Ore Geology Reviews 65 (2015) 821–839

Contents lists available at ScienceDirect

Ore Geology Reviews

journal homepage: www.elsevier.com/locate/oregeorev

Application of high resolution X-ray computed tomography to mineral deposit origin, evaluation, and processing

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ARTICLE INFO

Article history:
Received 10 May 2014
Received in revised form 25 September 2014
Accepted 29 September 2014
Available online 5 October 2014

Keywords:
X-ray computed tomography
Ores
Mineralogy
Gold
Platinum
Ore processing
Mineral inclusions
Fluid inclusions

ABSTRACT

High resolution X-ray computed tomography (CT) is the industrial equivalent of medical CAT scanning and provides a mechanism for non-destructive studies of the three-dimensional nature of geological materials. HRXCT produces two-dimensional images (slices) that reveal the interior of an object as if it had been sliced open along the image plane for viewing. A CT image is generated by differences in X-ray attenuation that arise from differences in density and composition within the object. By acquiring a contiguous set of slices, volumetric data for all or part of a sample can be obtained, allowing three-dimensional inspection and measurement of features of interest.

CT is particularly effective in the study of metallic ores that commonly contain minerals spanning the range of densities of natural materials. Available software can produce grain shape, size, and orientation data from the scanned volume, which can be particularly useful for oriented samples. CT is particularly useful for studies of gold and other precious metal-bearing minerals that typically have significant contrast even with common metallic mineral phases. CT precisely defines the in-situ location of mineral grains of interest within a sample, which then can be studied in conventional petrographic sections, and other forms of data collected, e.g. isotope or trace element geochemistry. Another area of application is fluid inclusions, which can be discerned even in opaque phases, and fluid and vapor volumes measured for sufficiently large occurrences.

We summarize CT principles and review available instrumentation, as well as scanning and data reduction protocols that provide unique three-dimensional information for diverse ore types and applications in mineral deposits geology. CT applications for economic geology and other fields will continue to expand as instruments continue to evolve and as scanning protocols and applications are extended for more precise quantification of three-dimensional relationships, particularly for fine-grained particles and small fluid inclusions in larger volumes and for separation of minerals with limited contrast.

1. Introduction

Following its development in the medical field for the imaging of soft tissue and bone, X-ray computed tomography (CT) was adapted to provide valuable three-dimensional information of opaque volumes for industrial applications. These developments, which required imagery of denser objects across a range of size classes and resolution requirements, have greatly enhanced the capabilities of this technology for geological investigations over the past two decades (e.g. Carlson et al., 2000; Cnudde and Boone, 2013; Ketcham and Carlson, 2001). CT uses X-rays to digitally cut a specimen to reveal its interior details via an image typically referred to as a slice. Each CT slice represents a certain thickness of the scanned object, and thus a CT slice image is composed of voxels (volume elements), in comparison with a typical digital image that is composed of pixels (picture elements).

The gray levels in a CT slice correspond to X-ray attenuation, which reflects the proportion of X-rays scattered or absorbed as they pass through each voxel. X-ray attenuation is primarily a function of X-ray energy and the density and atomic number of the material being imaged. A CT image is created by directing X-rays through the object from multiple orientations and measuring their resultant decrease in intensity. A specialized algorithm is then used to reconstruct the distribution of X-ray attenuation in a series of slice planes. By acquiring a stacked, contiguous series of CT images, data describing an entire volume can be obtained.

Because industrial CT systems image only non-living objects, they can be designed to take advantage of the fact that the items being studied do not move and are not harmed by X-rays. They employ the following optimizations: (1) Use of higher-energy X-rays, which are more effective at penetrating dense materials; (2) Use of smaller X-ray focal spots, providing increased resolution at a cost in X-ray output; (3) Use of finer, more densely packed X-ray detectors, which also

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http://dx.doi.org/10.1016/j.oregeorev.2014.09.034
0169-1368/

increases resolution at a cost in detection efficiency; (4) Use of longer exposure times, increasing the signal-to-noise ratio to compensate for the loss in signal from the diminished output and efficiency of the source and detectors.

All of these factors benefit the use of industrial CT systems to study dense volumes such as rocks, and because of the wide range of densities of ore minerals (commonly 4 to 20 g/cm^3), CT is particularly useful for the study of three-dimensional relationships in ore specimens. Ore minerals not only can be distinguished from a matrix of rock-forming minerals, but in many cases, differentiation of the metallic mineral species can be accomplished. Further, algorithms have been developed to produce quantitative information on grain size, shape, and textural relationships (e.g. Godel, 2013; Ketcham, 2005; Ketcham and Mote, 2004; Kyle et al., 2008). This article will review applications of CT techniques to contribute unique information for a variety of mineral deposit genesis and processing issues. This review will place emphasis on the instrumentation available and the scanning and data analysis protocols developed at the University of Texas at Austin High Resolution X-ray Computed Tomography Facility www.ctlab.geo.utexas.edu/. Many of the CT scans included in this review, as well as many others, are available on the facility website as three-dimensional reconstructions and animations, e.g. www.ctlab.geo.utexas.edu/geo/index.php — ore.

2. Essentials of computed tomography

Here we provide a brief overview of computed tomography, particularly as it relates to geology and economic geology investigations, updating the summary by Ketcham and Carlson (2001). Additional recent and useful reviews encompassing geological investigations include Baker et al. (2012) and Cnudde and Boone (2013) for microtomography and Fusseis et al. (2014) for synchrotron-based CT. A more in-depth treatment of CT principles is provided by Hsieh (2003).

2.1. Principles

2.1.1. Scanning configuration

The simplest common elements of X-ray radiography are an X-ray source, an object to be imaged through which the X-rays pass, and a series of detectors that measure the extent to which the X-ray signal has been attenuated by the object (Fig. 1). A single set of X-ray intensity measurements on all detectors for a given object position and scanner geometry is termed a view or projection. The principal objective of computed tomography is to acquire multiple views or projections of an object over a range of angular orientations. By this means, additional dimensional data are obtained in comparison to conventional X-radiography, in which there is only one view. However, radiography has proved to be an effective screening technique to identify volumes of particular interest for dedicated CT scanning, e.g. to determine detailed relationships among gold grains and other metallic minerals (Kyle and Ketcham, 2003; Kyle et al., 2008).

Most modern laboratory CT systems employ a cone-beam configuration, in which the X-ray beam originates from a small focal spot and illuminates a larger planar detector, with the specimen being placed on a rotational stage between the two (Fig. 1b). Detectors are typically 1024 or 2048 pixels on a side, and sometimes larger, and each row of pixels can correspond to a slice in the resulting volume, except at the very bottom and top. Because this configuration permits data for thousands of slices at a time to be gathered, it is very efficient, and a relatively large amount of time can be spent acquiring each projection to reduce noise. High resolution is obtained by geometric magnification from the source to detector, and generally the object is placed close to the source to maximize this effect. Resolution on these systems is generally limited by the X-ray source focal spot size. Cone-beam scans can have the issue that planar, near-horizontal interfaces near the top and bottom of the cone (i.e. at maximum vertical angle from the center plane) may not be well-resolved due to geometrical ambiguity, but this usually does not have a significant effect in scans of rocks.

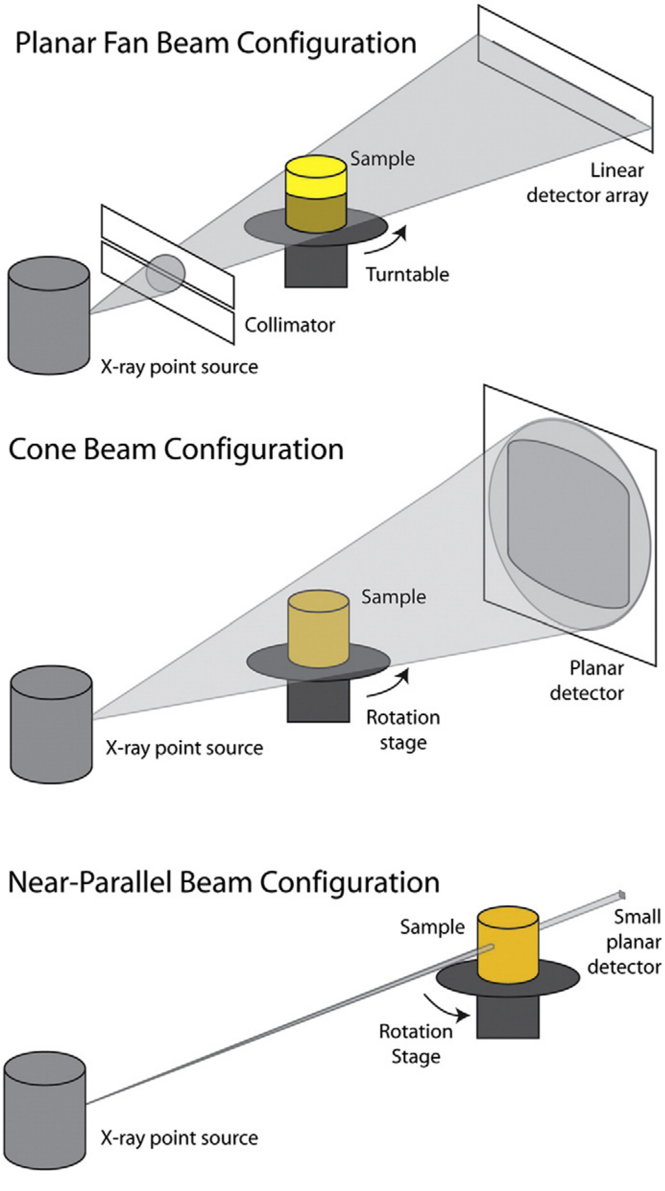

Fig. 1. Schematic illustration of the University of Texas at Austin high resolution X-ray computed tomography facility.

A variation on volume scanning arises from parallel-beam or near-parallel beam imaging (Fig. 1c), as is possible at synchrotron X-ray sources or using a synchrotron-inspired configuration pioneered by Xradia, Inc. (Sunnyvale, California). In these configurations, the planar detector is small (cm to mm or less) but retains high pixel density, essentially making the detector the resolution-controlling factor. This configuration can provide sharper imagery, particularly if it leads to a certain amount of X-ray refraction along coherent interfaces, leading to "phase contrast" imaging that can highlight the borders between adjacent objects of identical attenuation (Cloetens et al., 1996). Near-parallel-beam imaging is also superior at producing "zoomed" scans of sub-volumes within larger objects, and thus can be good for closer examination of features of interest revealed by coarser-resolution scans.

Another variant on cone-beam imaging is helical scanning, which features vertical translation during rotation. This technique has long been under development (e.g., Zhou and Pan, 2004), but is only now becoming widely available with increases in computer memory and processing speeds. Helical scanning can be useful because it resolves