest-power objectives available. Finally, the thin section may contain only elements of low spatial frequency that will not generate diffraction dots far enough radially from the central spot to be resolvable.

More study will be needed to establish the precision of spatial frequency measurements from diffraction patterns generated directly by thin sections with the microscope system. Experiments with a variety of film types and sources of illumination will, in all likelihood, lead to a reduction in the exposure times used to record diffraction patterns with the microscope (*9*).

A complete ODA system must have directional and frequency-filtering capabilities. In order to establish these capabilities for the microscope system, components will need to be designed and fabricated and the microscope body may have to be modified.

The possibility of applying the microscope technique in reflected light on a real-time basis should be investigated. This would be a valuable tool in the quantitative analysis of microfracture initiation and propagation and the analysis of overall fabric changes during experimental deformation of rock both in situ and in the laboratory.

The technique presented here can be used with a less expensive microscope, if it has a focusable Bertrand lens. Our experiments with relatively inexpensive microscopes indicated that the only major problem is alignment of the illuminating system (light-filter-condenser).

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9. In the work described in this article exposure times ranged from 1 to 3 minutes. A discussion of photography as applied to ODA is contained in (*3*).

10. This research was supported by the University of Wisconsin–Milwaukee and by the Advanced Research Projects Agency of the Department of Defense under contracts H0210003 and H0220016, monitored by the U.S. Bureau of Mines. The views and conclusions contained in this article are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the agencies cited above or of the U.S. government.

NEWS AND COMMENT

Cancer and the Environment (I): A Creaky System Grinds On

The Environmental Protection Agency's recent order declaring aldrin and dieldrin an "imminent hazard" and suspending production* of these pesticides was the culmination of a proceeding in which the dominant issues were characterized as "cancer and corn." And, in fact, the EPA administrator, Russell E. Train, concluded that the risks involved in continued use of these two compounds strongly suspected as human carcinogens would vastly outweigh the benefits they offer in the control of corn pests. Possibly the most potent of all the chlorinated hydrocarbons, aldrin and dieldrin thus join DDT as the tarnished miracles of modern agriculture.

Although this preliminary (but probably permanent) decision to ban aldrin and dieldrin is welcomed by environmentalists familiar with pesticide problems, they are anything but complacent about the present state of regulation of chemicals that may be dangerous environmental contaminants. Indeed, the decision to eliminate aldrin and dieldrin as a health hazard comes nearly 4 years after a ban was first requested. Furthermore, there is strong evidence that heptachlor, a chemical expected to be heavily used next year in corn fields of the Midwest as a substitute for aldrin, is itself a potent carcinogen.

The Environmental Defense Fund (EDF), the environmental law group that has led the fight against persistent pesticides, first petitioned for a ban on aldrin and dieldrin on 3 December 1970, the day after EPA came into existence. Several months later, William Ruckelshaus, then the EPA administrator, concluded that there was a "substantial question as to the safety" of these compounds (dieldrin poses the major problem because aldrin usually converts to dieldrin in soil, water, and living organisms).

But Ruckelshaus also concluded that there was insufficient evidence to suspend their production as an "imminent hazard," and he merely gave notice to the Shell Chemical Company—the sole manufacturer of aldrin and dieldrin—that he was initiating proceedings to cancel the pesticides' registration. Shell of course contested the cancellation, thereby virtually ensuring that it would be able to continue producing and selling the pesticides for another few years, while the proceedings wore on.

In response to an EDF petition, the U.S. Court of Appeals for the District

* The order does not suspend production for three permitted applications: restricted use for termites, the dipping of roots and tops of nonfood plants, and use in a totally effluent-free mothproofing system.