Title

Application of neutron computed tomography in the geosciences

Permalink

https://escholarship.org/uc/item/7jt52917

Authors

Wilding, M.
Shields, K.
Lesher, C. E.

Publication Date

2005-02-01

Available online at www.sciencedirect.com

SCIENCE DIRECT®

ELSEVIER

Nuclear Instruments and Methods in Physics Research A 542 (2005) 290–295

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

www.elsevier.com/locate/nima

Applications of neutron computed tomography in the geosciences

Martin Wilding[a,b,*], Charles E. Lesher[b], Kevin Shields[a]

[a]*McClellan Nuclear Radiation Center, University of California at Davis, 5335 Price Avenue, McClellan, CA 95652, USA*
[b]*Department of Geology, University of California at Davis, One Shields Avenue, Davis, CA 95616, USA*

Abstract

A research program that applies neutron computed tomography (CT) to geological problems has been developed at the McClellan Nuclear Radiation Center (UCD-MNRC) owned and operated by the University of California, Davis (UCD-MNRC). The high penetration of neutrons, their sensitivity to light elements, and their special sensitivity to hydrogen (in water or organic materials) make them an ideal tool for non-destructive examination of complex materials of geological interest. There are four research foci at UCD-MNRC related to geological material characterization: (1) quantification of textures of deformed crystalline rocks; (2) properties of multi-phase flow in porous rocks and sediments; (3) distribution of organic and inorganic carbon in silicate and carbonate rocks; and (4) CO_2 sequestration through fluid-rock reaction. Examples of these research activities will be presented. A new CT infrastructure is being installed at the UCD-MNRC to meet the needs of these four research programs. Among the upgrades are the development of a "micro" CT facility and standardized CT acquisition, compatible with X-ray CT. The latter will allow direct indexing between X-ray and neutron radiograph projections and subsequent CT reconstructions.

PACS: 87.59.F; 07.85.Y; 87.59.B

Keywords: Neutron computerized tomography; Neutron radiogrpahy; Fluid flow; Microbial structures

---

1. Introduction

The McClellan Nuclear Radiation Center (UCD-MNRC) is based on a 2 MW TRIGA® research reactor, originally built by the US Air Force for neutron radiography of aircraft parts. The facility is unique among US research reactors in that it was purpose built for neutron radiography and as such has beam tubes and configurations optimized for this technique. The MNRC has four neutron radiography beam tubes tangential to the graphite reflector surrounding the TRIGA® core. The beam tubes terminate in large

---

*Corresponding author. Department of Geology, University of California at Davis, One Shields Avenue, Davis, CA 95616, USA. Tel.: +1 530 742 5041; fax: +1 530 752 0951.
E-mail address: mcwilding@ucdavis.edu (M. Wilding).

0168-9002/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2005.01.151

radiography bays, capable of handling large aircraft components, and the neutron beams themselves are relatively large, with diameters of up to 30 cm while the L/D ratios vary from 150–270.

In February 2000, the University of California at Davis assumed operation of the MNRC, following the closure of the McClellan Air Force Base. Since then the University has begun to develop a multidisciplinary research program centered on the unique capabilities of the MNRC. Most of this research involves the use of neutron computed tomography (CT) in the analysis of complex materials and the most promising research has been in applications to the geosciences.

There are currently four research applications of neutron CT to the geosciences realized at MNRC. These are (1) the application of neutron CT to the textural analysis of deformed crystalline rocks, (2) the study of fluid flow through porous and deformed porous media, (3) the distribution of remnant organic materials in inorganic (carbonate) samples, and (4) the development of reactive flow fronts in carbonate rocks through interaction with CO_2-rich fluids.

In this presentation, we will give an overview of the results of each of these four applications to demonstrate the potential for applications of neutron CT to the geosciences. We will also discuss some of the future directions of the MNRC in terms of upgrades to the CT infrastructure and a facility goal of combining neutron and X-ray CT, providing a unique facility in the US for non-destructive analysis.

2. Neutron computed tomography at the McClellan Nuclear Radiation Center

Neutrons offer a unique opportunity to examine complex geological materials. Neutron CT is complementary to the equivalent X-ray technique. Neutrons have greater sensitivity to some elements, especially hydrogen and the advantage of Neutron CT is best seen when hydrogenous materials are considered. Such applications include examination for hydrogenous materials such as water, water-rich fluids and remnant organic material.

2.1. Neutron CT facilities at MNRC

The Neutron CT facilities at MNRC are contained within one of the four radiography bays. This bay has the highest flux (10^7 n/cm^2/s) and consequently a lower L/D (138). The tomography system comprises a positioning robot with a turntable mounted on it with a ^{6}Li-doped scintillation screen placed behind it. Visible light pulses are focused onto a Princeton instruments 1024 × 1024 CCD camera (30 μm pixel).

Typically, we use a series of 360 radiograph projections, collected at 0.5° intervals for the reconstruction. The radiographs are corrected for dark current and the flat field before reconstruction using the filter back-projection algorithm. We have used two different software packages, one developed at MNRC [1] and the other a software package used at Lawrence Livermore National Laboratory. The latter package can be used to correct for bad pixels and ring artifacts.

A recent acquisition at MNRC is the Volume Graphics, VG Studio® visualization package which we use for analysis of the reconstructed neutron CT volumes.

2.2. Neutron CT of coarsely crystalline igneous rocks

Coarsely crystalline igneous rocks frequently develop textures which reflect the migration of silicate liquids and deformation during crystallization. Understanding the three-dimensional nature of these textures has in the past relied on serial sectioning through rock samples. The thin sections are then photographed and the photographs then stacked to produce a three-dimensional volume. This practice is obviously very time- and labor-intensive. Neutron and X-ray CT [2,3] can be used to generate three-dimensional volumes of net attenuation and we have completed a series of feasibility studies looking at coarsely crystalline materials from Greenland. One of the most critical steps is to match the net attenuation to the mineralogy of the sample.

In the preliminary experiments, we selected a series of cores from the Greenland location and collected CT data. Then on one of the cores, we cut a conventional (petrographic) thin section and we were able to compare the net attenuation with the mineralogy effectively. The differences in attenuation between different mineral phases in these samples and grain boundaries match well, especially since the CT resolution is limited to 250 μm. The highest attenuating portions of these samples are the iron oxides which are the last portion of the rock to crystallize (Fig. 1). Aluminosilicate minerals (feldspars) have a tabular form; these are connected to form three-dimensional frameworks and are the first part of the crystal-liquid mush to crystallize. It is relatively straightforward to estimate the degree of compression and preferred orientation of the feldspar framework, using the methods developed by Philpotts [4].

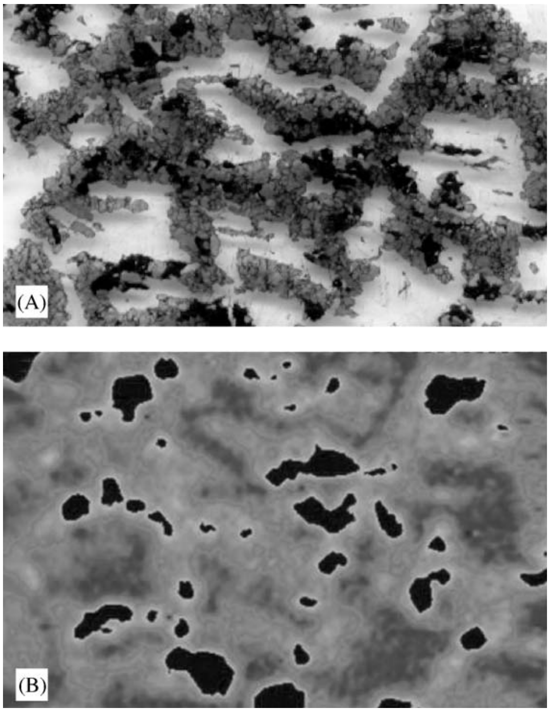

Fig. 1. Petrographic thin section of a coarsely crystalline core from the Skaergaard Intrusion, East Greenland. The thin section (A) was produced following collection of the neutron CT data set. The equivalent slices through the CT reconstruction (B) show a variation in grayscale which correlates with mineralogy of this sample.

This work has laid the groundwork for a more extensive study using Neutron CT to evaluate the changing texture in partly molten igneous rocks. This new project involves heating rock cores to temperatures close to the melting point and developing different molten fractions up to the point when the melt becomes free-draining. The Neutron CT data are used to evaluate the connectivity of the melt and to measure and evaluate the dihedral angles developed between the silicate liquid and the residual mineral phases.

2.3. Neutron CT studies of fluid flow in porous and deformed porous media

As is well known, neutrons are particularly sensitive to the presence of hydrogen. Neutron CT is therefore extremely applicable to hydrological problems such as the study of fluid flow in porous media. One such research direction has been the study of water flow in fractured ignimbrites (volcanic ash deposits), especially those from the Bandelier Tuff formation in New Mexico.

The Bandelier Tuff is important from a hydrological perspective because it forms the bedrock for the Los Alamos National Laboratory in the US. A thorough understanding of the movement of ground water through this formation is therefore important if the environmental impact of radioactive nuclide contamination is to be effectively addressed. One complication is the role of fractures and deformation bands in the Bandelier Tuff; these regions may be filled with clay-sized particles which act as an impediment to fluid flow, while under certain circumstances they may act as fluid pathways [5].

To illustrate this ongoing work, we show in Fig. 2 the results from a CT experiment on a fractured Bandelier Tuff sample. This sample has a deformation band approximately 1 cm wide comprising fine (clay-sized) material resulting from the mechanical abrasion during the deformation event. Approximately 10 ml of water was added to the top surface of this core before the CT data were collected, and the water was selected from an outfall pipe within the Los Alamos site to ensure

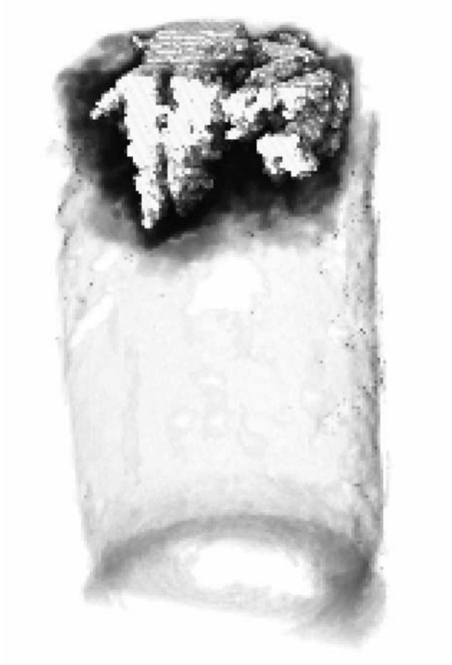

Fig. 2. Rendering of Neutron Computed Tomography data set for fractured ignimbrite core with added water. The segmented regions are shown corresponding to different water contents, the bright region showing the highest concentration of water. This volume has been clipped to show the channeling of the water along the deformation band.

that there would be no chemical reaction between the water and ignimbrite. Even though the pore size in these volcanic sediments is substantially less than the 250 μm voxel size, the presence of water can be easily detected.

2.4. Neutron CT studies of microbial structures in carbonates

Partial volume effects are also important in studying microbial samples in carbonate materials. The earliest traces of life on Earth are seen as organic rich remnants in different rock types including carbonates. Microbial communities formed intricate three-dimensional structures within carbonate mud and these textures reflect variously water temperature, salinity and nutrient content. The study of these remnants of ancient communities has direct bearing on the search for life in extreme environments on this planet and in addition has applications for the search for life on other planets. Such studies are frequently referred to as ‘‘astrobiology’’.

As would be expected, samples containing microbial traces from rocks in excess of 600 million years old are rare and valuable. Therefore, non-destructive techniques such as neutron and X-ray tomography are useful in their study. Although X-ray studies have inherently better resolution, neutron CT can be used to determine the three-dimensional structures of organic materials in inorganic matrices.

2.5. Neutron CT studies of CO_2 reaction fronts in carbonates

One possible solution to the current high atmospheric CO_2 levels is to trap CO_2 as a fluid in depleted petroleum reservoirs. Although this sounds a simple proposition, the situation is complicated because of the complex dependence of the dissolution and re-precipitation of carbonate on the chemistry of the injected CO_2-rich fluids.

As part of an ongoing collaboration with the super-critical CO_2 division at LANL, we have collected a series of Neutron CT data sets on cores reacted with CO_2-rich brines to evaluate the evolution of texture with fluid composition. The samples consist of a series of carbonate cores which were reacted with CO_2-rich fluids at high pressure and temperature. Neutron CT data sets were collected before the first flooding of the core and after two subsequent reactions. Although the instrument resolution is still only at 250 μm, the cores are not completely homogeneous and have a variation in gray level which corresponds to variation in bulk porosity when compared with conventional thin sections of the same starting material. Special attenuation was made ensure that the cores before and after flooding were aligned in the same way so that it was possible to make a direct comparison between corresponding slices in the Neutron CT data set.

The progression of the reaction front itself is seen dramatically as a ‘‘wormhole’’ in the carbonate cores [6,7]. In Fig. 3, the hole can be seen as

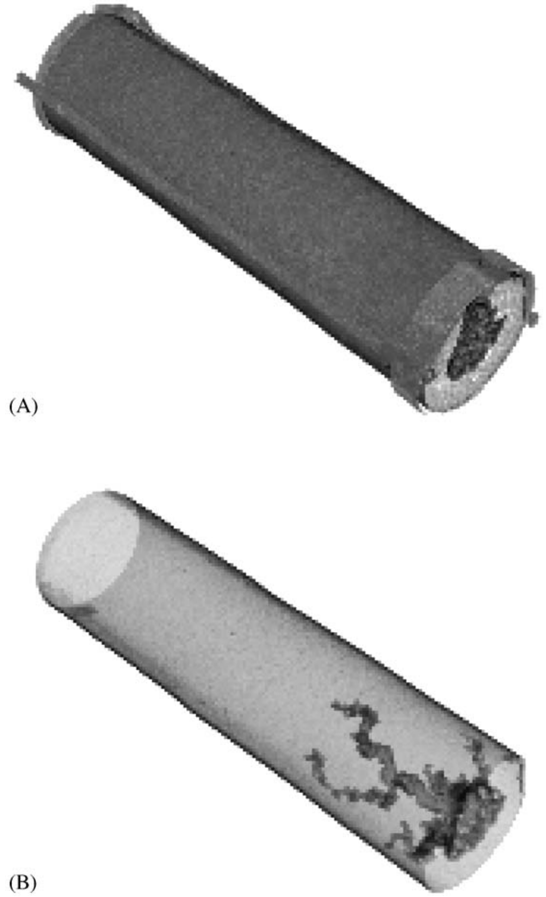

Fig. 3. Neutron computed tomography data set for reacted limestone core. The top figure (A) shows the entire core, while a segmented view (B) illustrates the dissolution of the carbonate by the CO_2-rich fluid.

an edge in the core, marking the point of injection of the fluid and marking the progression of the injected fluid through the core by dissolution.

Slices through the reconstruction before and after flooding can be compared, as shown in Fig. 4, to evaluate the development of texture as the reaction progressed. In Fig. 4A, a slice through the volume is shown with the variation in grayscale corresponding to the variation porosity of a limestone sample. In Fig. 4B, the same slice is shown following reaction with the CO_2-rich fluid.

The two slices through the CT volume suggest that the reaction pathway does indeed follow an existing, coarse porosity, but that there is a general coarsening of the texture, that is a constant re-precipitation of carbonate during the flooding of the sample with the reactive fluid.

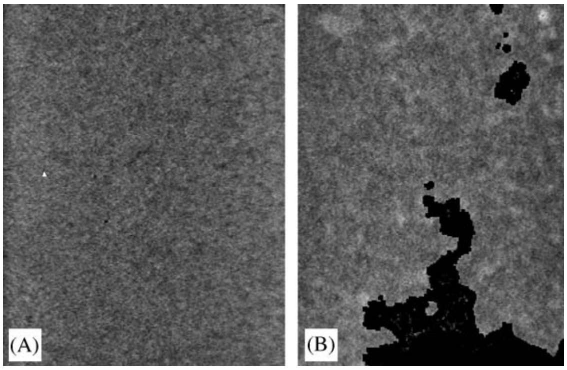

Fig. 4. Slices through the CT reconstructions of carbonate (limestone) core before (A) and after (B) flooding with CO_2-rich brine.

3. Instrumentation development at the McClellan Nuclear Radiation Center

The McClellan Nuclear Radiation Center is a joint recipient of an Innovation in Nuclear Infrastructure and Education (INIE) award from the US Department of Energy. Part of this award is dedicated to upgrade and development of the neutron CT facilities at MNRC. The ultimate goal is to develop a system that is compatible with the X-ray CT facilities at the Lawrence Livermore National Laboratory so that complementary neutron and X-ray data can be collected and reconstructed using similar instrumentation and image acquisition and reconstruction software.

To complete this task, the same rotational and translational stages have been acquired and are being installed together with the same motor controllers used at LLNL. This will enable full compatibility with the LLNL systems.

As a further developmental goal, we aim to develop instrumentation for combined neutron and X-ray tomography. This requires that the radiograph images during neutron and X-ray acquisition correspond. This means that ideally, the sample should not be moved from the rotational stage while data are collected using neutrons and X-rays and so an instrument is being developed where the sample stages, scintillation screen and detectors are fixed in one of the MNRC radiography bays and an X-ray source will be moved into place once the neutron beam shutter is secured. Again, this apparently simple modification to the MNRC infrastructure masks the complexity in reconstruction; different reconstruction geometries will have to be used and direct correlation between the voxels in the two types of CT reconstruction will not be a trivial problem. Extensive testing and development will therefore be the top research priority for this facility development before application to geological or other complex samples.

4. Summary

Following the acquisition of the MNRC by the University of California at Davis, a broad research program has been undertaken utilizing the unique radiography facilities. Neutron computed tomography (CT) has proved to be the most popular technique for evaluating the three-dimensional structure of complex materials and most research thus far has been directed at the study of geological samples. One of the most striking advantages of the CT technique is that the laborious and destructive serial thin-sectioning of geological samples can be completely avoided. The demands on the existing system are great however and part of the long-term facility development is to improve instrumentation in terms of both resolution and by offering combined neutron and X-ray CT.

In addition to the programs outlined, there is an opportunity for synergistic collaboration on the UCD campus. The Institute for Data Analysis and Visualization is a research unit at UC Davis dedicated to the visualization of multi-dimensional data sets (http://graphics.cs.ucdavis.edu/). This collaboration provides an opportunity to refine the neutron CT technique and applications at all levels. For example, problems inherent with neutron CT such as scattering from hydrogenous materials are addressed by modelling the scatter from objects of known geometry and development of appropriate corrections for radiographs. A similar approach can be applied to CT reconstructions in which known geometry surfaces or objects are present; these are again modelled and the radiograph corrected iteratively to optimize the CT reconstruction. Finally, interpretations of complex data can be achieved by fitting surfaces of know geometry or patterns to quantify the complex textures found in many geological samples.

Acknowledgments

Funds for this work have been provided by the US Department of Energy (DOE), Innovations in Nuclear Infrastructure and Education (INIE) grant to the Western Nuclear Science Alliance (WNSA).

References

[1] M.R. Gibbons, W.J. Richards, K.E. Shields, Nucl. Instr. and Meth. A 424 (1) (1991) 53.

[2] R.A. Ketcham, W.D. Carlson, Comp. Geosci. 27 (2001) 381.

[3] R. Marschallinger, Comp. Geosci. 24 (1998) 875.

[4] A.R. Philpotts, J. Shi, C. Brustman, Nature 395 (1998) 343.

[5] J.E. Wilson, L.B. Goodwin, C.J. Lewis, Geology 31 (10) (2003) 837.

[6] J. Chadam, P. Ortoleva, Y. Qin, R. Stamicar, Eur. J. Appl. Math. 12 (2001) 557.

[7] F. Renard, J. Gratier, P. Brosse, B. Brazin, Geophys. Res. Lett. 25 (3) (1998) 385.