

The quality of image analysis results depends to a great extent on the quality of the images that are used. The (in-)famous motto: “garbage in—garbage out” applies. Trying to recover an underexposed or otherwise corrupted image is an enormous effort. Moreover, the very process of image restoration can be considered a form of tampering with the original image, because it introduces information that may not have been there in the first place. When compared to the little extra time spent when taking the picture, having to restore input images constitutes an extremely poor return on investment. We therefore want to spend an entire chapter on how to acquire good images for image analysis.

With a view towards image analysis, three aspects deserve particular attention: (1) A correct analysis of shapes and preferred orientations requires high spatial resolution. This is obtained by choosing equipment with high resolving power and by focusing under appropriate f-stop or condenser settings. Correct digitization, i.e., conversion of the continuous image coordinates to discrete raster coordinates is important also. (2) Correct estimates of size and volumes depends on magnification. The scale should be constant throughout the image; if it varies it should be known such that the image can be rectified. (3) Correct identification of phases and segmentation depend very sensitively on image contrast, given that colors and gray values should have the same ‘meaning’ everywhere in the image. To achieve this, the illumination and the background have to be constant.

Most of the images that are going to be analyzed in this book come from microscopic and macroscopic sources: photomicrography and photomacrography. Proceeding from the largest scale to the smallest we will discuss a number of methods of image acquisition keeping in mind (1) best resolution, (2) constant magnification and (3) even illumination. Note, however, that this chapter does not serve as an introduction to photography, photomacrography or microscopy techniques—it merely highlights certain aspects that are important for image analysis.

2.1 Photography

One of the most common source for images is photography. We begin with pictures that are taken in the field, at the outcrop, using normal lenses or macro lenses for close-ups. Very few people still use photographic film, but the geometrical and optical aspects of picture taking are the same for film and digital cameras. We will discuss photographic optics first and talk about specific aspects of digital cameras later in this chapter. For a more thorough introduction to optics, a textbook (e.g., Hecht and Zajac, 2003) should be considered.

2.1.1 Field Photography

Field photographs are mostly used for illustration or reference. However, under certain circumstances,

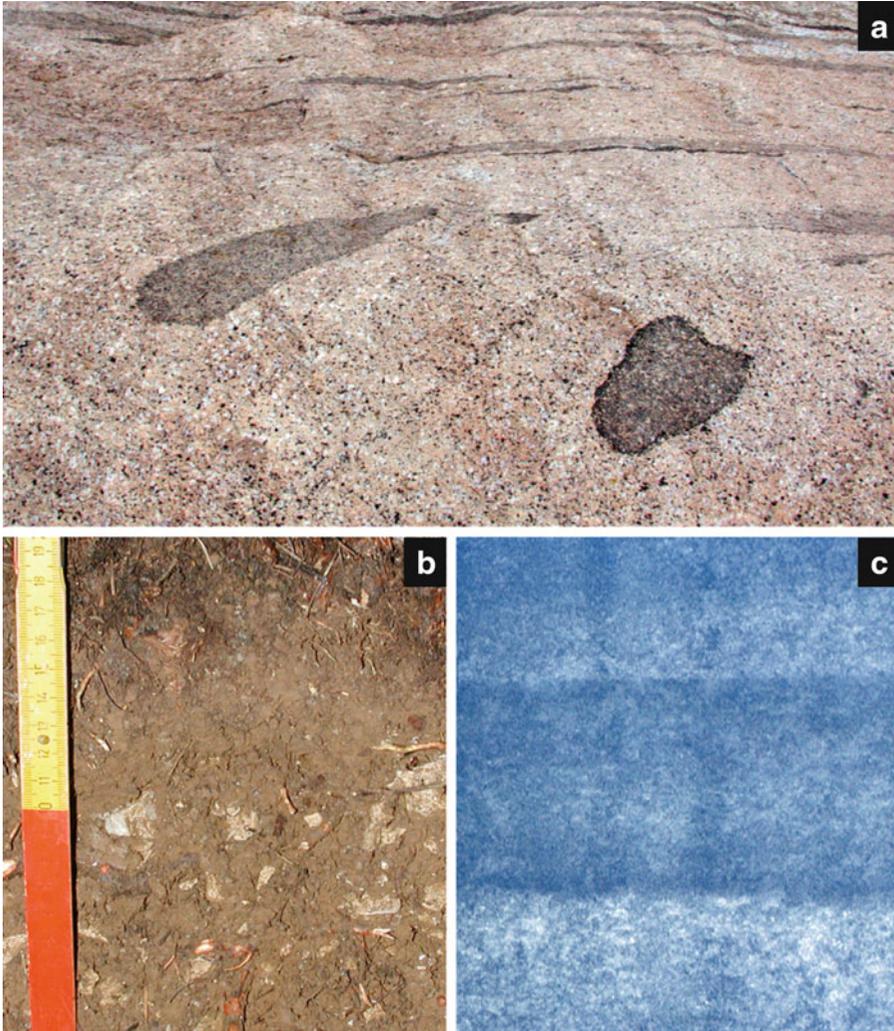


Fig. 2.1 Photographs of outcrops. (a) Outcrop showing ductile shear zone, pocket knife for scale; note, uneven surface producing uneven lighting in spite of diffuse day light conditions; (b) soil profile of rendzina (Image courtesy Christine Alewell); picture taken with flash; note central perspective and even illumination; (c) snow profile; picture taken in transmitted light; scale is missing

and in particular if they are flat, they may also be used as input for image analysis. However, no matter if the images are going to be used as illustrations or for image analysis, a few points are worth considering when acquiring them: (1) locality, (2) lighting, (3) perspective, and (4) scale.

First, with digital storage space being cheap and plentiful, it is worth taking a number of extra pictures at a scale large enough to show the entire outcrop. Using a series of shots one can then zoom in on the actual area of interest. Such overview pictures are often helpful to position and orient close-ups; they also present a record of the

sampling site, showing, for example, if the detail images are representative samples or not. If the camera does not have a GPS device, it may even be worth taking a picture of the topographic or geological map showing the location to make sure that the images can be geo-referenced later on.

Next, the lighting situation has to be considered. Direct sunlight is not recommended because between light and shadow more contrast is created than any film or chip can reproduce; diffuse lighting is best (Fig. 2.1). Direct sunlight should only be used if features of the surface topography such as fractures, cleavage, weathering etc. are to

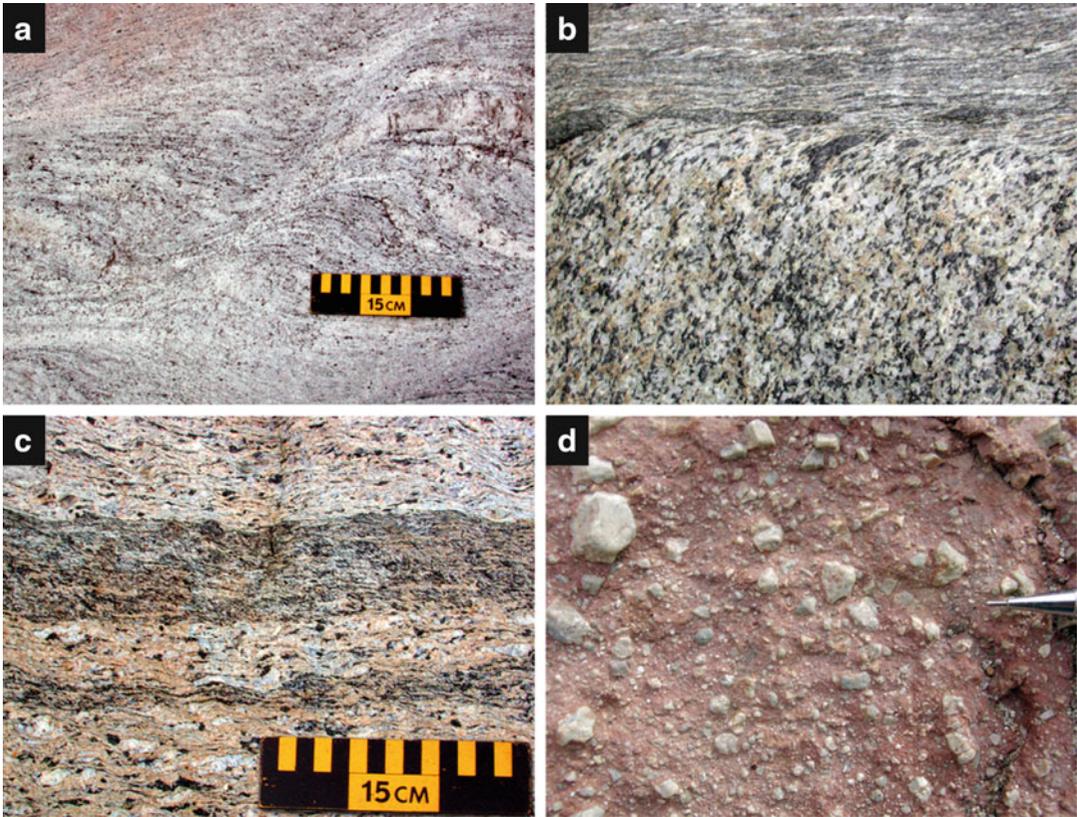


Fig. 2.2 Photomicrography in the field. (a) Glacially polished outcrop; (b) detail of ductile shear zone; (c) foliated granitic rock (*light*) with highly stretched enclaves (*dark*); (d) fault rock, tip of pencil for scale (Image courtesy Holger Stünitz). Note central perspective and diffuse lighting conditions

be emphasized; in these cases, oblique or grazing sunlight is best. Diffuse lighting is given if the day is overcast (Fig. 2.1a) or—on a sunny day—if the outcrop faces away from the sun. For smaller outcrops, a flash can be used (Fig. 2.1b). A special situation is given for snow, where homogenous illumination can be generated by digging a trench and viewing the snow in transmission (Fig. 2.1c).

When photographing smaller details (Fig. 2.2), indirect lighting is easily obtained by blocking the direct sun with a field note book or one's own body. When lighting is poor, additional light can be guided to the scene by using a reflector such as a white piece of paper or the aluminum back of the writing pad (Fig. 2.2d). Again, a flash could be used, but pictures taken with a flash should be checked immediately: it is often difficult to anticipate the effect of the flash when the picture is taken at close range.

Finally, if the picture is to be used for analysis, a central perspective should be used, i.e., the viewing direction should be normal to the surface, as is approximately the case for all outcrops shown in Figs. 2.1 and 2.2 with the exception of Fig. 2.1a. Keeping the magnification constant across the image also implies that distortions are avoided. Last but not least, a scale or an object of known size should be placed somewhere in the picture (Figs. 2.1 and 2.2). For completeness sake, one may consider taking two images, one with and one without the scale.

2.1.2 Photomicrography

In photography, the image is produced by the geometric projection of a scene on the image plane. Regular photographic cameras are designed

for situations where objects are large and at a large distance (compared to the focal length of the camera). The distance between an object and the lens, g , and the distance between the lens and the film or chip, b , are related to the focal length, f , of the lens through a simple geometric relation:

$$\frac{1}{f} = \frac{1}{b} + \frac{1}{g} \quad (2.1)$$

The magnification, m , is the ratio between image size, B , and object size, G :

$$m = \frac{B}{G} = \frac{b}{g} \quad (2.2)$$

from which it follows that the distance, b , between the lens and the image (film or chip) is

$$b = (m + 1) \cdot f \quad (2.3)$$

In field photography, objects are typically much larger than the image. In other words, $m \ll 1$ and the image distance, b , is on the order of the focal length, f , which is of the order of ~ 50 mm for film cameras, or ~ 10 – 30 mm for digital cameras. Focusing is achieved by adjusting the image distance, i.e., moving the objective.

Photomacrography covers the range of magnifications between field photography, where $m \ll 1$, and photomicrography, where $m > 1$ (see later). For a 1:1 magnification, $b = g$ and $B = G$, and the image distance, $b = 2f$. For increasing magnifications ($m > 1$), the objective has to be moved to increasing distances, b , from the image plane and this can only be performed by using a specially designed macro lenses or by introducing a bellows between the camera and the objective. While it is possible to acquire photomacrographs in the field, better results are generally obtained in the lab, where the camera and the light sources can be mounted in a fixed position and the specimen can be fixed as well.

Coarse grained rocks are typical objects for photomacrography and polished sections of such rocks can be used for image analysis. The polished surface of an oolitic limestone is shown in Fig. 2.3a. The image has been acquired

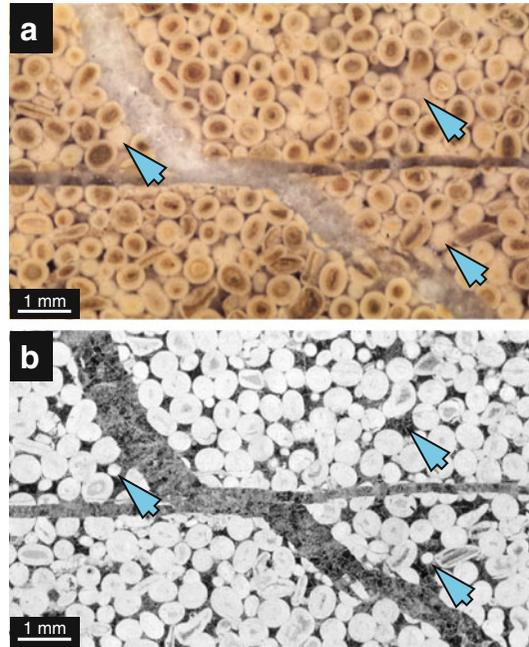


Fig. 2.3 Two dimensions? (a) Polished surface of oolitic limestone; (b) acetate foil replica of surface shown in (a). Arrows point to identical sites

using a reprographic unit. The sample was placed in a shallow tray and covered with a thin film of water to enhance the color contrast. The light sources were placed at 45° on either side.

The ooids can be recognized as ‘swimming’ in a completely transparent calcite cement. Due to the transparency it is possible to see particles that do not intersect the surface but lie a few mm below it. In other words, the image does not show a perfectly two-dimensional section but the projection of the top layer (0–2 mm) of the rock. As we will learn later (in Chaps. 11 and 12), the extrapolation from 2-D to 3-D is easier if the image represents a truly 2-D sample such as provided, for example, by an acetate foil (Fig. 2.3b).

An acetate foil is a replica made by pressing the softened foil onto the cleaned and etched polished surface and letting it dry again. Such a foil shows the microscopic topographic details of the surface roughness without intruding into the rock. Areas with roughness (microcrystalline layers of ooids) appear white; smooth areas (crystal faces of calcite cement) appear dark (Fig. 2.3b).

Images made from surface replicas are much closer representations of 2-D section. Grains that lie below the surface—and that are visible through the transparent cement (Fig. 2.3a)—are not represented on the surface replica (arrows on the right of Fig. 2.3a, b). Other grains appear much larger on the polished surface than on the replica (arrow on the left). In other words, if a grain size analysis were to be made using the polished section, the size of the ooides and the density of the packing would probably be overestimated. Therefore, for the analysis of particles that are suspended in a transparent matrix, surface replicas should be used because they are easier to analyze and interpret than polished sections.

2.2 Optical Scanners

Another option for acquiring images of a polished surface at a magnification, $m = 1$, is to use a flatbed scanner. Best results are obtained if the surface is wetted and put into optical contact with the glass of the scanner. (To avoid major cleaning sessions, water should be used instead of glycerin.) A black towel screens off all stray light and creates a uniform (black) background (Fig. 2.4). Acetate foils can also be scanned, but as they are usually warped they need to be weighted down (often requiring rather heavy weights to accomplish an acceptable flatness). A black paper should be placed between replica and weight, and reflective mode should be used.

Thin sections can also be scanned with a slide scanner (normally used for 35 mm photographic slides), provided that a special holder is available that allows the thin section to be inserted into the slide scanner. Fitting the holder with parallel or crossed polarizer foils, plane or cross polarization can be achieved (Fig. 2.5).

The maximum resolution of slide scanners is usually quite high (4,000 ppi or more), and as a consequence, the complete scan of a thin section may easily come out to be an image of 70 MB or more. A resolution of 4,000 ppi corresponds to a pixel size of 6.35 μm which, at a 1:1 magnification would imply a resolved length of 6.35 μm . The truly resolved length, however, may be larger

(i.e., the true resolution may be poorer) if the indicated resolution is not the physical one but obtained by software interpolation. Note, also, that the nominal physical resolution is only achieved if the focus of the slide scanner can be adjusted to the thin section. An example of a thin section that has been recorded with a slide scanner is shown in Fig. 2.6.

2.3 Light Microscopy

The most common source of images for the image analysis applications discussed in this book is the optical microscope, and in particular the polarization microscope. The details of polarization microscopy are not explained here—the reader is referred to standard textbooks and/or to a number of excellent tutorials that can be found on the internet (e.g., [Molecular Expressions](#), [JOptics](#), [Microscopy Resource Center](#), [MicroscopyU](#), [Education in Microscopy and Digital Imaging](#)). Here, we will only briefly review the type and quality of the images that are obtained by the four most commonly used modes of polarization microscopy.

2.3.1 Modes of Polarization Microscopy

2.3.1.1 Unpolarized Light or Plane Polarization

The polarizers are not inserted or only one is inserted. This situation is called ‘no polarization’ (nopol) and yields an image as shown in Fig. 2.7a. A nopol image is basically an absorption image (showing absorption contrast) where optically opaque regions appear dark and optically transparent parts bright. Absorption contrast is unrelated to the crystallographic orientation of the mineral grains; rather it is related to the amount of impurities, inclusions, etc. If the second polarizer is inserted in an orientation ‘parallel to the first one, the situation is called ‘parallel polarization’ (parpol); the parpol image is also an absorption image, as before. In very few minerals, pleochroism—a change of contrast or

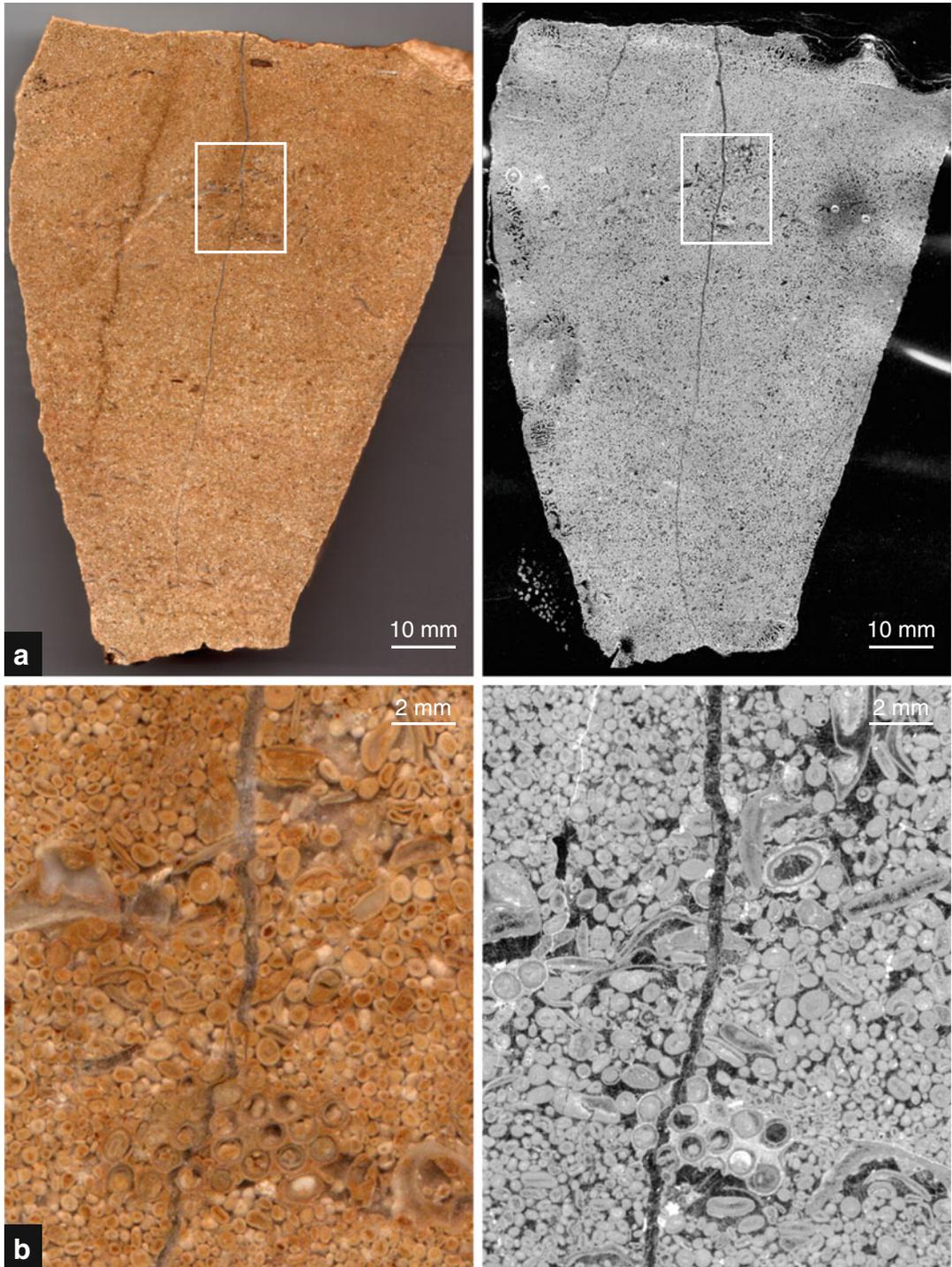


Fig. 2.4 Acquiring images with a flatbed scanner. (a) Polished surface of oolitic limestone and acetate foil are scanned on a A4 scanner at its maximum resolution (600 ppi); (b) enlarged details (see *frames* in (a))

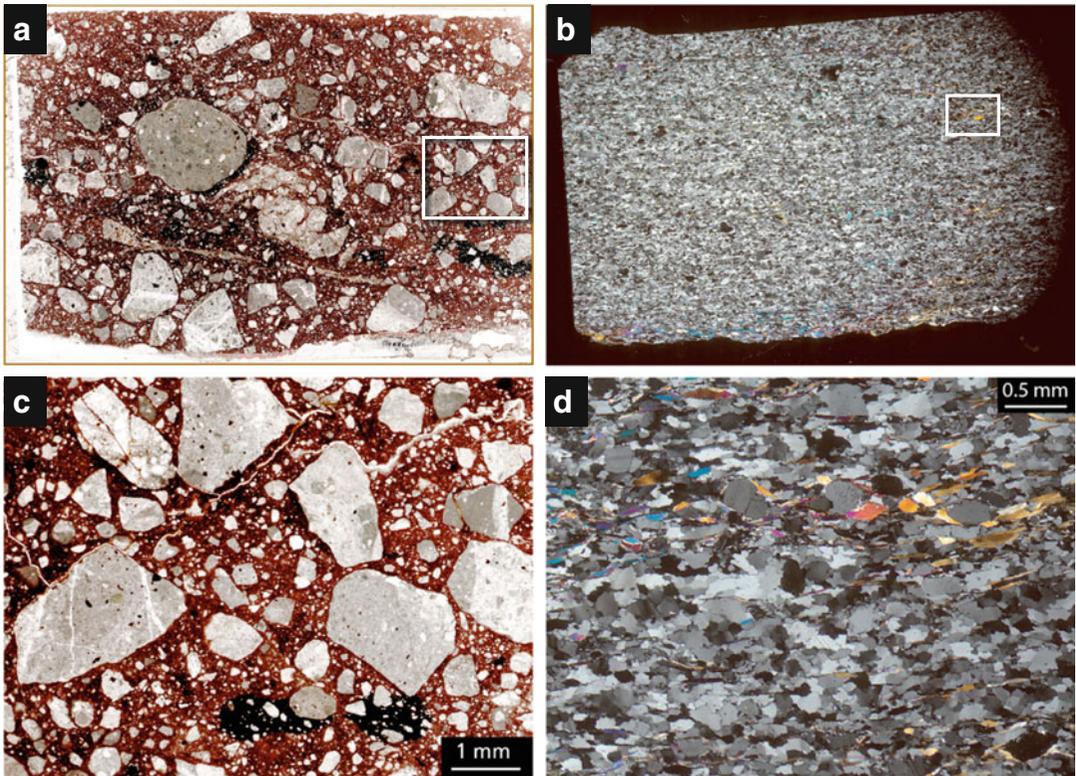


Fig. 2.5 Acquiring images with a slide scanner. Thin sections are scanned using special slide holders at high resolution (4000 ppi); *white* frames in (a) and (b) indicate enlarged details (c) and (d): (a) and (c) consolidated fault rock, plane polarization; (b) and (d) quartz mylonite, cross polarization

color (i.e., absorption) as a function of crystallographic orientation—may be observed. Otherwise, as in the case of quartz, the nopol and parpol images are essentially the same.

2.3.1.2 Cross Polarization

The polarizers are inserted at orthogonal orientations, 0° and 90° . This arrangement is called cross polarization (crosspol). Here, the image contrast is due to interference which in turn depends on the orientation of the optic axes of the minerals with respect to the microscope table or image plane (Fig. 2.7b). Crosspol images show interference contrast that depends on the birefringence of the mineral, the thickness of the section and the full orientation (azimuth and inclination) of the optical axes with respect to the microscope table (or image plane). Later (in Chaps. 21 and 22) we will use the interference contrast to derive crystallographic orientations.

Note that the upper polarizer is sometimes denoted the analyzer, but we will use the same term for both of them.

2.3.1.3 Cross Polarization and Wave Plate

Two polarizers are inserted as before (0° and 90°) and the wave plate, extinguishing at 546 nm, is inserted at 45° with respect to the polarization direction of the crossed polarizers. The wave plate (also called a full-wave plate or a lambda plate) is made from quartz or gypsum. On its own, the wave plate appears magenta colored (sensitive tint). The purpose of inserting a wave plate is to better discriminate the orientations of the optic axis (compare Chap. 21). The combined optical path length of the wave plate and the crystals in the thin section determines the hue and saturation of the resulting interference colors. If a positive optic axis is parallel to the fast direction of the wave plate

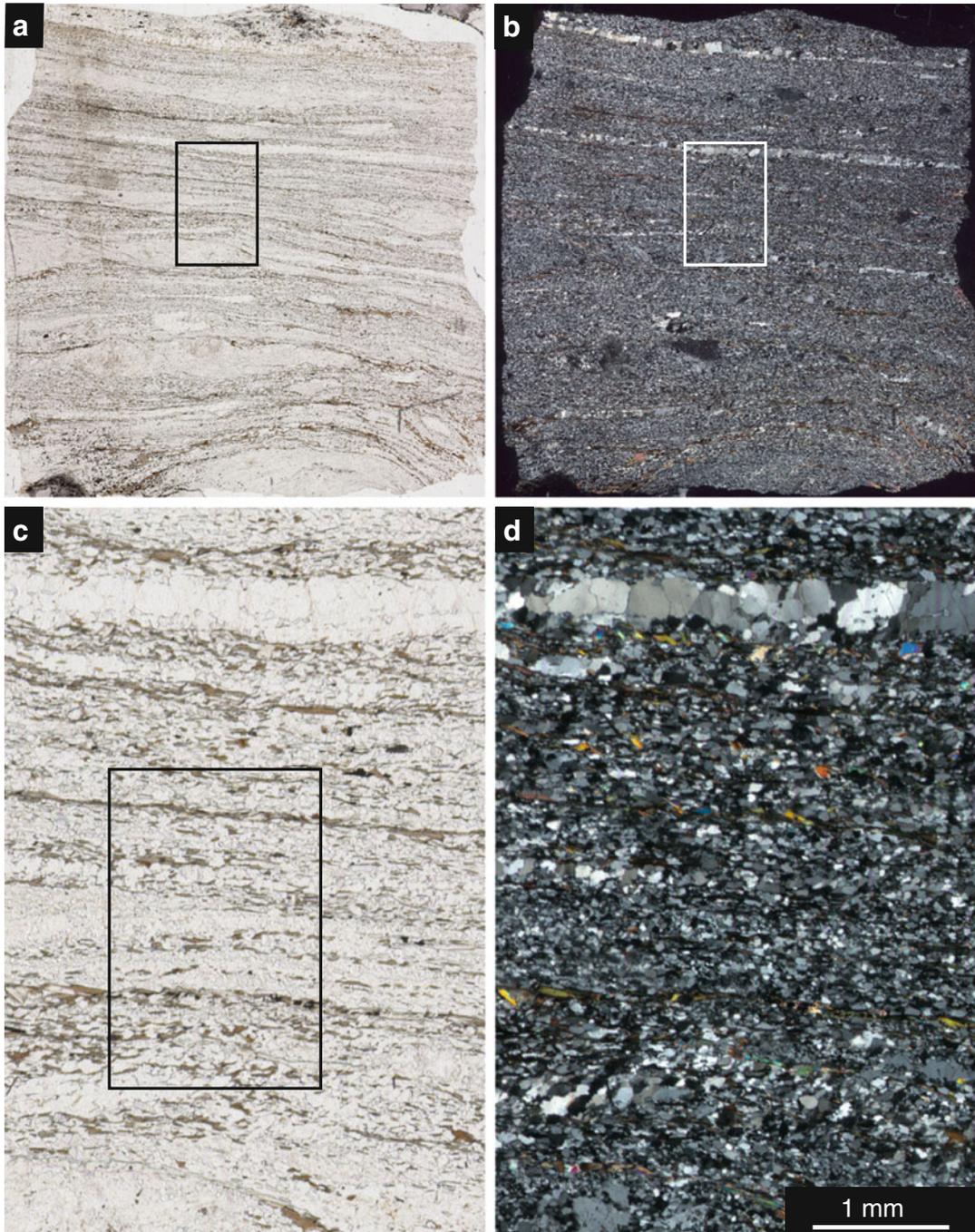


Fig. 2.6 Resolution of slide scanner. (a) Entire thin section of foliated granitoid rock in plane polarization; (b) entire thin section in cross polarization; (c) detail of (a), area in *rectangle* is shown enlarged in Fig. 2.9; (d) detail of (b)

(or a negative one normal to it), the path lengths are added and the color appears as first-order blue. If a negative optic axis is parallel to the fast direction of the wave plate (or a positive one

normal to it), the path lengths are subtracted and the color is first-order yellow (Fig. 2.7c). Interference colors will be discussed in more detail in Chap. 21. In short, crosspol images with the

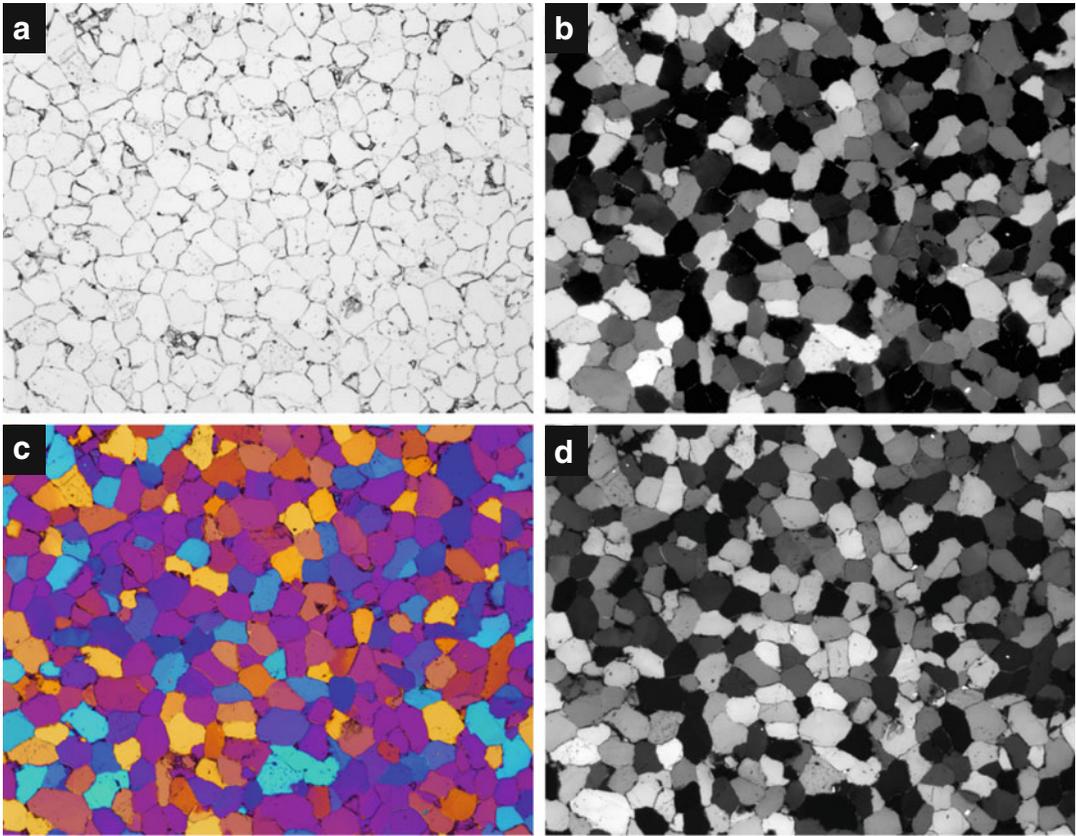


Fig. 2.7 Light microscopy. Thin section of quartzite shown in different modes: (a) plain transmitted light; (b) cross polarization; (c) cross polarization and wave plate; (d) circular polarization

lambda plate inserted also show interference contrast; the color depends on the birefringence of the mineral, the thickness of the section and the full orientation (azimuth and inclination) of the optic axis with respect to the image plane.

2.3.1.4 Circular Polarization

Two polarizers are inserted as before (0° and 90°) and two parallel quarter-wave plates are inserted at 45° with respect to the polarization directions of the polarizers. One is placed between the thin section and the lower polarizer; one between the thin section and the upper polarizer. This situation is called circular polarization (cirpol). Again, the image shows an interference contrast (Fig. 2.7d) and the contrast depends on the birefringence of the mineral and the thickness of the section, but only on the inclination—not the azimuth—of the optic axis with respect to the image plane.

2.3.2 Illumination

High quality images, crucial for successful image analysis, require that the thin sections are of high quality too. Most importantly, they should be clean and without scratches. They should also be of uniform thickness from the center to the edges, so as to avoid artificial interference contrast—the thinner the section, the smaller the path difference, the lower the interference color (more on interference colors in Chap. 21).

Even a perfect thin section will give bad results if the lighting is not perfectly centered and even. To ensure optimal lighting conditions in the microscope, the so-called Köhler illumination is adopted. The procedure is shown schematically in Fig. 2.8. The last step (stopping down the condenser) has to be done with great care because, for visual observation, we tend to stop down the condenser to very small apertures because we

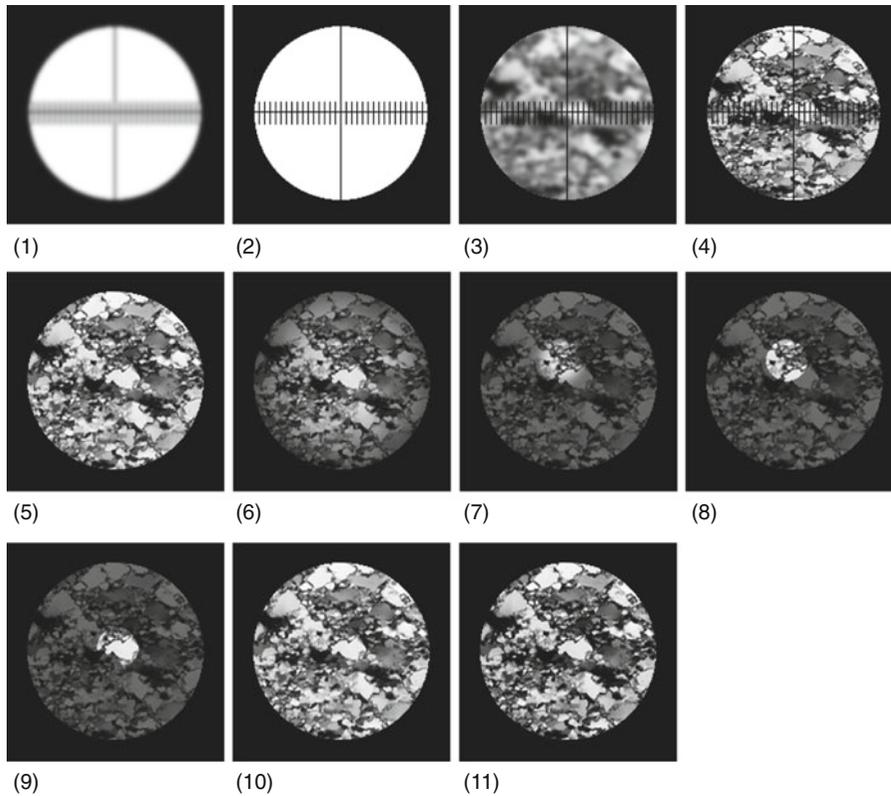


Fig. 2.8 Köhler illumination. Procedure: (1) observe cross hair in eye piece; (2) focus cross hair; (3) observe thin section; (4) bring image of thin section into same plane of focus as cross hair of eyepiece; (5) start with well focused image; (6) install appropriate condenser (with numerical aperture matching that of objective) and open condenser diaphragm completely; (7) close illumination diaphragm; (8) focus image of closed diaphragm by moving the condenser up and down; (9) center image of illumination diaphragm using condenser screws; (10) open illumination diaphragm until the rim of the opening barely disappears from the field of view; (11) stop down condenser

prefer high contrast and an increased field of view. However, the more we stop down, the more we decrease the optical resolution. A slight stopping down is fine because it reduces the remaining aberrations of the optical system and decreases flare, and so stopping down as described in Fig. 2.8 (step 10) strikes a balance between not enough and too much.

2.3.3 Magnification and Resolution

Microscopes are designed for magnified views of small objects, in other words, magnification, $m \gg 1$. Contrary to the photographic cameras, where $m \ll 1$, object distances are large and image distances short, microscopes are designed for short object distances, g , and large image distances, b . Thin sections are placed very close to

the front of the microscope objective ($g \leq 1$ mm), while the image is created at the other end of the tube ($b = 170\text{--}200$ mm). Focusing is achieved by adjusting the object distance, g , i.e., by moving the microscope table while the image distance, b , is fixed by the length of the tube.

The magnifying power of a microscope objective is engraved as $2.5\times$, $5\times$ etc. on its side. Multiplied with the magnifying power of the eyepiece ($15\times$, $20\times$, etc.) the total magnifying power of the microscope can be calculated. However, the precise value for the magnification of a given objective-eyepiece combination can only be determined by taking a micrograph of a micrometer scale and determining the number of pixels per μm .

The largest magnifying power that microscope objectives can achieve is $100\times$. Combining this with a $20\times$ magnifying power of an

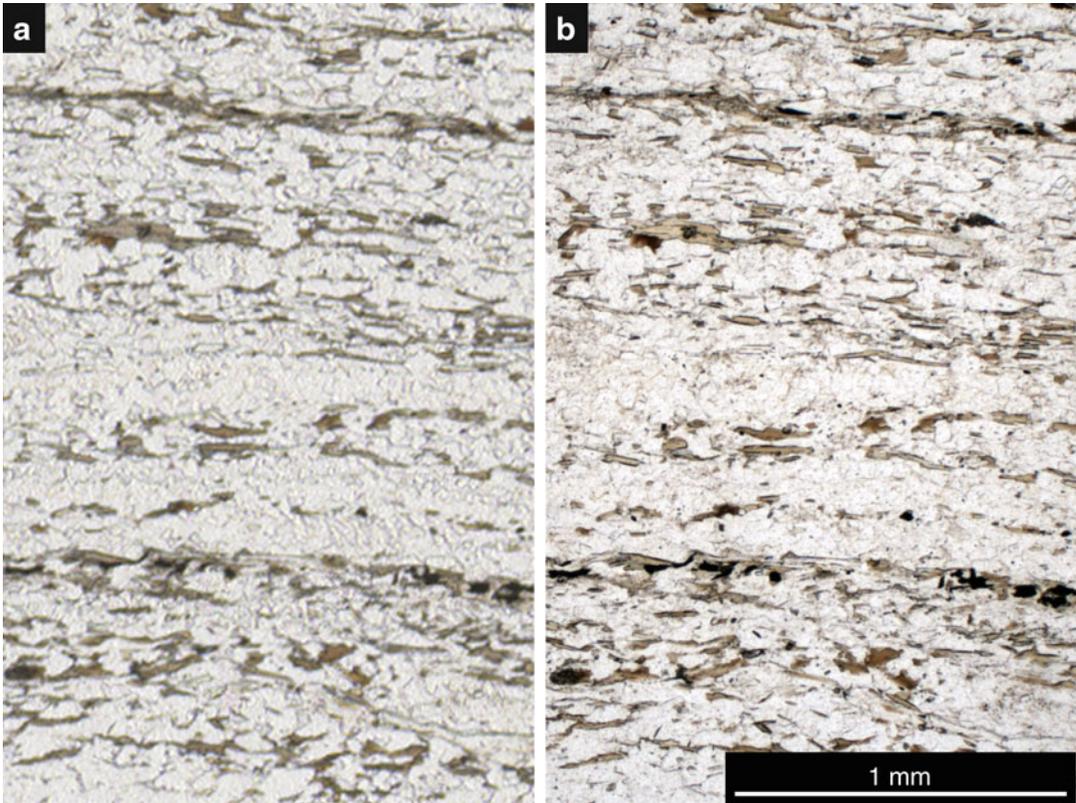


Fig. 2.9 Comparison between slide scanner and low magnification microscopy. (a) Detail of scanned thin section of foliated granitoid rock (see Fig. 2.6c); (b) same area taken with light microscope, ZEISS NEOFLUAR Epiplan 2.5 \times /0.075, plane polarized condition, area in frame is shown at higher magnification in Fig. 2.14

eyepiece, for example, this would yield a total magnification of 2,000 \times . By re-sizing the image digitally, the magnification could be increased even further. However, the resulting magnification would be an ‘empty’ magnification because the larger image does not reveal any new detail; the resolution would not increase. An example is given by the thin section shown in Fig. 2.9. An image has been acquired once using a slide scanner and a second time using an optical microscope with a low-power (2.5 \times) objective.

The magnification in Fig. 2.9a is identical to that of Fig. 2.9b. Yet, quite obviously, there is a lot more detail visible in the image taken with the microscope. The reason for this is the higher resolving power of the microscope objective. In general, the resolving power increases with increasing magnifying power. Still, the resolving power is a separate quality by which excellent and not so excellent objectives can be distinguished.

The resolving power is given by the numerical aperture, a number which is also engraved on the side of microscope objectives. For example, the numbers ‘2.5 \times /0.075’ indicate that the magnifying power is 2.5 \times and the numerical aperture is 0.075.

Optical microscopes are diffraction-limited systems and both the lateral resolution and the depth resolution depend on the numerical aperture of the microscope objective. The numerical aperture, NA, in turn, depends on the opening angle, u , of the imaging system:

$$NA = n \sin(u) \quad (2.4)$$

n is the refractive index of the medium. In dry microscopy $n = n_{\text{air}} = 1.0$. If oil immersion is used $n = n_{\text{oil}} = 1.5$ and NA can be as high as 1.3.

Due to the wave nature of light, the light emanating from an (infinitely small) point source does not converge to an (infinitely small) image

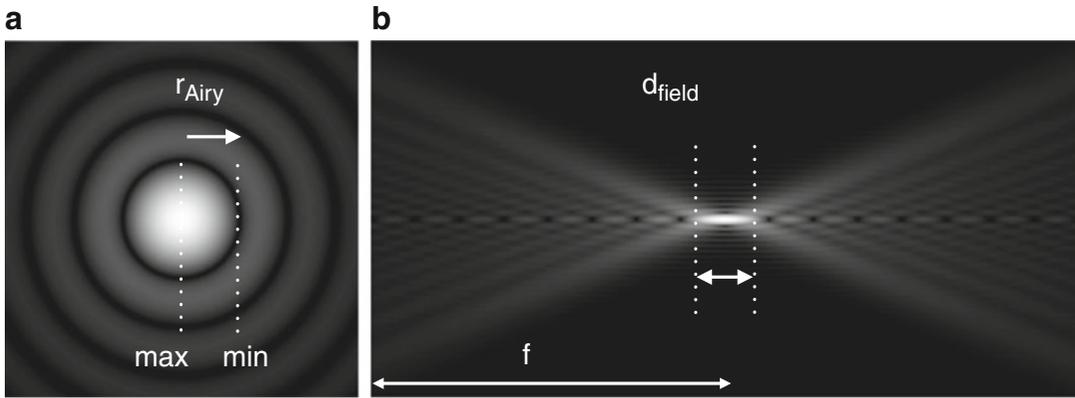


Fig. 2.10 Point spread function (PSF). (a) Lateral resolution in image plane (x-y plane) determined by radius of Airy disk; (b) depth resolution determined by constant size (magnification) of Airy disk along the z-axis of the optical system; longitudinal section, f = focal length, direction of optical axis

point. Instead, it creates an extended image featuring a central bright spot with concentric rings (Fig. 2.10a). The brightness distribution is described by the point spread function, PSF, and the central bright spot is the Airy disk. The radius of the Airy disk, r_{Airy} , depends on the wavelength of the light and the numerical aperture of the optical system:

$$r_{\text{Airy}} = \frac{1.22 \lambda}{2 \text{NA}} \quad (2.5)$$

The lateral resolution is given by the Rayleigh criterion which says that two points can be resolved if the distance, d , between them is at least equal to the radius of the Airy disk.

$$d = \frac{1.22 \lambda}{\text{NA}_{\text{obj}} + \text{NA}_{\text{cond}}} \quad (2.6)$$

Note that d depends on the numerical aperture of the entire system, i.e., on the NA of the condenser, NA_{cond} , and the NA of the objective, NA_{obj} . Matching the NA of the condenser to the NA of the objective, such that $\text{NA}_{\text{obj}} = \text{NA}_{\text{cond}}$, leads to the smallest value of d , i.e., to the best resolution. This is the reason for not stopping the condenser more than is absolutely necessary (see Fig. 2.8, step 11, and Sect. 2.3.2 on illumination).

The PSF not only extends in the x-y plane of the image, but also in the third dimension

(Fig. 2.10b) along the axis of the optical system. Based on the Rayleigh criterion, the depth of field is given by:

$$d_{\text{field}} = \frac{\lambda}{2 n \sin^2(u)} \quad (2.7)$$

For dry systems this reduces to:

$$d_{\text{field}} = \frac{\lambda}{2 \text{NA}^2} \quad (2.8)$$

In summary, both the lateral resolution and the depth resolution depend on the wavelength and the numerical aperture of the optical system (Figs. 2.11 and 2.12). At 550 nm, i.e., the green wavelength, where the human eye is most sensitive, a low-power objective ($2.55\times$ with $\text{NA} = 0.075$) can resolve points that are $4.47 \mu\text{m}$ apart and the depth of field is $\sim 50 \mu\text{m}$; while a high performance dry objective ($50\times$ with $\text{NA} = 0.8$) resolves $0.42 \mu\text{m}$, i.e., more than 2,000 lines per mm, with a depth of field of $1.1 \mu\text{m}$. Note that in the case of a regular thin section (thickness $\approx 25 \mu\text{m}$), a low-power objective can bring the entire thin section into focus, from top to bottom, whereas the high-power objective can resolve a little more than 4 % of its thickness.

Note that in photography or during observational work at the microscope, when focusing, we try to create a situation where we can resolve as fine

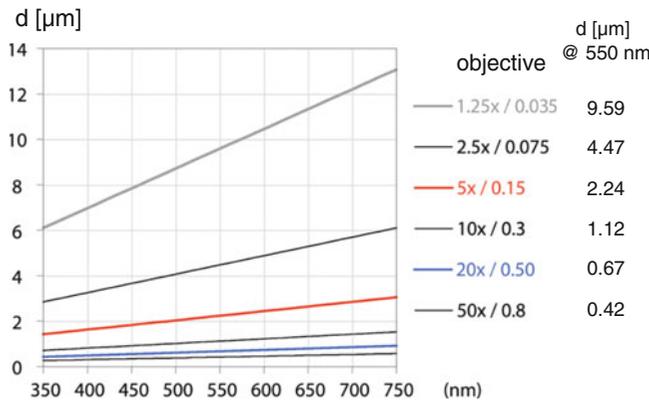


Fig. 2.11 Lateral resolution. Resolved length, d , as function of wavelength, λ , for different microscope objectives; values of d at 550 nm wavelength are indicated

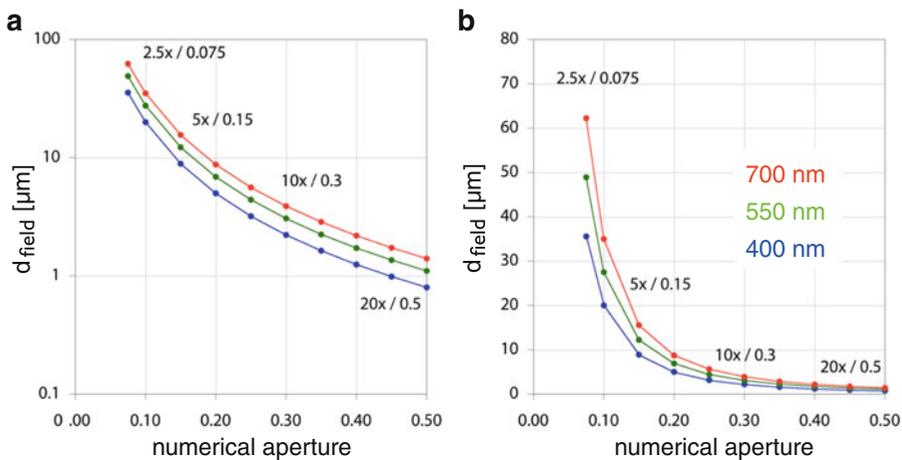


Fig. 2.12 Depth resolution. Depth of field, d_{field} , as a function of numerical aperture is shown for three different wavelengths: (a) logarithmic plot; (b) linear plot

a detail as possible but where we also have as large a depth of field as possible; the former is obtained with high-power objectives, the latter with low-power objectives. However when we consider resolution in three dimensions, we realize that the smallest resolved volume (given by the lateral resolution and depth of field: $d \cdot d_{\text{field}}$) decreases from $978 \mu\text{m}^3$ for a $2.5\times/0.075$ objective to $0.194 \mu\text{m}^3$ for a $20\times/0.5$ objective, by a factor of 5,000!

an image sensor. Image sensors are typically CCD (charge-coupled device) or CMOS (complementary metal oxide semiconductor) chips. In either case, the image is usually generated as a matrix of square pixels recording brightness. The spectral sensitivity of an image sensor typically extends from less than 400 nm to more than 1,000 nm (Fig. 2.13a). For color cameras, color separation is effected by placing a Bayer filter grid in front of the sensor (see Fig. 2.13b for filter transmission). Two green filters, one red and one blue filter are placed across groups of four pixels as shown in Fig. 2.13c, combining four monochromatic pixels to create one color pixel. As a consequence, the physical resolution of a color

2.4 Digital Cameras

Very few photographic cameras still use photographic film; in most cases the film is replaced by

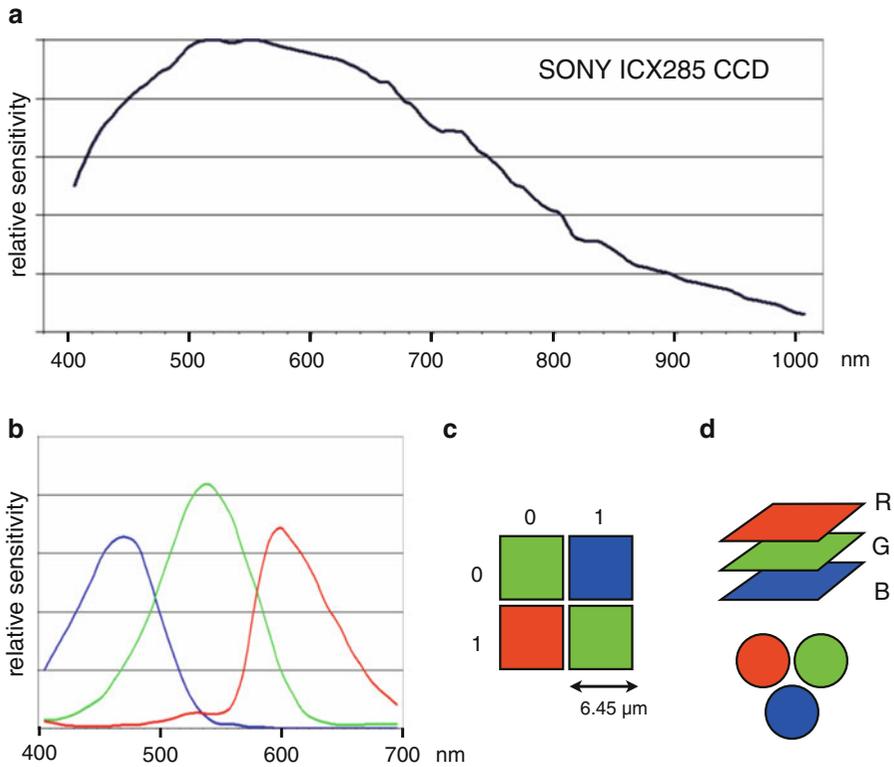


Fig. 2.13 Example of image sensor. (a) Spectral sensitivity of CCD image sensor without filter; (b) spectral sensitivity of CCD image sensor with Bayer filters for red, green and blue pixels; (c) recording color through Bayer filter, typical width of pixel is 6–7 μm, position of two green, one red and one blue filter in the even (0) and odd (1) columns and rows of the chip are indicated; (d) rendition of color as three color channels (RGB) in color images and three fluorescent spots on the monitor

sensor is decreased by a (linear) factor of 2 compared to an unfiltered, monochromatic sensor. Full resolution is restored through interpolation (de-mosaicking) in the course of calculating the three color channels (Fig. 2.13d).

When matching an image sensor to an optically produced image, the size of the pixels on the sensor and optical resolution of the optical system have to be matched. The Nyquist sampling theorem requires that the sampling frequency should be twice the highest frequency of the image. Translating this to the spatial resolution of optical systems, the pixel size should be < 0.5 dm (resolved length times magnification). Table 2.1 shows the comparison of the μm/pixel recorded at

Table 2.1 True size represented by one pixel in image compared to resolved length of objective; values measured for Axiocam camera and ZEISS Axioplan microscope; note that the true pixels size is approximately one half of the resolved length

objective	no. of pixels	true length [μm]	true size of pixel [μm]	resolved length [μm]
2x	205	500	2.44	4.47
5x	79	100	1.27	2.24
10x	156	100	0.64	1.12
20x	155	50	0.32	0.67
50x	158	20	0.13	0.42

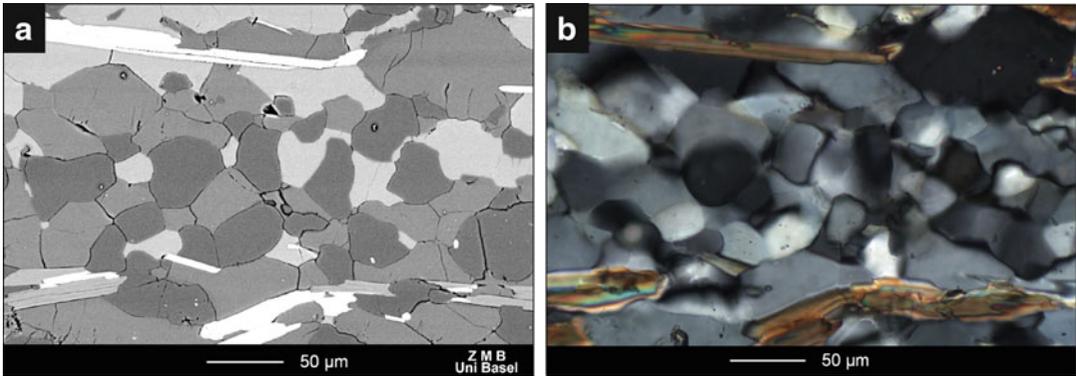


Fig. 2.14 Scanning electron microscopy. (a) Micrograph of polished surface of foliated granitoid rock (Image courtesy Rüdiger Kilian), backscatter electron contrast (BSE) showing different mineral phases: *white* = biotite, *very light gray* = K-feldspar, *light gray* = muscovite, *gray* = plagioclase, *dark gray* = quartz; (b) same area taken with optical microscope, circular polarization (see Fig. 2.9b): here contrast is mainly due to orientation of crystals with respect to polarizers

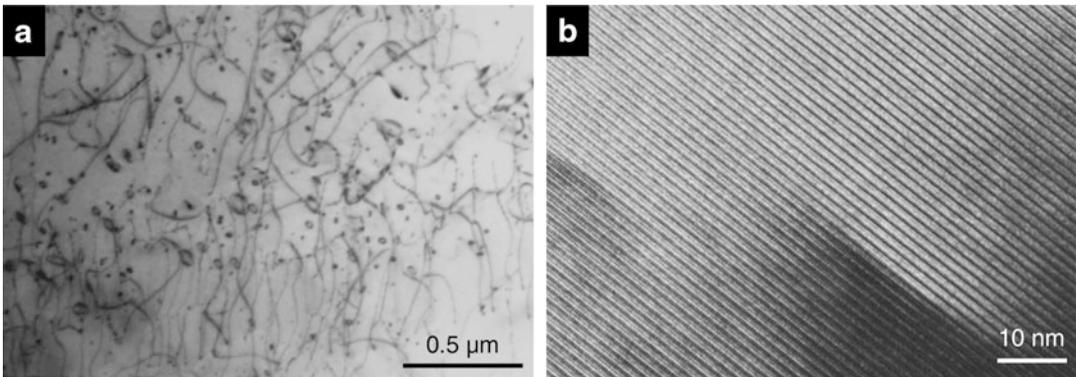


Fig. 2.15 Transmission electron microscopy. (a) Free dislocations in quartz, bright field contrast (Image courtesy John Fitz Gerald); (b) Chlorite, lattice planes, high resolution image (Image courtesy Andreas Kronenberg)

various magnifications with the Axiocam camera of a ZEISS microscope. The table shows that the Nyquist criterion is fulfilled at all scales.

that they are uncovered. However, for TEM analysis special sample preparation is necessary.

2.5 Electron Microscopy

For higher resolution and higher magnification, electron microscopy is used. In scanning electron microscopy (SEM), spatial resolution is limited by the excitation volume for secondary or back-scattered electrons. In transmission electron microscopy (TEM), the resolution is limited by the wavelength of the electron beam.

For SEM, it is possible to use the same thin sections that are used for light microscopy, provided

2.5.1 Scanning Electron Microscopy (SEM)

In SEM analysis the surface of a sample is scanned with an electron beam and the intensity of secondary electrons is recorded producing an image where the brightness reflects surface topography. If a back-scattered electron (BSE) detector is used, the brightness reflects atomic number. SEM/BSE images of polished sections show different mineral phases with different shades of gray (Fig. 2.14a).

Comparison with a micrograph taken under circular polarization shows that the SEM/BSE micrograph is a truly 2-D section, whereas the light micrograph shows a projection of a 25 μm thick volume of rock. In the SEM/BSE micrograph, grain boundaries appear as linear traces; in the light micrograph, they are seen projected and if they are oblique to the thin section surface they appear as wide strips. The second difference is the contrast: in the BSE/SEM micrograph contrast reflects composition; in the light micrograph, the contrast reflects a combination of mineral composition and crystallographic orientation. SEM/BSE micrographs constitute excellent input for image analysis.

2.5.2 Transmission Electron Microscopy (TEM)

Image formation in a TEM is analogous to that in light microscopy, and TEM micrographs are occasionally used for image analysis. For periodic

structures, such as crystals, contrast is always some form of phase contrast. Under bright field conditions, defect structures such as dislocations may be seen (Fig. 2.15a); direct resolution reveals lattice planes (Fig. 2.15b).

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