

Applications of Neutron Radiography and Neutron Tomography

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INTRODUCTION

In radiographic methods, the attenuation of an incident beam on passing through an object is used to study the internal structure of this object. The availability of techniques to “look inside” large, optically intransparent objects without having to destroy them is obviously appealing and has had a profound impact in many fields, most clearly in medicine, but also in condensed matter studies. The development of radiography started with Röntgen’s discovery of X-rays in 1895, where the absorption of X-rays by bones were demonstrated publicly in 1896 by obtaining a radiograph of a hand. The medical applications were obvious, and already in World War I, mobile X-ray units were routinely deployed. The main shortcoming of X-ray radiography in early medical applications is that often it cannot be used to distinguish different kinds of soft tissue and that the two dimensional projections are sometimes difficult to interpret. This changed dramatically with the development of “computerized axial tomography” for which the Nobel prize was awarded in 1979 to Hounsfield and Cormack. Computed tomography, as it is now frequently called, is the three-dimensional reconstruction of the interior of an object from many radiographs taken at different angles, and this combination of data sets enables to distinguish between different soft tissues, such as kidneys and liver.

Medical computed X-ray tomography scanners were used soon afterwards to investigate minerals and rocks, for example in an early study of chondritic meteorites (Arnold et al. 1983). These had a comparatively poor spatial resolution of ~1 mm. As there is no need for low radiation doses in material science studies, and as the penetrating power of high energy X-rays is larger and higher spatial resolutions can be obtained, dedicated scanners for material science have been developed. Commercially available “table top” scanners now offer spatial resolution of less than 1 μm . More recently, the advantages of synchrotron radiation (monochromatic, collimated and extremely brilliant beams) have been exploited in tomography. For example, the CT system at SPring-8 has a spatial resolution of about 1 μm (Uesugi et al. 2001).

With the availability of neutron beams for research in the early 1950’s, a similar development of neutron radiography and tomography occurred. This was, in part, driven by the need to investigate objects for which X-ray radiography could not be employed, namely the investigation of reactor fuel assemblies, which are intransparent to X-rays. A brief history of the development of neutron radiography, together with a list of general references has recently been presented by Berger (2004).

Neutron radiography and neutron tomography are now mature techniques, and this chapter gives a brief overview over some aspects relevant to their application in earth sciences. An example of a neutron radiograph and a neutron tomograph of a rock is shown in Figure 1.

The main advantage of using neutrons as a probe in comparison to other radiographic and

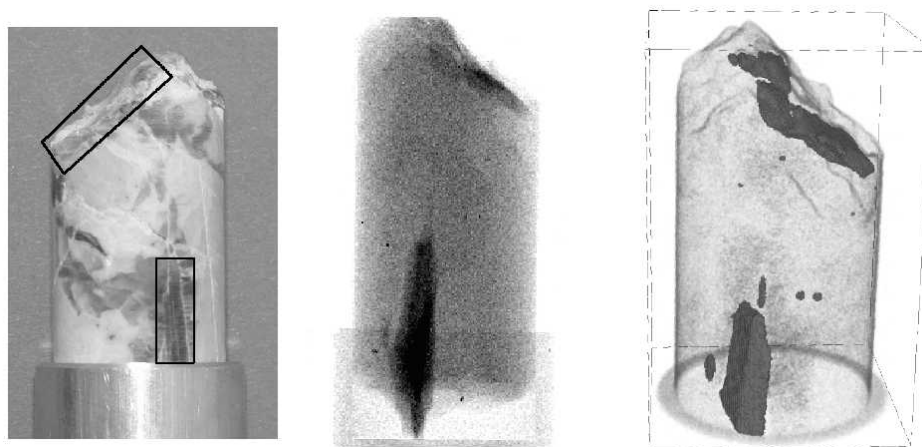


Figure 1. Photograph (left), neutron radiograph (center) and computed tomograph (right) of a pegmatite. The diameter of the sample is 35 mm. The linear attenuation coefficient of hydrogen-rich mica grains is very different from those of the surrounding anhydrous minerals, and hence the mica grains can easily be distinguished. Image processing software can then be used to e.g., determine the volume fraction of mica in the sample. These measurements and image processing were performed at the PSI, Switzerland.

tomographic techniques is that due to the high penetrating power of neutrons, large samples can be investigated with little or no radiation damage, and that light elements can be detected in an environment dominated by heavy elements. Clearly, like any other techniques, neutron radiography has its strengths and limitations, and a large number of complementary approaches, such as X-ray, synchrotron or γ -ray tomography, nuclear magnetic resonance tomography or proton radiography are now available. In the earth sciences, neutron radiography and neutron tomography have only rarely been used up to now, and it is hoped that the present outline will stimulate researchers to exploit the unique capabilities of these techniques.

FUNDAMENTAL ASPECTS

The principle of radiographic and tomographic methods is to measure the attenuation of an incident beam along a line through an object as shown in Figure 2.

For a parallel and monochromatic beam the attenuation measured by a detector element is given by

$$-\ln\left(\frac{I}{I_0}\right) = \int \mu(x,y) ds \quad (1)$$

where I_0 and I are the incident and the detected beam intensity, $\mu(x,y)$ is the linear attenuation coefficient at (x,y) and the integration is along the straight line from the final aperture to the detector. The attenuation is due to scattering and absorption. The very different interaction mechanisms of neutrons and X-rays with matter result in very different μ and are the origin of the distinct capabilities and limitations of neutron and X-ray radiography.

The scattering of neutrons is conventionally separated into “coherent” and “incoherent” scattering. The coherent scattering cross section, σ_{coh} , the incoherent scattering cross section, σ_{inc} , and the absorption cross section, σ_{abs} , of elements are tabulated in standard reference works (see e.g., Dianoux and Lander 2002 and references cited therein). All scattering and

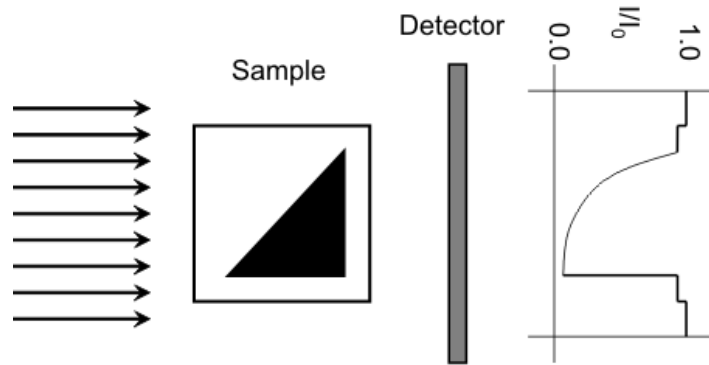


Figure 2. 2D schematic view of a neutron radiographic experiment. In this simplified drawing, a parallel neutron beam is used to illuminate a sample. The position sensitive detector records the attenuation of the beam after transmission through an inhomogeneous sample. The measured intensity is a projection of the distribution of the linear attenuation coefficients within the sample.

absorption processes contribute to the attenuation of the transmitted beam and the linear attenuation coefficient μ is given by

$$\mu = \sum \frac{\sigma_i \rho_i N_A}{m_{\text{molar},i}} \quad (2)$$

where $\sigma_i = \sigma_{\text{coh},i} + \sigma_{\text{inc},i} + \sigma_{\text{abs},i}$ is the sum of the coherent and incoherent scattering and absorption cross section of the i^{th} element (usually given in barn, where $1 \text{ barn} = 10^{-24} \text{ cm}^2$), ρ_i is the density of the i^{th} element (in g/cm^3), and $m_{\text{molar},i}$ the molar mass of element i . For example, the normalized transmitted intensity I/I_0 for thermal neutrons (with wave length $\lambda = 1.78 \text{ \AA}$) after transmission of 1 cm of pure aluminum ($\rho = 2.7 \text{ g/cm}^3$, $m_{\text{molar}} = 26.9815 \text{ g/mol}$, $\sigma = 0.239 \text{ barn}$) is 0.985. The cross section, and hence the penetrating power of neutrons of a given wave length, depends on the neutron energy, this will be discussed below.

From Figure 2 it is evident that the experiment will depend on the characteristics of the neutron beam (brilliance, divergence, spectral distribution) and the properties of the detector. Both aspects will be discussed below.

Neutron beams

Depending on the type of experiment, neutron radiography can be performed essentially with all available neutron sources, including portable ones. In one special case, namely in “neutron-induced autoradiography” the neutron beam is only used to activate certain elements in the sample under investigation, so that the emission can then be measured by placing the object on a detector (generally an image plate, see below). This approach has, for example, been used to investigate paintings and other cultural heritage objects in order to reveal hidden details with a non-destructive method (Fischer et al 1999; Schillinger 1999). In geoscientific applications, neutron-induced autoradiography have been used to map the distribution of a number of elements in rock samples (Flitsyan 1998; Romer et al. 2005).

In practice, the overwhelming number of radiographic and tomographic studies are performed at dedicated stations at neutron scattering facilities. It is therefore of interest to establish, for which purposes which of the different radiography/tomography stations are best suited. The neutron flux and the divergence of the incident beam are parameters which need to be taken into account. A well-established criterion to characterize the beam divergence is the L/D -ratio, where L is the length of the flight path from a pinhole with diameter D (typically

a few cm) to the sample. High L/D -ratio therefore indicate a small beam divergence. The experimental determination of the L/D -ratio is standardized (see references in Berger 2004) as it is by no means straightforward to compute it for neutron guides. L/D -ratios vary from ~50 up to values >10,000 (Schillinger 1999; Schillinger et al. 2000).

Cold neutrons are generally guided to the neutronography station by a slightly curved neutron guide. This has the advantage that the background is much reduced, as γ -radiation and fast neutrons travel in straight lines and hence do not reach the sample. At other installations the radiography station is located at the end of a flight tube facing a cold neutron source. At such stations, the spectral distribution of the neutron beam is significantly broader compared to that at the end of a guide.

Depending on the specific installation, the flux of thermal neutrons from beam ports can be significantly higher than for cold neutrons. Currently, the most intense beam for neutronographic investigations is available at the Institute Laue Langevin in Grenoble, where a thermal neutron flux of $\sim 3 \times 10^9$ (neutrons $\text{cm}^{-2} \text{s}^{-1}$) illuminates the sample at the end of a 15 m flight path. At other sources the available flux is generally one to three orders of magnitude smaller.

It is also possible to use fast neutrons with energies of a few MeV (Nordlund et al. 2001; Sanami et al. 2001; Bücherl et al. 2004). These have a significantly greater penetrating power than thermal neutrons, which is necessary if, for example, very hydrogen-rich compounds are investigated.

Detectors

There is a wide variety of detectors available for neutron imaging work, which differ from the detectors often used in diffractometers and spectrometers, since point or linear detectors (such as ^3He -counters) are inappropriate. An informative summary on currently used detectors has recently been presented by Lehmann et al. (2004).

The choice of a detector for a specific experiment should be based on considering the following aspects: (1) the spatial resolution of the detector assembly is one of the limiting factors determining the size of the smallest features which can be observed. (2) For dynamic imaging, the time resolution is important and is given by the number of images which can be collected and processed in a given period of time with a sufficient signal-to-noise ratio for the observation of non-periodic processes. For periodic processes, “stroboscopic” techniques can be used, these are discussed below. (3) The dynamic range and linearity of the detector is important if accurate intensity values are essential. This is always very important for neutron tomographic studies. (4) The sensitive area of the detector limits the size of objects which can be studied by neutron tomography but is not as crucial for radiography, where individual images can be combined or where large objects can be “scanned.” (5) Quantitative studies require digital data—this is one of the main draw-backs of film-based methods.

For those detectors which are based on the detection of photons (i.e., X-ray film, image plates or video cameras), converters (scintillators) are employed, in which an incident neutron triggers a reaction so that photons can be measured. Neutron converters are based on elements which absorb neutrons and emit secondary radiation. This secondary radiation is then absorbed by a photo stimulable phosphor, and can then be detected optically or leads to the formation of a latent image. Typical converter materials are ^6Li -doped ZnS, Gd_2O_3 or $\text{Gd}_2\text{O}_2\text{S:Tb}$. The choice of the thickness of the converter is a compromise, as the neutron detection efficiency increases with thickness, but the spatial resolution decreases (Baechler et al. 2002).

For neutron radiographic work, photographic X-ray film used to be the most commonly used detector, but it has now, with few exceptions, been replaced by imaging plates (see below). Films still play a role in routine quality control, such as in the testing of components for aviation and space technology, where rigorous and standardized procedures have been

established, and where the advantages, such as the good spatial resolution (20-50 μm), outweigh the disadvantages, such as the non-linear response of the film, the necessary wet-chemical processing and that the data is initially only analog.

Image plate detectors for X-rays use Eu-doped BaFBr layers as a storage phosphor dispersed in an organic binder supported on a polymer sheet. An incident photon will excite an electron into a metastable state, where it is trapped, and hence a latent image is formed. If the image plate is later scanned by a red laser, a recombination process is induced, during which blue light is emitted. Such image plates can be adapted to neutron detection by adding gadolinium (usually as Gd_2O_3) to the phosphor layer. On neutron capture, the gadolinium releases a conversion electron, which will then create a storage center (Thoms et al. 1997; Schlapp et al. 2002). The resolution of an image plate is slightly worse than that of photographic film (~50–100 μm). Image plates replace film, as they have a higher sensitivity, high linearity and a higher dynamic range. Also, the intensity data is immediately available in a digital form. They are generally used as “off-line IP,” i.e., the IP-holder is detached from the scanner. This allows for custom made dimensions of the detector, but off-line IPs cannot be used efficiently for neutron tomography, as the read-out and erasure procedure cannot be fully automated.

Video cameras based on conventional pick up tube technology (e.g., orthicon or vidicon tubes) are rapidly replaced by CCD-based cameras. Most modern CCD based cameras are cooled by Peltier elements in order to increase the signal-to-noise ratio. With the exception of facilities with a very high flux, cameras can be used for the observation of processes with a time resolution of a few tenths of a second. At very high flux facilities, a time resolution of a few ten μs can be obtained in very favorable conditions. For example, the interaction of a water jet with a metal melt has been recorded with “high-frame” neutron radiography with 1125 frames/s (Sibamoto et al. 2002). However, short exposure times with a poor signal to noise ratio, the limited dynamic range available in high speed cameras, and the need to use image intensifiers generally restrict the available resolution to ~200-500 μm for studies of fast processes. The improvement of the spatial and temporal resolution of CCD-cameras is an active field of research (Schillinger 1999; Koerner et al. 2000; Schillinger et al. 2005) and significant improvements have been achieved in the last years. As the CCDs are sensitive to radiation, they cannot be exposed to the direct beam. Hence, the camera is housed in a light-tight and radiation-shielded box and aligned at 90° to the neutron flight path. The camera sees an image of the neutron converter on a mirror placed at 45° to the neutron beam and the optical axis of the camera. Video cameras are often used in conjunction with image intensifiers, which, while increasing the sensitivity, significantly constrain the achievable spatial resolution.

The development of new detectors is an active area of research. The characteristics of amorphous silicon flat panels have recently been discussed by Lehmann and Vontobel (2004). They seem to offer improvements at least in two areas, size and resistance against radiation damage. While CCD-based detectors have an active area of a few cm^2 only, amorphous silicon flat panels with an active area of about $20 \times 30 \text{ cm}^2$ are available. This is of interest for those experimental stations in which the beam is collimated so that a large area is illuminated. In the neutronography station GENRA-3 at the GKSS facility in Geesthacht, Germany, for example, the beam illuminates an area of $\sim 45 \times 45 \text{ cm}^2$. Other new developments include CMOS-based detectors (Lehmann and Vontobel 2004).

NEUTRON RADIOGRAPHY

Neutron radiography is an established technique exploited commercially in materials science, e.g., for testing of parts in aviation and space technology. Neutron radiography has been used to determine water contents and diffusion in rocks and related compounds, such as bricks and concrete (Nordlund et al. 2001; El-Ghany El Abd and Milczarek 2004; Masschaele

et al. 2004). Standard static neutronography is, however, of little interest in the earth sciences, as neutron tomographic experiments provide much more information and these will be discussed below. Neutron radiography can also be used for the observation of processes. In the context of *in situ* observations, this is of interest, as sample environments, such as high temperature furnaces, can be constructed so as to be nearly transparent to the neutron beam (Kahle et al 2003b).

Dynamic neutron radiography

For the observation of processes, two distinct methods are available, namely “dynamic neutron radiography” for non-periodic and “stroboscopic neutron radiography” for periodic processes. The latter will only briefly be introduced, as there are so far no geoscience-related applications. The observation of non-periodic processes at non-ambient conditions, especially at high temperatures, is very promising and two examples will be mentioned here.

The first example is “falling sphere” experiments. Radiographic studies of falling sphere experiments (Fig. 3) have widely been used in the earth sciences, as they present a unique opportunity to study densities and viscosities of melts at non-ambient conditions. At synchrotrons, falling sphere experiments in high pressure cells have been used to study melts at high pressure (e.g., Mori et al. 2000, Suzuki et al. 2002). These experiments are very challenging, and care has to be taken to avoid systematic errors, e.g., due to convection, non-uniform heating, ill-defined starting time of the sphere motion, or short falling times. At least for ambient pressure, high temperature investigations, neutrons offer a viable alternative, where most of these experimental problems can be avoided (Kahle et al. 2003a). Also, dynamic neutron radiography allows to observe sphere falls over large distances (~10 cm) and for a large range of velocities (~0.05-10 cm/min).

Large sample volumes also allow to use falling sphere experiments to investigate inhomogeneous melts with a significant fraction of crystallites. This would be problematic with alternative approaches, such as rotational viscosimetry (Dingewell 1995). However, first attempts indicated that possibly the main problem will be to ensure that the crystalline fraction neither floats to the top of the melt nor sinks to the bottom over the time required for the measurements, i.e., for a few hours.

The large illuminated sample volume also allows to study other processes. In a preliminary study, it has been shown that melt dynamics can be monitored (Fig. 4). Here again, large samples can be used and observation times can range from a few seconds to a few hours.

Further obvious applications for dynamic neutronography include the observation of bubble formation, of hydrogen diffusion, and of changes in interfaces between melts with different densities under shear.

COMPUTED NEUTRON TOMOGRAPHY

The images obtained from neutron radiographic investigations are two dimensional projections of the distribution of linear attenuation coefficients in the sample. In analogy to the developments in X-ray tomography, the advent of sufficiently powerful computers and suitable detectors allowed neutron tomographic investigations. Computed neutron tomography is now an established technique in the material sciences.

Due to its immense importance in diagnostic medicine, all aspects of the data processing required to obtain tomographic images from radiographs have been studied extensively and the most often used algorithms are well documented (e.g., Kak 1988). Also, due to the large market for data analysis software, a variety of commercial and public domain software packages have been developed. As the data analysis in tomographic experiments is quite independent of the ap-

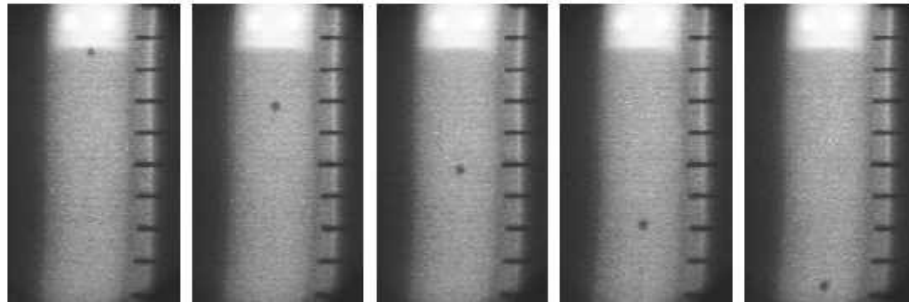


Figure 3. Time dependent neutron radiography. Here a sphere made of strongly absorbing material (Hf, Gd, Ta) falls in a silicate melt at high temperatures ($T > 1000$ °C). From the speed the viscosity of the melt can be determined. The distance between the markers on the left of each frame is 1 cm. Exposure times were 1/10 s. Total falling times range from a few minutes to an hour, so that several thousand positions of the sphere s function of time can be determined. These measurements were performed at the LLB, France.

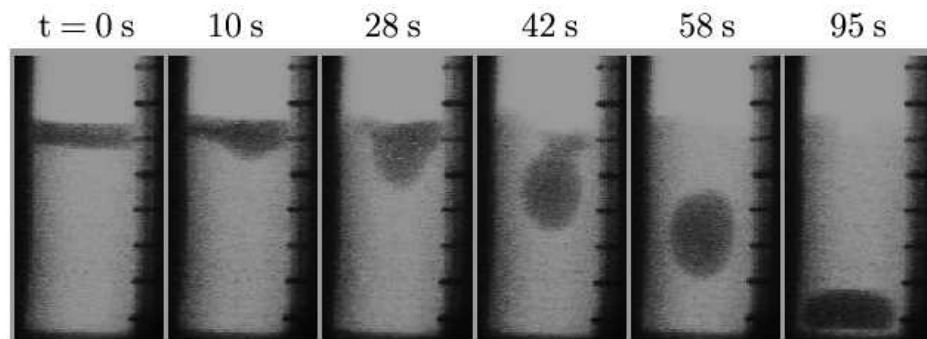


Figure 4. Dynamics of two immiscible melts. In this feasibility study, a brass plate was put on top of a silicate melt. After melting, the brass then descended through the silicate melt. These observations can be used to “calibrate” numerical models. These measurements were performed at the LLB, France.

plication, it is comparatively easy for a novice to obtain useful images if the main technical aspects are understood. Hence, in the following, only a few technical details will be mentioned.

If scattering and the energy dependence of the linear attenuation coefficient is neglected, tomography is the reconstruction of the distribution of the linear attenuation coefficients, $\mu(x,y)$ in the two-dimensional case described by Equation (2) or, in the more general case $\mu(\mathbf{x})$, where \mathbf{x} describes a location in three dimensions. From the projections $\int \mu(\mathbf{x}) ds$, which can be measured for different straight paths s , the distribution of $\mu(\mathbf{x})$ must then be found by reconstruction. There are several techniques available, with the most important ones being (1) “filtered back projection,” which relies on the Radon transform, (2) Fourier reconstruction and (3) algebraic reconstruction. The accuracy of these three approaches should be very similar. Alternative approaches have been explored by several authors, e.g., use of maximum entropy methods (Zawisky et al. 2004).

The reconstruction of the distribution $\mu(\mathbf{x})$ is, of course, limited by the resolution of the individual images. It can be shown that if the detector would be the limiting factor, the maximal resolution could be achieved if the transmission is measured for $\pi/2 \times$ (number of pixels /line) sample orientations. In practice, due to the beam divergence and other limiting factors, it is not possible to achieve this optimal resolution. Instead the required rotation by 180° is covered

in steps of slightly less than 1° , so that ~200-400 images are collected. Depending on the available flux and detector, a full data set can be collected in a few hours.

Tomography relies on accurate intensity measurements, and this implies that the influence of inhomogeneities or fluctuations in the beam intensity and differences in the efficiency of detector elements have to be minimized and corrected for. Hence, corrections with “flat field” (open beam) frames and “dark images” with a closed beam shutter are performed. An internal scaling can be obtained by comparing parts of the image which are not obscured by the sample during a rotation. The software required for the transformation of the individual frames to a three-dimensional rendering of the structure is commercially available from several companies. Fast computers with large (a few GB) random access memory are required for the processing of high resolution images.

Applications of neutron computed tomography in the material sciences are very wide ranging. In geosciences, there are comparatively few applications. Neutron tomography is very well suited to investigate the distribution and intergrowth of minerals (Figs. 5 and 6).

This is of interest, as the description of the textures of coarse grained igneous rocks is essential for an understanding of their formation process. Tomography can efficiently provide information of grain sizes and pore systems (de Beer et al. 2004). It can also be used to visualize the flow of liquids in bulk rocks (Wilding et al. 2005; Dierick et al. 2005).

A paleontological study visualized fossilized leaves of a cornifer in an eocene fossil assemblage, with neutron tomography (Abele H, Ballhausen H, Cywinski R, Dawson M, Francis J, Gähler R, Stephens R, Van Overberghe A, pers. com.) (Fig. 7). This indicated a close relationship of the fossil cornifer to present day “monkey puzzle trees” (*araucaria araucana*).

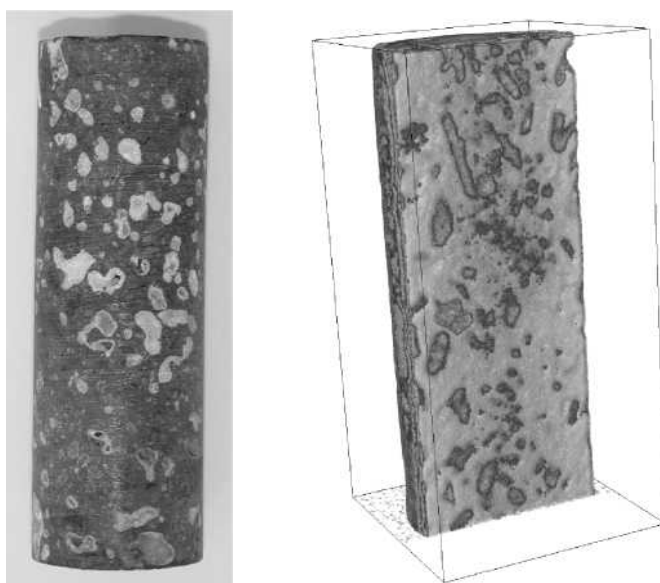


Figure 5. Photograph (left) and slice through a computed tomograph (right) of a basanite, a volcanic rock of felsic composition with an aphanitic texture. The surfaces of the pores are covered with water-containing zeolites. Image processing software can be used to determine the volume fraction of the pore system and to investigate if this is an open or closed pore system. These measurements and image processing were performed at the PSI, Switzerland.

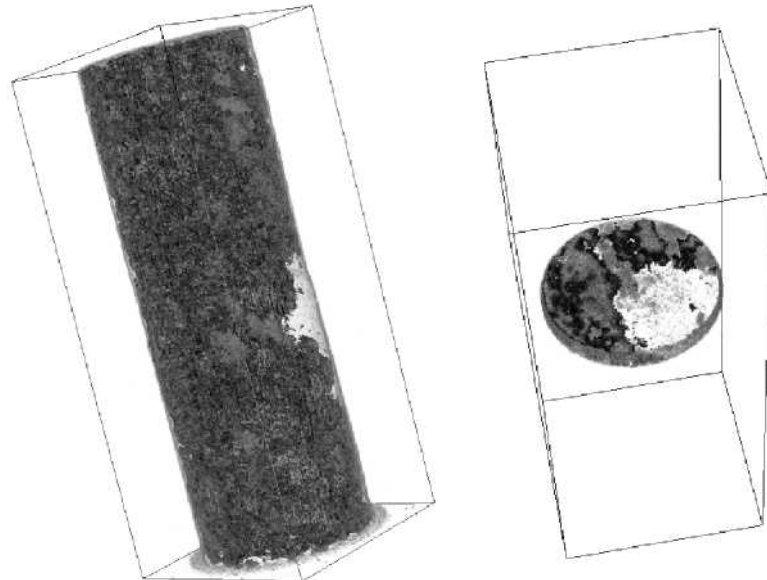


Figure 6. In a garnet-mica schist, individual mineral species can be identified in the tomogram (left). The slice on the right shows the intergrowth of garnet with the other minerals in the sample. Garnet is anhydrous and hence much more transparent to neutrons than the hydrous minerals such as mica. These measurements and image processing were performed at the PSI, Switzerland.

From a practical point of view, most tomographs are obtained from objects whose largest dimension is smaller than the detector edge and which can be fully illuminated by the neutron beam. Hence, currently available setups limit the edge lengths of the object under investigation to about 20 cm. However, it is possible to perform a tomography of so-called “regions-of-interest” of objects larger than the detector or beam with additional computational effort (Schillinger et al. 2004).

In the simplified description given above, a monochromatic incident beam has been assumed. For a polychromatic neutron beam, a formally correct description would have to incorporate the energy dependence of the linear attenuation coefficient, and hence $\mu(\mathbf{x})$ would have to be replaced by $\mu(\mathbf{x}, E)$. For cold and thermal neutrons, the absorption cross section is generally proportional to $1/v$, i.e., the higher the neutron energy (the shorter the wavelength and the higher the velocity v) the higher the penetration power. This may lead to so-called “beam hardening,” i.e., the mean energy of the transmitted spectrum is shifted

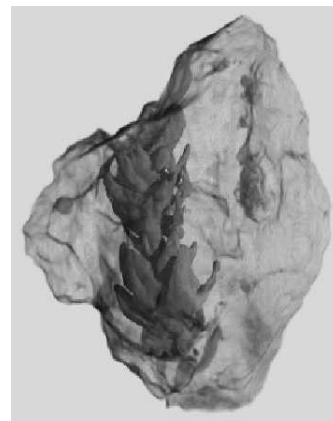


Figure 7. Tomography of fossilized leaves of a conifer enclosed in a sediment. This image was produced at the ILL (Grenoble) by a collaboration of researchers from the University of Leeds and the University of Heidelberg (Abele H, Ballhausen H, Cywinski R, Dawson M, Francis J, Gähler R, Stephens R, Van Overberghe A. pers. comm.). A comparison with leaves from present day plants indicates a close relationship to the monkey puzzle tree. Such studies may help to determine the evolution of leaf morphology and of the distribution of plants.

to higher energies with respect to the incident spectrum. This may lead to problems in the tomographic analysis of materials containing strong neutron absorbers, and may lead to artifacts in edge regions or for weakly attenuating regions, surrounded by strongly attenuating regions (Schillinger 1999). In addition, the exponential attenuation can also be violated due to incoherent scattering, especially in the presence of elements with a large incoherent and a small absorption cross section. Finally, coherent elastic scattering of neutrons may lead to a discontinuity in the energy dependence of μ if the lattice spacing is large enough as to lead to Bragg scattering. Then, the attenuation coefficient for neutrons with a wave length shorter than that corresponding to the Bragg edge will be larger than the attenuation coefficient for long wavelength neutrons. These effects may become significant in detailed investigations and the development of algorithms to correct for such effects is a current field of research (Hassanein et al. 2005; Kasperl et al. 2005).

FURTHER EXPERIMENTAL APPROACHES

Stroboscopic techniques

Periodic processes can be observed with neutron stroboscopic imaging. The principle is straightforward: a shutter is installed between detector and sample and synchronized with the repetition rate of the process. The shutter must be able to open and close on a short time scale relative to the time required to complete one period. The shutter is opened for a short time for a given part of the process, closed for the remainder, and opened again when the cycle repeats. The detector is therefore illuminated only for a fraction of the cycle. The detector must be able to accumulate information so that after a few hundred passes a reasonable signal-to-noise ratio is obtained. Then, the synchronization is changed, so that the shutter is open at a different fraction of the periodic process. Current technology allows to observe periodic processes with a time resolution of a few hundred microseconds. Technical aspects of this approach, which has been very successfully applied to study combustion engines and fuel injection systems, have recently been discussed by Brunner et al. (2005) and Schillinger et al. (2005).

Phase contrast imaging

Phase contrast imaging is well known in optical microscopy, where it allows to resolve features below the diffraction limit. For this development, a Nobel prize was awarded to F. Zernike in 1953. Phase radiography with neutrons has been first been demonstrated recently by Allman et al. (2000).

While a detector placed very close to the object will register the absorption contrast only, a detector placed in the near-field region will register the influence of the refractive index on the propagation of the neutron wave. This leads to an enhancement in contrast. However, the demands on the spatial coherence are stringent for phase contrast neutronography. To achieve this spatial coherence, pin holes with a diameter of a few tenth mm are used. This increases the L/D -ratio, but also leads to a drastic decrease of the flux at the sample. A number of papers have now been published (e.g., McMahon et al. 2003; Kardjilov et al. 2004) which have demonstrated, that polychromatic neutron beams can be used for phase-contrast radiography. Due to the increased incident intensity in comparison to monochromatic beams, this leads to a significant decrease in measurement times.

While phase contrast measurements can be used to only enhance the contrast, quantitative studies in which the variation of the beam intensity along the beam direction is measured and analyzed with a transport-of-intensity equation are possible. This then allows to distinguish between those materials, which have the same linear attenuation coefficient but a different refractive index (Lehmann et al. 2005).

Neutron interferometry

Neutron interferometry, based on the use of large perfect crystals as beam splitters, is a well established technique, mainly employed to study properties of neutrons (Bonse and Rauch, 1979). Neutron interferometry can also be used to image objects and recently, an interferometry-based neutron phase contrast tomography with a spatial resolution of about 50 μm has been developed by Zawisky et al. (2004). However, the limited space for a sample environment and the complexity of such experiments will very likely limit the applicability of this approach for earth science related studies.

COMPARISON TO X-RAY TOMOGRAPHY

The main differences between X-ray- and neutron-based investigations are due to the difference in the interaction between photons and neutrons with matter, and due to the very different beam characteristics of X-ray and synchrotron radiation and neutron beams. Neutrons can detect light elements, such as hydrogen, in a matrix of heavy elements, and that makes them ideally suited to study water in an anhydrous matrix. The brilliance of synchrotron beams, however, is several orders of magnitude larger than that of neutron beams, and hence for the investigation of very small samples with very high resolution, X-ray and synchrotron radiation will always be preferable. A list of linear attenuation coefficients for thermal neutrons and 100 keV electrons and a comparison of X-ray and neutron tomographic images of an ammonite and an eclogite have recently been published by Vontobel et al. (2005).

Further comparative studies emphasize that in many cases it will be beneficial to have a variety of radiations available and to be able to compare radiographs or tomographs (e.g., Masschaele et al. 2004). This is possible at some facilities. For example, the new ANTARES facility at the FRM-II in Munich allows to use cold and thermal neutrons, γ -radiation, and X-rays from a 320 kV tube (in a quasi-parallel beam geometry, as the X-ray source is 12 m away from the sample). As only the converter or detector is changed, while the sample is unmoved, images obtained with the different radiations can be superimposed or subtracted without further manipulation (Schillinger et al. 2006).

SUMMARY AND OUTLOOK

Neutron radiography and neutron tomography are techniques which are mature and readily accessible. They can be used to study the interior of large, complex objects with a resolution of $\sim 100 \mu\text{m}$, and observe non-periodic processes with a temporal resolution of a fraction of a second. Neutron radiographic investigations have already been carried out at high temperatures. There have been no radiographic investigations at high pressures up to now and there are several problems which need to be overcome in the construction of large volume autoclaves suitable for such studies. There have also been no tomographic investigations at high temperatures, although it should be straightforward to adopt available furnaces for such experiments. Time resolved studies of systems relevant to the earth sciences are also in their infancy, yet it is conceivable that dynamic neutron radiography will play a prominent role here in the future.

The relatively large number of neutron radiography stations, which are available at nearly all neutron scattering facilities (e.g., FRM-II in Munich, PSI in Villigen, NIST in Gaithersburg, ILL in Grenoble) allows comparatively easy access to these techniques and hence, especially in conjunction with complementary techniques such as γ -ray, synchrotron or X-ray radiography and tomography, open new and exciting possibilities to study the interior of and processes in complex materials of relevance to the earth sciences.

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