Computers & Geosciences 73 (2014) 61–70

Contents lists available at ScienceDirect

Computers & Geosciences

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

3D-modeling of deformed halite hopper crystals by Object Based Image Analysis

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ARTICLE INFO

Article history:
Received 27 April 2014
Received in revised form
19 August 2014
Accepted 20 August 2014
Available online 28 August 2014

Keywords:
OBIA
SVM
3D modeling
Halite
Hopper crystals
Accuracy assessment

ABSTRACT

Object Based Image Analysis (OBIA) is an established method for analyzing multiscale and multi-dimensional imagery in a range of disciplines. In the present study this method was used for the 3D reconstruction of halite hopper crystals in a mudrock sample, based on Computed Tomography data. To quantitatively assess the reliability of OBIA results, they were benchmarked against a corresponding "gold standard", a reference 3D model of the halite crystals that was derived by manual expert digitization of the CT images. For accuracy assessment, classical per-scene statistics were extended to per-object statistics. The strength of OBIA was to recognize all objects similar to halite hopper crystals and in particular to eliminate cracks. Using a support vector machine (SVM) classifier on top of OBIA, unsuitable objects like halite crystal clusters, polyhalite-coated crystals and spherical halite crystals were effectively dismissed, but simultaneously the number of well-shaped halites was reduced.

1. Introduction

The non-destructive 3D-reconstruction of geological objects from X-ray computed tomography (CT) is of major importance to geosciences (Mees et al., 2003). Besides impressive applications in paleontology and the detection of other peculiar well-preserved structures, CT-derived 3D models are superior for reconstructing the fabric of deformed rocks. In the current context the spectral and geometrical properties of halite hopper crystals, as inferred from CT, were used to automatically identify suitable crystals for a later strain analysis.

Deformed halite cubes in lithified sediment occur worldwide (e.g. Haidinger, 1847; Görgey, 1912; Haude, 1970; Gornitz and Schreiber, 1981; Benison and Goldstein, 2000; Kendall, 2000). Halite is a cubic mineral that crystallizes as cubes, as far as crystal growth is not inhibited. In non-consolidated sediment, e.g. mud, halite crystallizes as euhedral cubes with reduced sides in a hoppered shape, as observed in the Dead Sea (Gornitz and Schreiber, 1981). Similar halite hopper crystals occur in Alpine rock salt deposits. Their shapes comprise tetragonal bodies, rhombohedrons, parallelepipeds or mixtures of these (Görgey, 1912). Halite deforms under low stress conditions (e.g. Urai et al., 2008) and it can be plausibly assumed that the Alpine halite hopper crystals were deformed by plastic creep. As such, by reconstructing the shape of halite crystals the form and orientation of the average strain ellipsoid can be deduced.

In previous work (Leitner et al., 2013) we used the shape of halite hopper crystals embedded in mudrock for deformation analysis. A sample comprising mudrock with halite hopper crystals was subject to CT scanning, yielding a stack of gray level images. Although the crystals in the CT images could be readily identified by the eye, perturbing noise prevented the use of standard pixel-based image processing for the extraction of crystal shapes. In the above, first approach the contours of the halite hopper crystals were traced manually on each image. From this image stack, a 3D model of the halite hopper crystals was compiled which then served for strain analysis.

The present study is based on the same CT scan, but this time we used Object Based Image Analysis (OBIA) for the automatic extraction and analysis of halite crystals. OBIA is a widespread and matured method to process remotely sensed images and multi-dimensional (3D+t) life science image data (Blaschke et al., 2012), with geological applications emerging in the recent years (Marschallinger and Hofmann, 2010, Marschallinger et al., 2011, Fadel et al., in press). While manual tracing is time consuming, error-prone and hard to reproduce, an OBIA-based 3D-reconstruction is controlled by transparent and reproducible rule-sets. The CT images were first automatically classified according to halite crystal features, followed by a 3D reconstruction of halite crystals. An OBIA rule set was developed that can be re-applied to similar data

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http://dx.doi.org/10.1016/j.cageo.2014.08.010
0098-3004/

(see Appendix A). The paper in hand discusses the advantages and arising problems of OBIA for the automated reconstruction of halite crystals embedded in mudrock.

2. Materials and methods

2.1. Halite hopper crystals and X-ray computed tomography

Halite [NaCl] hopper crystals in a mudrock matrix are abundant in Alpine rock salt deposits. Mudrock with halite cubes is traditionally referred to as "Tonwürfelsalz" (also: "Kropfsalz") in the Alpine salt mining literature. The halite crystals appear deformed to the naked eye, in representative samples, halite cubes range from 2–4 mm to 10–30 mm in size (Fig. 1a and b). The halite hopper crystals do not touch and show concave crystal surfaces with pronounced edges (hopper shape). The outer shapes of the crystals are cuboids, rhombohedrons or rhombic prisms. The sample of mudrock with halite hopper crystals subject to CT was taken from the Altaussee mine (ALT-4D; ca. 160 × 160 × 40 mm^3; Fig. 1c).

Computed tomography is a nondestructive analysis method that creates maps of X-ray attenuation. To first order, X-ray attenuation rises with increasing density and atomic number, and falls with increasing X-ray energy. Halite consists of Na- and Cl-ions, whereas mudrock mainly consists of Si, O, Al, Fe, Mg. Tomography works by projecting X-rays through the object being analyzed along many paths from many orientations, and using a reconstruction algorithm to transform the raw data into a series of cross-sectional images referred to as slices (Ketcham and Carlson, 2001). Computed tomography (CT) slices correspond to a certain thickness of material defined by the imaging conditions. Stacking CT slices, a volumetric data set is created the elements of which are referred to as "voxels" (volume elements) rather than pixels (picture elements).

Data for this study were produced with an Xradia MicroXCT scanner at the University of Texas High-Resolution X-ray CT (HRXCT) Facility at Austin. The use of a field of reconstruction of 160 × 160 mm^2, an inter-slice spacing of 0.25 mm and a radiometric resolution of 16 bit per pixel yielded an image stack of 166 TIFF image slices with a size of 1024 × 1024 pixels each. Accordingly, the metric resolution was 0.156 mm × 0.156 mm × 0.25 mm = 0.006084 mm^3 per voxel.

2.2. Object Based Image Analysis (OBIA) and software

Instead of single pixels, OBIA uses spatially contiguous image objects as the building blocks for image analysis. Typically, an OBIA workflow starts with a straightforward image segmentation that is gradually improved using dedicated image processing methods controlled by domain expert knowledge. As such, OBIA is an iterative process of (re-) segmentation and (re-) classification that has proven advantageous over classical pixel-based image analysis approaches (Blaschke, 2010; Blaschke et al., 2014). In contrast to pixel-based methods, object-based methods enable utilization of combined shape and radiometric statistics of each object. Additionally, topological relationships among the objects like neighborhoods, distances and spatial connections can be used to classify and analyze objects. From a geosciences perspective, the scope of OBIA has been extended from 2D remote sensing data to macro- and micro-image analysis (Marschallinger and Hofmann, 2010; Hofmann et al., 2013), 3D object reconstruction (Schönmayer et al., 2006; Marschallinger et al. 2011; Heidrich et al., 2013) and analysis of 3D laser scanner data of the earth surface (Tiede et al., 2006). Most of the above examples are based on the so-called Definiens Cognition Network Technology (Athelogou et al., 2007; Haenschel et al., 2008) which uses the Cognition Network Language (CNL) for the development of rule-sets and automated image analysis. In the case present a dedicated rule set for the 3D-reconstruction of halite hopper crystals was developed using the software eCognition Developer 8.9™ form Trimble Germany GmbH (http://www.ecognition.com; Trimble, 2013a, b).

3. Results

3.1. Gold standard

With its roots in finance, the term "gold standard" defines a procedure to provide the most reliable results; new methods in a specific field can be benchmarked to the gold standard. Currently gold standards are mainly used in medicine and medical image segmentation (Timmermans and Berg, 2003; Sweeney et al., 2013): as an example from medical image analysis, a radiologist with long-standing experience in a given field manually segments radiological image data. In the present context, our gold standard is the 3D model of halite crystals that was set up by an expert who manually traced the shapes of halite crystals from the CT images for later strain analysis.

On a CT image halite hopper crystals can be readily identified due to their low gray values as compared to the surrounding mudrock (Fig. 2). Crystal shapes are typically angular, in most cases crystals are isolated individuals, on occasion they form aggregates. Cracks are clearly visible when they form traceable dark lines on the image. However, the rock is full of cracks and the detectability on a CT image strongly depends on their width and

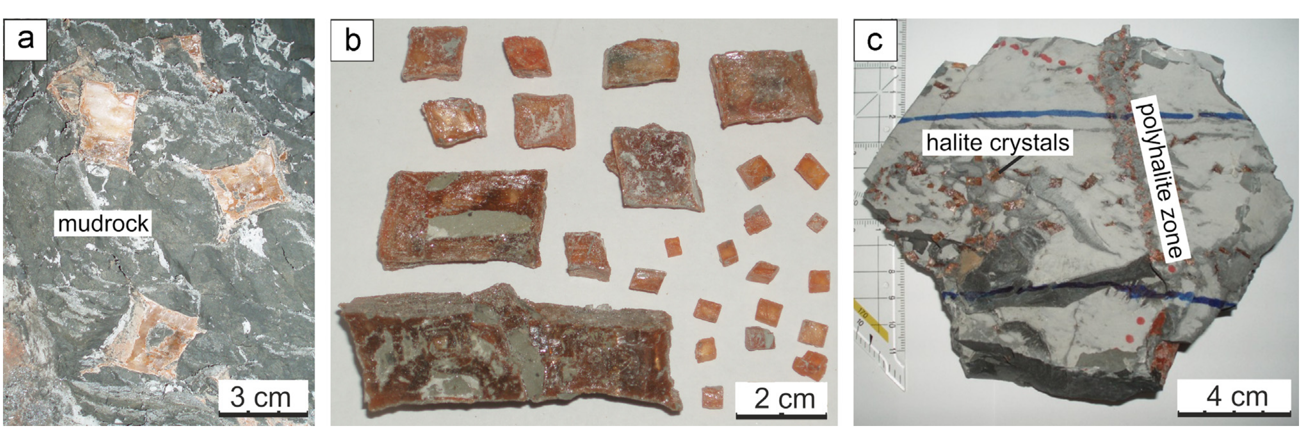

Fig. 1. (a) In-situ halite hopper crystals, size 30–40 mm. (b) Variously sized deformed halite hopper crystals. (c) Sample ALT-4D with small halite hopper crystals (4–7 mm). Colored lines for in-situ orientation.