Applications of X-ray computed tomography in the geosciences

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Abstract: X-ray computed tomography (CT) is a non-destructive technique with wide applications in various geological disciplines. It reveals the internal structure of objects, determined by variations in density and atomic composition. Large numbers of parallel 2D sections can be obtained, which allows 3D imaging of selected features. Important applications are the study of porosity and fluid flow, applied to investigations in the fields of petroleum geology, rock mechanics and soil science. Expected future developments include the combined use of CT systems with different resolutions, the wider use of related X-ray techniques and the integration of CT data with results of compatible non-destructive techniques.

X-ray computed tomography (CT) is a non-destructive technique that allows visualization of the internal structure of objects, determined mainly by variations in density and atomic composition. It requires the acquisition of one- or two-dimensional radiographs for different positions during step-wise rotation around a central axis, whereby either the source and detector or the sample are moved. This is followed by the reconstruction of two-dimensional cross-sections perpendicular to the axis of rotation.

CT images record differences in the degree of attenuation of the X-rays, which is material- and energy-dependent. The interactions that are responsible for this attenuation are mainly Compton scattering and photoelectric absorption. The contribution of the photoelectric effect depends on the effective atomic number and is especially important at low energies. At high energies, the Compton effect predominates and attenuation is mainly determined by density.

X-ray CT was developed as a medical imaging technique in the early 1970s (Hounsfield 1972, 1973). The possibility of its use in geology and engineering was soon recognised, resulting in large numbers of publications from the early 1980s onwards. Early applications include studies in the fields of soil science (Petrovic *et al.* 1982; Hainsworth & Aylmore 1983), meteoritics (Arnold *et al.* 1982), petroleum geology (Vinegar 1986; Vinegar & Wellington 1986), palaeontology (Haubitz *et al.* 1988), geotechnics (Raynaud *et al.* 1989) and sedimentology (Kenter 1989).

In this introductory paper, we present some general information about the technique and a brief overview of its applications in geology, with references to some recent studies. More detailed information can be found in recent review articles by Duliu (1999) and Ketcham & Carlson (2001).

Acquisition of transmission data

The basic components of X-ray CT scanners are an X-ray source, a detector and a rotation system. Various possible configurations exist, whereby the selected configuration is determined by sample size and the desired resolution, besides availability and access restrictions. Ideally, the X-ray beam should be parallel rather than fan- or cone-shaped (with a finite size of the origin), in which case the resolution is only determined by detector quality. High resolution (10 μm) can also be attained with microfocus X-ray tubes. Another aspect of acquisition is the energy spectrum of the X-ray source. Unless the X-rays are produced by radioactive decay, they are always polychromatic with a wide range in energy. This complicates quantitative analysis and creates artefacts in the CT images, due to the stronger attenuation of X-rays with lower energies. Monochromatisation by diffraction eliminates these problems, but involves a great decrease in intensity and is therefore only feasible for systems with high initial intensities, such as linear electron accelerators and synchrotron installations.

Most X-ray CT studies of geological materials are carried out using medical scanners of different generations, which differ mostly in configuration of the source and detectors. The highest

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resolution that can be obtained with medical scanners is rather low, in the order of 600 µm × 600 µm × 1 mm.

Scanners that have been developed specifically for material research are now also available, both with fan-beam and cone-beam configurations. The latter allow the acquisition of data for many cross-sections at the same time, but their use involves more complicated reconstruction procedures. The advantages of CT systems for material research include the possibility of using higher X-ray intensities and the possibility of attaining higher resolutions by using microfocus X-ray tubes and by rotating the specimen rather than the source and detector. CT images of the highest quality are obtained with synchrotron radiation, which has the advantage of near-parallelism of the X-ray beam and the possibility of monochromatisation. A drawback of high-resolution systems is that high resolutions can only be obtained for small samples, e.g. <2 mm diameter for a 5 µm resolution in microfocus CT scans.

Reconstruction of CT images

The mathematical principles of backprojection procedures required for reconstruction have been known for a long time. In X-ray CT, a pre-reconstruction transformation of the radiographs is required to enhance contrast and sharpness of the CT images. This is done by applying a digital filter to the obtained signals. Various types of filters can be used for this operation. To be able to perform a reconstruction for a specific cross-section, data for the entire object must be available for this level, in radiographs for all different angles. The object should be completely in the field of view for each of these angle positions, i.e. surrounded by air in each radiograph, which limits the maximum sample size.

Image quality optimization requires a reduction of artefacts, which are inherent to the technique of X-ray CT. Several common types of artefacts can already be reduced to some extent by optimising acquisition conditions, but a further reduction during reconstruction is often needed. This is the case for: (i) misalignment artefacts, related to an imperfect alignment of source, detector and axis of rotation; (ii) ring artefacts, related to detector defects; (iii) star artefacts, related to the presence of dense objects; and (iv) line artefacts, related to the presence of anomalously bright pixels in the radiographs. The most important artefacts in CT images are related to 'beam hardening', which refers to the preferential attenuation of low-energy X-rays when a polychromatic X-ray beam passes through an object. This effect can be reduced to some extent by using a hardware filter, which involves a loss in intensity of the X-ray beam and a lowering of contrast in the radiographs. For beam hardening artefact reduction during reconstruction, linearisation procedures are highly recommended for monomineralic systems (Hammersberg & Mangard 1998). For polymineralic systems, a dual energy approach allows a dramatic improvement in image quality (De Man *et al.* 2001).

The development of simulators is a useful approach for artefact reduction, as they allow optimisation of the choice of acquisition parameters in function of the object to be studied. A major problem with this approach is the fact that the X-ray spectrum is often unknown and very difficult to measure (Hammersberg *et al.* 1998).

Applications in the geosciences

Suitable materials

X-ray CT can be used for qualitative and quantitative analysis of internal features of geological materials, if those features are marked by sufficiently great differences in atomic composition and/or density.

A strong contrast mainly exists between solid phases and the atmosphere. An important application of X-ray CT is, therefore, the study of porosity, including porosity represented by pores with dimensions below the resolution of the CT images. Examples of applications in this field include studies of soil macro-porosity (e.g. Perret *et al.* 1999) and reservoir rock characterization (e.g. Van Geet *et al.* 2000). The contrast with the atmosphere is also used as a means of visualizing the external morphology of objects, e.g. for surface roughness analysis (e.g. Fohrer *et al.* 1999) or for documenting the morphology of fossils (e.g. Rogers 1999).

The contrast between liquid phases and the atmosphere finds wide applications in the study of hydraulic properties, both in soil science (e.g. Mooney 2002) and petroleum geology (e.g. Peters *et al.* 1996). Recent technological improvements allow the discrimination between empty and (water-)filled pores (Roels *et al.* in press). In earlier studies, heavy elements had to be added as tracers (e.g. Mori *et al.* 1999), which has also been done to monitor gas transport (e.g. Karacan & Okandan 2001).

Visualization of the distribution of different solid phases generally requires pronounced variations in atomic composition. The few published studies mainly concern materials with iron-bearing minerals (e.g. Tivey 1998; Spiess *et al.* 2001) or minerals with exceptionally low attenuation values (e.g. Taylor *et al.* 2000). Synchrotron CT with monochromatic X-rays is required to differentiate between less contrasting materials.

For many applications, a correlation with results obtained by more traditional techniques, such as optical microscopy and scanning electron microscopy, is required (e.g. Van Geet *et al.* 2001).

Non-destructive analysis

One of the strengths of X-ray CT is its entirely non-destructive nature, at least at the scale of the sample. This aspect renders the technique highly suitable for monitoring of active processes, such as water and solute movement (e.g. Kasteel *et al.* 2000; Perret *et al.* 2000) and deformation (e.g. Besuelle *et al.* 2000; Wong 2001). These experiments can be carried out at elevated pressures and temperatures, which is a major advantage over more conventional techniques, e.g. in studies of fracture characteristics at reservoir conditions. The non-destructiveness of the technique also allows analysis of valuable or unique specimens, such as fossils (e.g. Rowe *et al.* 2001) and meteorites (e.g. Gnos *et al.* 2002).

3D rendering

CT analysis can produce large numbers of contiguous parallel cross-sections, which allows 3D visualisation of selected features and quantification of 3D volumes. Examples of applications that exploit this aspect of X-ray CT include studies of soil macroporosity (e.g. Capowiez *et al.* 1998; Pierret *et al.* 2002) and rock textures (e.g. Denison & Carlson 1997).

This volume

The opening paper in the present collection, by **Carlson *et al.***, gives an extensive illustration of the possible applications of X-ray CT in igneous and metamorphic petrology, meteoritics and palaeontology. The paper, which is based on studies carried out at the High-resolution X-ray CT Facility of the University of Texas at Austin, demonstrates how CT analyses can contribute to wider investigations by providing information that cannot be obtained by other methods. In a second review, **Akin & Kovscek** discuss applications of CT in petroleum geology, covering measurements of porosity and multiphase fluid flow characteristics. Experimental design and image processing methods are also covered.

CT analyses of pore characteristics are the subject of the next four contributions. **Jones *et al.*** present the results of synchrotron CT studies of various porous materials, carried out at three different research facilities (Brookhaven, Argonne and Grenoble). They address the potential of high resolution (2–10 μm) synchrotron CT analysis for porosity characterization in unconsolidated sediments and sandstone samples, using Wood's metal (a low-melting Bi-Pb-Sn-Cd alloy) for contrast enhancement in one example. The study also illustrates the use of X-ray fluorescence tomography in environmental geochemistry studies. **Van Geet *et al.*** present the results of porosity measurements with microfocus CT, which are compared with results obtained by more traditional methods. The authors describe procedures for artefact reduction, which is necessary to allow quantitative analysis of grey values. They discuss the use of a linearization technique for monomineralic rocks, such as limestone. For heterogeneous materials, a dual energy approach is proposed. **Vandersteen *et al.*** examine different methods for the quantification of fracture apertures by microfocus CT, using phantom objects and optical microscopy for calibration and verification. Their results are of importance in investigations requiring quantitative characterization of planar voids, e.g. in soil research and reservoir studies. **Sellars *et al.*** describe studies of fractures that developed by applying triaxial stress to cubic quartzite blocks with tabular gaps. The fracture patterns revealed by 3D rendering of CT data help to verify the predictions made by numerical models that are currently used to assess fracture development around deep mining excavations. The authors also comment on limitations imposed by the presence of artefacts, which hinder the production of 3D images of fractures.

Vogel & Brown present a geostatistical assessment of variations in gamma ray attenuation in scans with different resolutions. Their study assesses heterogeneities in bulk density that occur in a dolomite formation at a nuclear waste disposal site. The authors provide an evaluation of the effect of resolution and scale on semivariogram parameters.

The next four papers focus on fluid flow in rocks. **Géraud *et al.*** examine the hydraulic properties of a rock with very low porosity by using capillary saturation experiments. Using a fluid with high attenuation values, they are able to document differences in microporosity between different constituents of a granite, which affect flow patterns within the test samples. **Hirono *et al.*** use X-ray CT for direct imaging of fluid flow along faults in heterogeneous deformed rocks. These laboratory experiments, using KI as a tracer, help to clarify the relationship between the texture and hydraulic properties of fault zones.

Rousset-Tournier ***et al.*** present a study of water migration during drying experiments in sandstones. Their findings show that drying behaviour is influenced by the method of saturation. **Ruiz de Argandoña** ***et al.*** describe the patterns of water uptake during the total immersion of a porous limestone, showing that CT helps to relate water movement to petrographical characteristics of the rock. Both of the last two studies address issues that are important in the field of cultural heritage conservation.

In a first of three studies of soil behaviour, **Anderson** ***et al.*** describe the determination of porosity and hydraulic conductivity in soils by X-ray CT measurements during solute breakthrough experiments. Differences between measured values and simulated breakthrough curves derived by a finite element method are explained by the existence of small-scale heterogeneities, which can be assessed by X-ray CT. **Rogasik** ***et al.*** use X-ray CT to study variations in structure, macroporosity and calculated bulk density for soils with different textures and under different management systems. A quantitative study of compaction around earthworm burrows is also included. **Delerue** ***et al.*** present a novel quantitative method for 3D image analysis of soil macroporosity using CT images to obtain calculated hydraulic conductivity and permeability values. The method is based on the segmentation of the pore space into elementary objects and quantification of their characteristics, followed by the creation of a network model that allows conductivity calculations.

Two papers describe the results of compression tests using specially designed triaxial cells, both providing detailed information on the experimental set-up. **Karacan** ***et al.*** describe a triaxial cell that permits permeability measurements during deformation. Using X-ray CT to monitor deformation experiments with this cell, the authors evaluate changes in porosity, permeability and fluid flow under conditions of brittle and ductile failure. **Thomson & Wong** describe a system for performing triaxial tests under undrained conditions, which they use as a means for studying the deformation behaviour of unconsolidated sands. They discuss the observed void ratio redistributions and indicate directions for future research. **O'Neill** ***et al.*** present a qualitative assessment of a test that simulates the evolution of backfill material of an opencast mine. They use CT to unravel the nature of particulate interactions undergoing creep settlement.

The last group of papers illustrates the applications of X-ray CT in a number of geological disciplines. **Flisch & Becker** investigate sedimentary and deformation structures in lake deposits by CT scanning of sediment cores. They illustrate the potential of CT for core analysis and the study of unconsolidated sediments. The contribution by **Schreurs** ***et al.*** illustrates an application of X-ray CT in structural geology that involves the CT-monitoring of deformation experiments with sand-box models. These authors document changes in structure in three dimensions through time, which allows analysis of complex geological structures in contractional and extensional settings. A palaeontological study is presented by **Stock & Veis**, who perform micro-focus CT analyses of Jurassic echinoid fragments. Some of the features that they describe are interpreted as diagenetic modifications.

Future developments

One expected trend is the combined use of various CT instruments, whereby a material is scanned at different resolutions. For example, a rock core can be scanned at full size with a medical scanner at moderate resolution, followed by microfocus and synchrotron CT analysis of subsamples of different sizes. Optical microscopy and scanning electron microscopy will continue to be important sources of additional information.

A more widespread use can be expected for certain special procedures that have been developed for medical applications. One technique that has already been used in a number of geological studies is dual energy scanning (e.g. Kalendar *et al.* 1987), which allows quantification of density and effective atomic number. It involves the processing of scans that were recorded for energies at which the relative contributions of Compton scattering and photoelectric absorption are different. A promising technique is 'region of interest' scanning, providing high resolution CT images of a region in the interior of a sample. It requires high resolution acquisition for the region of interest, combined with a second scan of the same plane for the full width of the object, at low resolution; the second scan is used to provide information about the part of the object that is outside the field of view during acquisition for the high resolution scan (e.g. Gentle & Spyrou 1990).

The potential of a number of powerful techniques that are related to X-ray CT is still largely unexplored for geological materials. They mainly require a monochromatic or very intense X-ray beam, which means that they are mainly available at synchrotron installations. Examples are fluorescence X-ray tomography, recording element distributions down to trace level concentrations (e.g. Simionovici *et al.* 2001); phase contrast X-ray tomography, which allows visualisation of discontinuities by phase shifts of a coherent

X-ray beam, in materials with low attenuation coefficients (e.g. Cloetens *et al.* 1997, 1999), and diffraction X-ray tomography, which allows mapping of variations in mineralogical composition (e.g. Hall *et al.* 1998).

An integration of X-ray CT results with data obtained by other non-destructive techniques can be expected to become more common. Neutron tomography is a compatible technique, because neutrons interact with the nuclei of atoms, whereas X-ray CT is based on an interaction with electrons (e.g. Winkler *et al.* 2002). This results in large differences in element sensitivity whereby neutron tomography, in contrast to X-ray CT, is highly sensitive to elements such as hydrogen and carbon. A more widely used compatible technique is Nuclear Magnetic Resonance (NMR) analysis, which allows imaging of fluid flow in porous media and also provides information about pore size distributions (e.g. Watson & Chang 1997; Amin *et al.* 1998; Baraka-Lokmane *et al.* 2001). Its use for geological materials is limited by the rather low resolution and by the problems that can be caused by the presence of iron compounds.

Since medical CT scanners became widely available, CT results for geological materials have been successfully integrated with other analytical data in various geological disciplines. It is expected that in the near future, CT will be used more and more as a routine research tool. In future studies, CT data will be obtained for much greater numbers of samples, allowing a statistical evaluation of a large body of CT results.

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