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High-resolution X-ray computed tomography in geosciences: A review of the current technology and applications

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ABSTRACT

High-resolution X-ray Computed Tomography (HRXCT) or micro-CT (μCT) is a frequently used non-destructive 3D imaging and analysis technique for the investigation of internal structures of a large variety of objects, including geomaterials. Although the possibilities of X-ray micro-CT are becoming better appreciated in earth science research, the demands on this technique are also approaching certain physical limitations. As such, there remains a lot of research to be done in order to solve all the technical problems that occur when higher demands are put on the technique. In this paper, a review of the principle, the advantages and limitations of X-ray CT itself are presented, together with an overview of some current applications of micro-CT in geosciences. One of the main advantages of this technique is the fact that it is a non-destructive characterization technique which allows 4D monitoring of internal structural changes at resolutions down to a few hundred nanometres. Limitations of this technique are the operator dependency for the 3D image analysis from the reconstructed data, the discretization effects and possible imaging artefacts. Driven by the technological and computational progress, the technique is continuously growing as an analysis tool in geosciences and is becoming one of the standard techniques, as is shown by the large and still increasing number of publications in this research area. It is foreseen that this number will continue to rise, and micro-CT will become an indispensable technique in the field of geosciences.

Contents

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1. Introduction

1.1. History and principle of X-ray CT

Since the discovery of a new type of radiation by Wilhelm Röntgen, *X-rays* have been used extensively in various research fields. A pertinent feature of this radiation type is its capability to penetrate material in varying degrees. This is mathematically formulated by Beer's law, which expresses the transmitted intensity I of a monochromatic X-ray passing an object:

$$I = I_0 e^{-\int \mu(s) ds} \tag{1}$$

where I_0 is the incident beam intensity and $\mu(s)$ is the local linear attenuation coefficient along the raypath s. The energy-dependent linear attenuation coefficient μ is determined by four effects, i.e. photoelectric effect, incoherent (Compton) scattering, coherent (Rayleigh) scattering and pair production. The latter can only occur at energies above 1.022 MeV and is thus not relevant in most X-ray CT setups. More information on this topic can be found in (Attix, 1986; Knoll, 2000).

This property was soon used for medical (Frost, 1896; Miller, 1896) and non-medical (Brühl, 1896) applications. In geosciences, the internal structure of a great diversity of geological samples has been examined by radiographic imaging mainly in the last 50 years (Calvert and Veevers, 1962; Hamblin, 1962; Bouma, 1964; Howard, 1968; Baker and Friedman, 1969; Herm, 1973; Sturmer, 1973; Bjerreskov, 1978; Monna et al., 1997; Louis et al., 2007; Schmidt et al., 2007). Constant improvement of the equipment still makes it a very extensively used technique in a wide range of applications, of which the most known are medical radiography and security systems.

A major drawback of this technique is the loss of information in one dimension. Radiographs, which are sometimes called *projection* or *shadow* images, project a 3D object on a 2D detector plane, losing depth information. This can lead to misinterpretation of the images.

A new technique to overcome this disadvantage was developed in the 1970s called *Computerized transverse axial tomography* (Hounsfield, 1973; Ambrose, 1976; Ommaya et al., 1976) (abbreviated *CAT* or *CT*). By acquiring projection images from different directions, a 3D volume is reconstructed using dedicated computer algorithms. This 3D reconstruction technique was almost immediately used for medical applications, allowing visualisation of the human body and brain (Gawler et al., 1974; Ledley et al., 1974; Paxton and Ambrose, 1974). Applications in other research domains such as wood technology (Onoe et al., 1983; Taylor et al., 1984), palaeontology (Conroy and Vannier, 1987; Zollikofer et al., 1998), soil science (Petrovic et al., 1982; Crestana et al., 1985, 1986; Anderson et al., 1988; Braz et al., 2000), marine sciences (Boespflug et al., 1995) and geosciences in general (Vinegar and Wellington, 1987; Wellington and Vinegar, 1987; Coles et al., 1991), as well as industrial applications (Hopkins et al., 1981) followed shortly.

From Eq. (1), it can be understood that the integrated linear attenuation coefficient can be easily derived at each point of a radiograph:

$$\int \mu(s) ds = -\ln\left(\frac{I}{I_0}\right). \tag{2}$$

By application of a rotational movement of the sample relative to the X-ray source and detector system, a number of different angular *projection images* are made. By using appropriate reconstruction algorithms (Herman, 1980; Herman and Natterer, 1981; Kak and Slaney, 1988), the local value of μ can be calculated for each point inside the scanned volume. The value of μ depends on the material density ρ and the mass attenuation coefficient μ/ρ, which is a tabulated and energy-dependent value and is approximately proportional to Z^3 in the X-ray energy range typically used for CT, with Z as the atomic number (Attix, 1986; Knoll, 2000). Knowledge of this value thus does not allow a unique identification of the material or its density, unless one of them is known in advance.

It must be noted that this is only valid for monochromatic X-rays which follow a straight path. It will be demonstrated in following sections that these assumptions are not met, resulting in reconstruction artefacts.

X-ray CT has become more commonplace in the earth sciences for imaging geological samples at ambient conditions (Ketcham and Carlson, 2001; Rivers et al., 2004; Lesher et al., 2009). Medical CT and industrial CT systems, with typical spatial resolutions of 250 μm voxel size, are often used for their large core scanning capabilities (Baraka-Lokmane et al., 2009) and dual energy scanning possibilities for the chemical analysis of core samples (Purcell et al., 2009). When one is performing the study of core samples, the surface as well as the internal features, including bedding features, sedimentary structures, natural and coring-induced fractures, cement distribution, small-scale grain size variation and density variation can now be analysed (Coles et al., 1991; Orsi et al., 1994; Coles et al., 1998). Extensive research has included applications on the complex porosity and pore geometry of carbonate reservoirs (Purcell et al., 2009), rock-fluid analysis (PyrakNolte et al., 1997; Purcell et al., 2009; Wennberg et al., 2009), the performance of diverting agents in unconsolidated sandstones (Vinegar and Wellington, 1987; Wellington and Vinegar, 1987; Ribeiro et al., 2007a,b), the physical properties of permafrost layers (Calmels and Allard, 2008), gas hydrate dissociation (Denison et al., 1997; Okui et al., 2003), and many other topics in geosciences.

Although X-rays and gamma-rays are the most commonly used type of radiation in CT, the same principle can be applied to protons (Ito and Koyamaito, 1984; Takada et al., 1988), neutrons (Koeppe et al., 1981; Overley, 1983; Baechler et al., 2002; Lehmann and Wagner, 2010) and heavy particles (Crowe et al., 1975; Ohno et al., 2004; Shinoda et al., 2006) as radiation source. These techniques are beyond the scope of this paper, and are therefore not discussed further.

1.2. Towards micro-CT

Over the years, medical CT scanners have been drastically improved in terms of image quality, imaging speed and deposited radiation dose. Following technological advances, different generations of CT scanners have been conceived (Goldman, 2007), with recent developments towards dual-energy (Flohr et al., 2006; Primak et al., 2007; Graser et al., 2009) and energy selective CT (Barber et al., 2011). Temporal resolution has improved to less than 100 ms (Flohr et al., 2009). In contrast, spatial resolution remains limited to several hundreds of micrometres due to the dimension of the investigated object, i.e. a human patient.

A new research field emerged in high-resolution X-ray tomography, commonly called *micro-CT*. This method was first discussed in the 1980s, using X-ray tubes (Sato et al., 1981; Elliott and Dover, 1982, 1985), gamma-ray sources (Gilboy et al., 1982; Gilboy, 1984) and