Gamma Computed Tomography Performance for Petrophysical Characterization of Sandstone Rocks

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ABSTRACT

The gamma ray tomography techniques for industrial processes evaluation have been pointed out as the most promising in order to visualize the structure and the distribution of solids, liquids and gases inside multiphase systems, such as industrial columns or pipes, without interrupting the operation in pharmaceutical, biochemical, petrochemical and chemical industries. The reservoir rocks of fluids have, also, multiphase mixtures in their interior, since the fluids stored in the pore spaces within the reservoir rocks could be gas, oil, and water. However, no studies related to gamma tomography for analysis of oil reservoir rocks have been found in the literature. One type of rock of economic interest is the tar sand rock which has a great potential to act as reservoirs of oil, thus the knowledge of its petro-physical properties related to the filling of fluids in their pores; its structural properties, its internal geometry can contribute significantly to the exploration and recovery of the hydrocarbons of the rocks reservoirs, providing subsidies to the oil engineers in the recovery of hydrocarbons (oil) in their interior, having a significant economic relevance. In this work, the tar sand rock was characterized using the 3th generation gamma-ray industrial process tomography technique developed at IPEN /CNEN-SP. The internal arrangement, distribution of the pores, mineral composition, the fluid and mineral densities of the analysed rocks were evaluated. A high spatial resolution was obtained in the reconstructed image.

Keywords Industrial tomography, sandstone rocks, porosity, tar sands.

Industrial Application General.

1 INTRODUCTION

The gamma ray industrial process tomography techniques for industrial processes evaluation has been indicated as the most promising in order to visualize the structure and the distribution of solids, liquids and gases inside multiphase systems such as industrial columns or pipe, capable to obtain measurements in real conditions without interrupting the operation. (Johansen et al 2010, Falahi et al 2016, Mesquite *et al* 2016). Thus, a great interest in the development and applications of gamma-ray industrial process tomography systems (IPT) for the study of multiphase systems in pharmaceuticals, biochemical, petrochemical and chemical industries is observed in the literature (Chen et al 2001, Chen e*t al* 1998, Schubert, A. *et al* 2011, Loane *et al* 2016]. The reservoir rocks of fluids also have multiphase mixtures in their interior, since the fluids stored in the pore spaces within the reservoir rocks could be gas, oil, and water. However, no studies related to gamma tomography for characterization petrophysical of reservoir rocks have been found in the literature. A rock capable of producing oil, gas, or water is called reservoir rock. A reservoir rock should be sufficient porosity and permeability to allow oil and gas to accumulate and be produced in commercial magnitudes (Hu et al 2017, Wisconsin 2018). It is well-known the reservoir rock is constituted of a basis of minerals and void spaces, also, called pores. Oil, gas, or/and water can come into and fill in the pores if these are interconnected. Usually, interconnected pores are interlaced within the mineral framework.

One type of the rock of economic interest is the sandstone rock due to its potential to act as reservoirs of fluids (water and hydrocarbons). Sandstones can be defined as sedimentary rocks composed of fragments of sand minerals. Sandstones are mixtures of mineral grains and fragments from the erosion of various types of rocks. Therefore, theoretically, the total number of minerals should be known, nevertheless, this does not occur because, naturally, the processes that determine the mineralogical composition of the sandstones are quite complex, not being defined by the pure and simple mixing of minerals provided by different types of rocks that make up the source area (Ming *et al* 2014, Sugio 1980). The grains that form the sandstones are generally of the quartz (SiO_2) mineral, but may be of any other mineral (mainly feldspar) or lithic (rock) fragment, once they have the dimensions of the grains of sand. For the petroleum area, the sandstones act as excellent reservoirs of hydrocarbons, since they have specific characteristics, such as: high porosity and permeability. There are a large number of studies carried out in the Paraná Basin, Brazil, related to geological factors such as stratigraphy, structural framework, temporal aspects, etc., which aid in the understanding of hydrocarbons generation and migration processes. In this region, sandstone composed of siliciclastic grains impregnated in the pores by heavy oil (bitumen), also called of tar sand or oil sand, are found. On average, tar sand contains 10-15% petroleum, the remainder being composed of the mineral matrix (Osern, 2003; Cabral, 2006).

The outcrops of tar sands (or oil sands) of the Pirambóia formation in the State of São Paulo, Brazil, are one of the most important oil occurrences in the Paraná Basin, since the volume of these outcrops exceeds the volume of small accumulations discovered in subsurface (Cabral, 2006). There are approximately 25 occurrences of tar sand in the cities of Anhembi, Bofete, Guareí and Angatuba. In this formation it is composed of white, grey, yellowish and reddish sandstones, with medium and large cross-stratifications and plane-parallel laminations. The tar sands have medium granulometry, with sub-grained and sub-angular grains, poorly selected (Cabral, 2006).

In spite of the large number of studies found in the literature on tar sand rocks studies for exploration and exploration of their reservoirs, showing the large hydrocarbon reserves in Brazil, the recovery of these reserves has been very low. Geophysics allied to geology has been used as a tool to characterize the rocks that store water and hydrocarbons (Hu *et al* 2017, Wisconsin 2018). However, in some cases, the information they provide is not sufficient for an efficient recovery and extraction of hydrocarbons from rocks.

Currently, the characterization of reservoir rocks involves several analysis, such as optical and/or electron microscopy, porosity and permeability measurement through nitrogen gas injection, etc. (Melrose, 1988). These analysis, although consolidated, are very time-consuming, mainly for the preparation of samples taken from the rock. Also, X-ray microtomography (MRX), through the acquisition and processing of three-dimensional images in the pore scale of the sample, allows the creation of a three-dimensional digital model of the pores and mineral associations for the study of lithologic facies and their microstructures (Poszytek *et al* 2016; Klobes *et al* 1997). However, for this technique the analysis of oil reservoir rocks needs to be fragmented in small samples. In this scenario, the application of gamma ray industrial tomography for multiphase analysis is more suitable since it allows carrying out the tomography measurements in rock sample of large and different dimensions.
In this work, tar *sand* rock from the Paraná Basin was studied and its morphology and porosity characterized. The purpose is to increase the knowledge of the internal structure of these rocks. For the development of this work was used the 3rd generation gamma ray industrial tomography (Mesquita *et al* 2016, 2012) developed at the IPEN / CNEN-SP, which is a non-destructive technique, that allows measuring rocks of different dimensions and formats. Nowadays, there is a great interest in improving the knowledge of the morphology (internal rearrangement mineral composition, densities, direction and interconnectivity and dimension of the pores) inner the rock.

2 METHODLOGY

Tar sand rock sample was collected in outcrop of the Bitumen Farm, located in the Anhembi city, São Paulo State, Brazil, in the eastern region of the Paraná Basin. Formerly, this farm was the prospection area of the tar sands for oil recovery. The Figure 1 shows the picture of the collected sample for its characterization.

The tomography measurements were carried out using a third generation computed tomography developed at IPEN, as shown in the Figure 2. This system comprises four NaI(Tl) detectors of 25 x 50 mm^2 (diameter, thickness) shielded with lead containing a septa of 2 x 5 x 50 mm^3 (width, height, depth). The detectors were placed on a gantry in fan-beam geometry in opposite to the gamma ray source. The detectors move 35 times in a step angle of 0.165 degree, emulating 140 detectors per projection (35 steps x 4 detectors). The counting time for sampling was 5 seconds. Thereafter, the support table containing the gantry and the ^{192}Ir gamma source (Figure 2) rotates one degrees forward, and this process go on up to completing 360 degrees, totalizing 360 projections. For a total of 50400 samples (140 'virtual detectors' x 360 projections) the system takes 63,000 seconds or 17.5 hours to obtain each tomographic image. The ^{192}Ir radioactive source with an activity of 7.4 GBq (200 mCi) was placed into a radioactive shield-case with an aperture angle of 36 degrees (Figure 2). This system was previously described by Mesquita et al (2016, 2012).

Figure 1: Picture of the tar sand rock sample of approximately 25 x 25 cm.

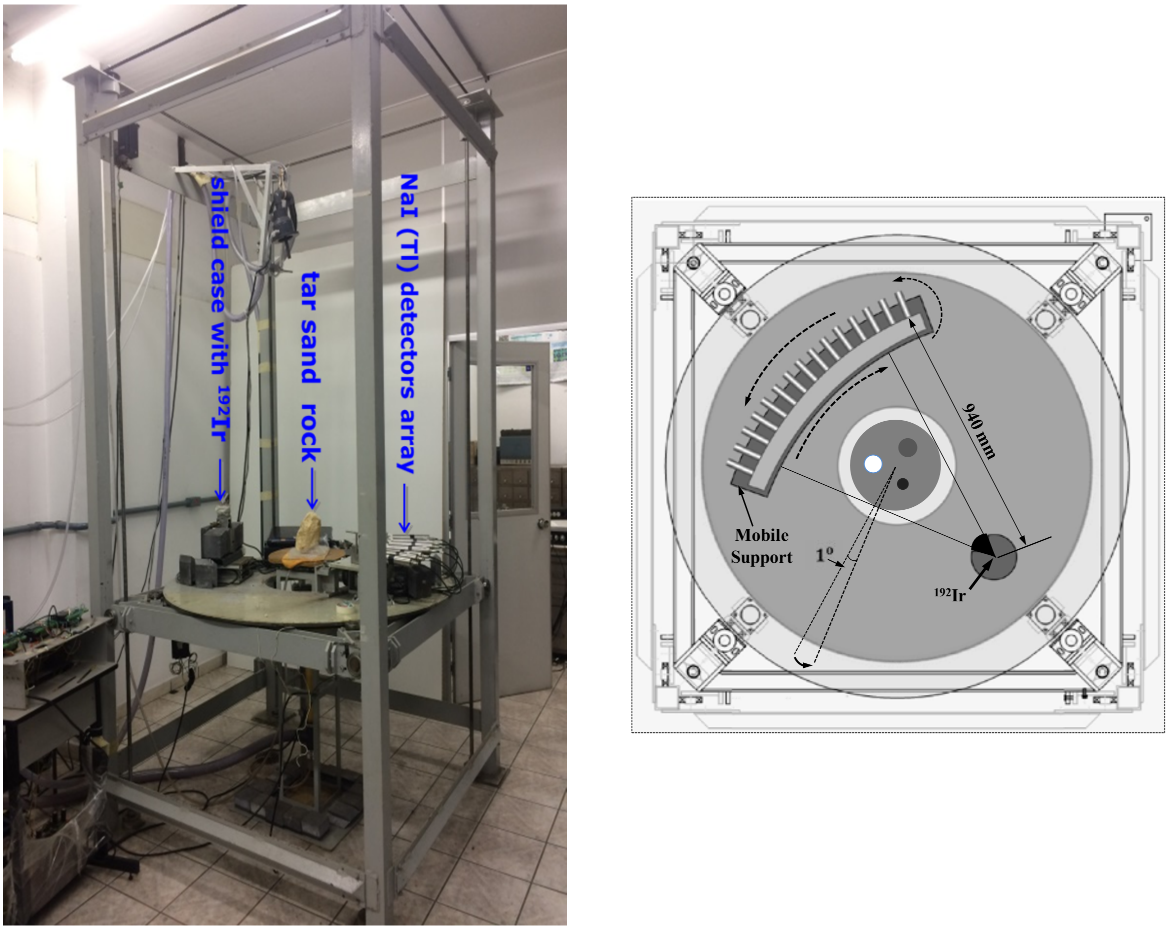

Figure 2: Picture (a) and Diagram of the top side (b) of the 3rd generation industrial tomography.

Previously, tomography measurement was carried using a multiphase phantom constituted of known materials in order to convert the linear attenuation coefficient in density. The phantom consists of a PMMA ($\rho \approx$ 1.19 g/cm3 [6]) solid cylinder containing three holes: one filled with steel ($\rho \approx$ 7.874 g/cm3[6]), another with aluminum ($\rho \approx$ 2.698 g/cm3[6]) and the third one empty (filled with air) and surrounded with glass, as illustrated in Figure 3 (Velo et al 2018).

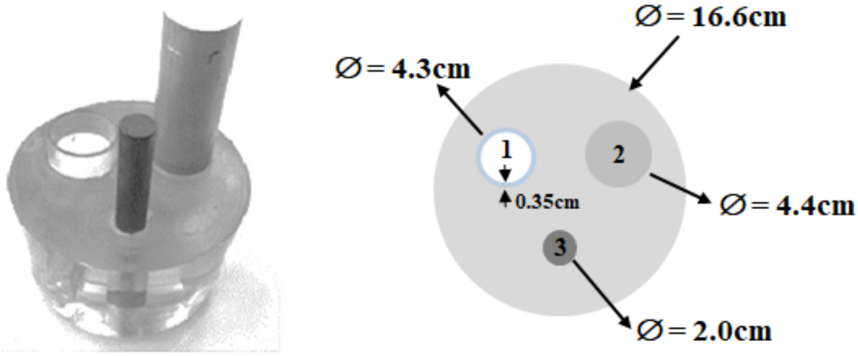

Figure 3: Picture (A) and Illustration of the multiphase phantom scheme. 1- Air surrounded with glass wall, 2-aluminum bar and 3-steel bars. The phantom is made of acrylic (B)

Afterward, the tomography measurements were carried out in two different heights of the same tar sand sample. Previously, the sample was dried in an oven at 150°C for 120 hr to remove humidity and waters that may be stored in the pores of the rocks.

The images were reconstructed using Filtered Back Projection (FBP) (Kak, 1979, Kak and Stanley, 2001) in the grid matrix of 512 x 512.

3 RESULTS AND DISCUSSION

Figure 4 shows the reconstructed image of the multiphase phantom using a FBP algorithm. From this image, it was calculated the average of the linear attenuation coefficient of the objects: air, PMMA, glass, aluminium and iron, subsequently, it was correlated with their respective densities, as shown in Figure 5.

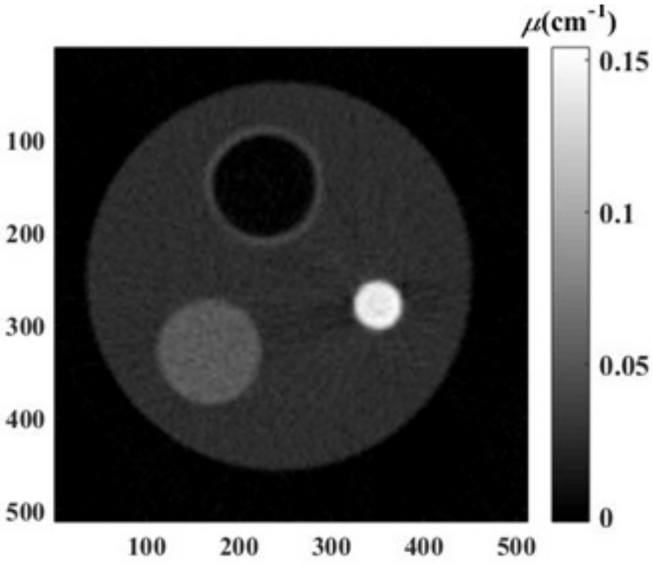

Figure 4: Reconstructed image of the multiphase phantom

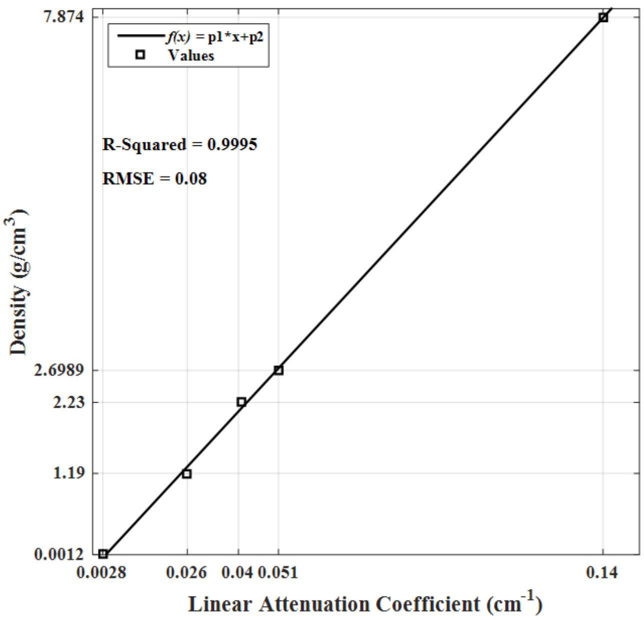

Figure 5: Density x Linear Attenuation Coefficient Relation

Fig 6 presents the reconstructed images of the tar sand sample measured at two different heights. The color-bar index value represents the index pixels in density (ρ (g/cm^3)). The conversion of the linear attenuation coefficient in density was performed using the relation presented in Figure 5. A high spatial resolution in the tomography configuration was obtained with the selected parameters, as it can be observed in Fig. 6, although the low temporal resolution, requiring 17.5 hours to obtain each tomographic image. The distribution of the porosity and permeability can be seen in the Fig. 6 clearly.

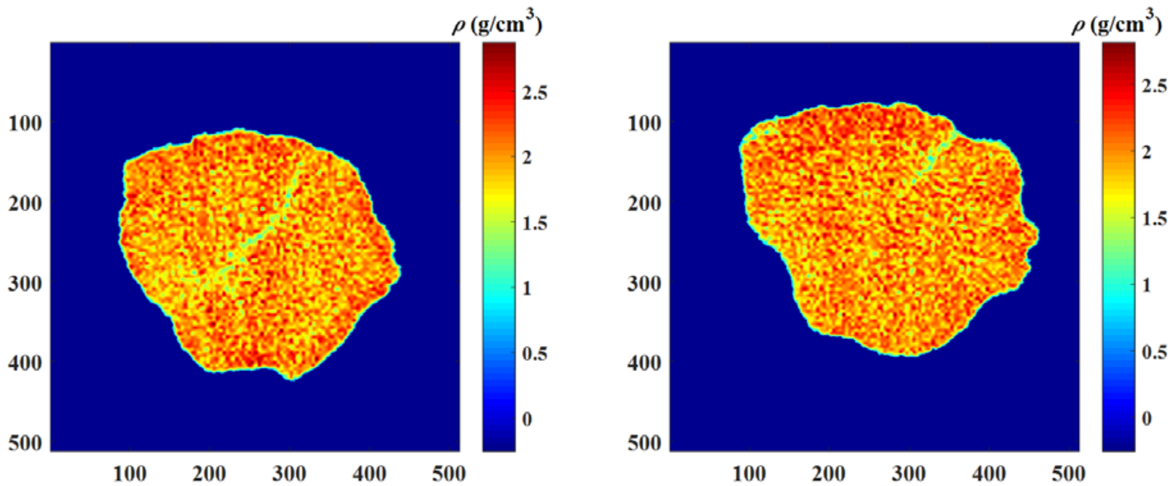

Figure 6: Reconstructed images of the tar sand sample measured at two different heights of the same tar sand rock sample

A different density material that comprises the tar sand rock can be assessed in the sample. In the composition analysis, four different densities were found, that correspond to the density values of the following materials, namely, quartz (SiO_2), clay, feldspar and bitumen. Table I summarizes the density values obtained in this work compared to that stated in the literature (Mochinaga et al 2006, NIST, 2018, AQUA-CALC, 2018], as well the percentage of these materials in the tar sand sample.

The segmented images for the quartz grains, clay, feldspar and the bitumen shown in Fig.7 were obtained from the Density x linear attenuation coefficient correlation. The percentage of each material was obtained after the image binarization, where the pixels that belongs to the rock were converted to 1 and those who does not belongs to the rock obtained value of 0. In this way, it was possible to achieve the total numbers of pixels that belongs to the rock. The percentage of materials in the images was calculated dividing the quantity of pixels representing the material with the total number of pixels obtained by the binzarization. In the mineral composition analysis, for the most of particles present in the samples, a density around 2.4 g/cm^3 was estimated from the reconstructed image by inference to the curve presented in Fig. 5. This estimated value suggests that these particles are, probably quartz grains since it is very close of the quartz density value, that is 2.32 g/cm3 (NIST, 2018) and, also, this mineral is known to be one of greater contents the tar sand rocks (Hu et al, 2018)**.** Also, the pores filled with bitumen may be clearly observed in the image [Fig 7d], however it is only small part of whole rock volume, where the percentage of bitumen in the rock surface evaluated was around 4.0%. A primary application of porosity is used to quantify the storage capacity of the rock and, subsequently, defining the volume of void space and bitumen available inner the rock.

Table I – Density of the material and the percentage of each material that comprise in the tar material sample.

Material	Estimated Density (g/cm^3)	Density (literature) (g/cm^3)	% of the material in the rock
Quartz	2.4	2.32 *	Sample 1 : 75.16 % Sample 2: 72.55 %
Clay	1,7	1.75 **	Sample 1 : 18.85 % Sample 2: 21.63 %
Feldspar	2.6	2.56 **	Sample 1 : 2.01 % Sample 2: 1.61 %
Bitumen	1.0	1.01 ***	Sample 1 : 3.98 % Sample 2: 4.21 %

* (NIST, 2018)
** (AQUA-CALC, 2018)
*** (Mochinga et al 2006)

4 CONCLUSION

The gamma ray industrial process tomography shown to be a technique efficient to characterize the tar sand rock. The mineral composition, the distribution of the porosity, the bitumen can be seen clearly in the reconstructed image, where the four constituents of the rock can be identified through their densities. The mayor mineral constituents of the rock found was quartz grain, where the percentage of quartz in the rock surface evaluated was around 75.0%, and its density was estimated to be 2.4 g/cm^3 . The percentage of bitumen in the rock was around 4.0% with estimated density of ~ 1 g/cm^3, while the percentage of the clay and feldspar in the tar sand surface evaluated were of ~20% and 2% respectively. The density estimated for clay was of ~1.7 g/cm^3 and for feldspar were 2.6 g/cm^3.

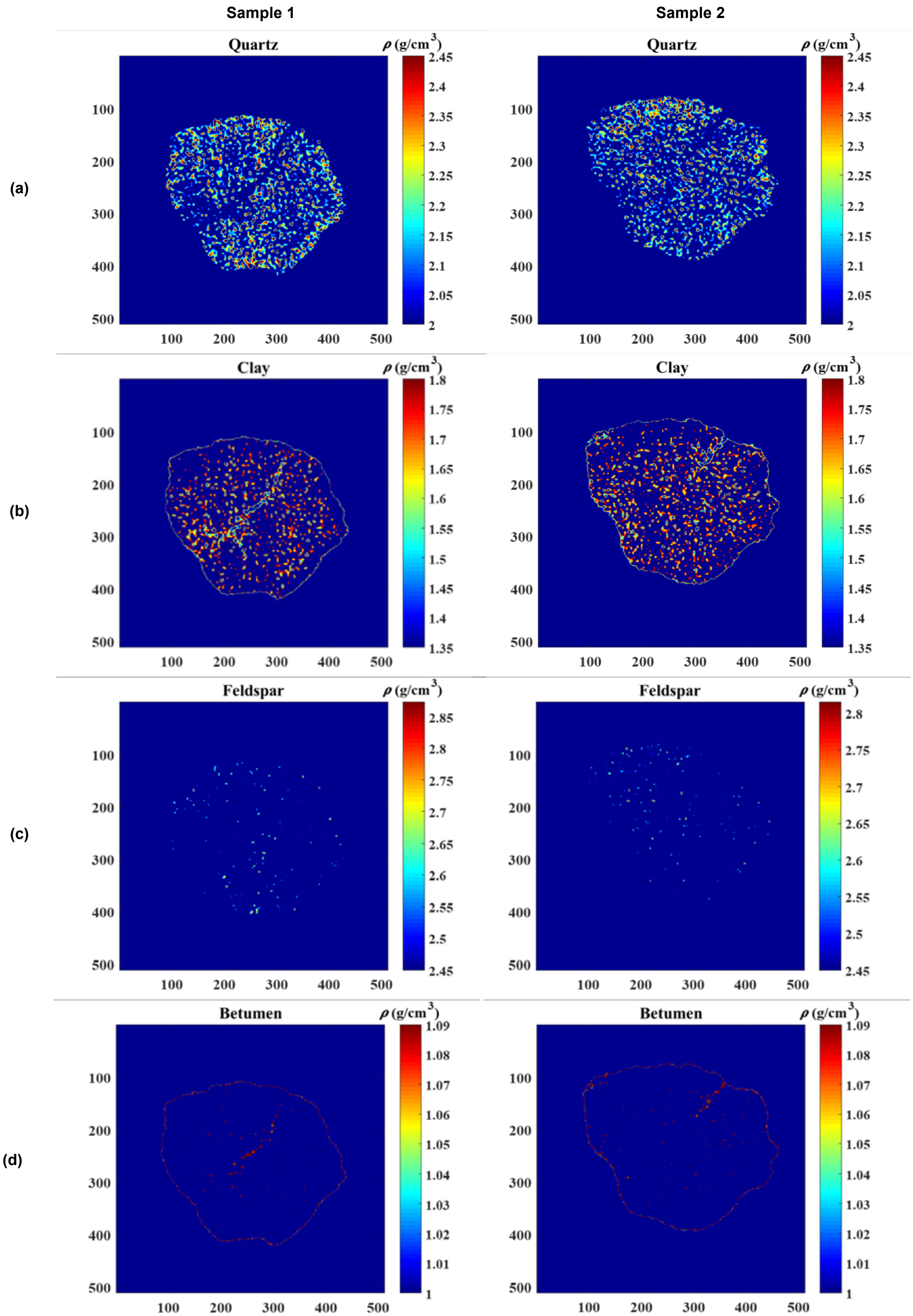

Figure 7. Segmented image for Quartz grains, Clay, Feldspar and Bitumen for two different height of the tar sand sample.

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