METHOD PAPER



Exploring the application of dual-energy CT to discriminate sediment facies in a varved sequence

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Abstract

Dual-energy X-ray computed tomography consists of imaging objects using two incident X-ray beams of different energy to distinguish the different compounds within a sample based on their density (electron density, ρ_e) and elemental composition (effective atomic number, Z_{eff}). The stoichiometric calibration for dualenergy X-ray computed tomography was already successfully implemented to identify single and homogeneous minerals easily and non-destructively. It is here applied for the first time to a more complex and heterogeneous sample, a varved sediment core with three distinct facies. The output of dual-energy X-ray computed tomography was compared against elemental geochemistry obtained at the same resolution using a micro-XRF core scanner. The three individual facies can be successfully differentiated using dual-energy X-ray computed tomography because their range of ρ_e and Z_{eff} values allow their discrimination. Correlations with elemental geochemistry are also discussed but are less conclusive, probably because of variations in grain size and porosity, and because these high resolution analyses were not performed at the exact same location. The paper not only eventually discusses the limitations when using dual-energy X-ray computed tomography on sediments but also demonstrates its potential to quantitatively study sediment cores in a non-destructive way.

KEYWORDS

3D visualisation, debris flow, geomaterials, non-destructive analysis, turbidity, X-ray tomography

1 INTRODUCTION

X-ray computed tomography was developed in the 1970s by Godfrey Hounsfield and Allan MacLeod Cormack as a medical imaging technique to obtain images of the human body's inner structure. In a CT scanner, the X-ray source

faces the detector, and they rotate together around the patient: after acquiring bidimensional radiographic projections at various angles from 0° to 360°, they are processed by a mathematical algorithm (i.e., image reconstruction) to obtain a set of slices permitting the 3D visualisation (Bushberg et al., 2012).

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Although this technology originated for medical purposes, its potential was soon recognised and applied to several fields like archaeology (Re et al., 2015), biology (Mizutani & Suzuki, 2012), wood technology (Onoe et al., 1983), palaeontology (Conroy & Vannier, 1987), marine science (Boespflug et al., 1995) as well as geoscience (Baker et al., 2012; Coles et al., 1991; Griggs et al., 2015; Vinegar & Wellington, 1987).

A few years after its invention, Alvarez and Macovski (1976) elaborated the concept of dual-energy CT (DECT), consisting of imaging patients using both low and high X-ray energy spectra. This combination allows the discrimination and identification of objects based on their chemical composition and density, based on differential contribution of photoelectric absorption and Compton scattering as a function of energy (Duchesne et al., 2009). Several groups have implemented DECT methods in the medical field to improve materials characterisation (Bazalova et al., 2008; Jackson & Hawkes, 1981; Rutherford et al., 1976; Torikoshi et al., 2003; Tsunoo et al., 2004).

Van Geet et al. (2000) applied DECT for the first time in the field of geology, adapting the mathematical formula previously elaborated by Coenen and Maas (1994): they quantified the chemical composition of reservoir rocks, henceforth expressed as effective atomic number (Z_{eff}), and electron density (ρ_e), the latter being, in general, directly proportional to the more common mass density. Then, several geologists conducted experiments in order to improve this technique for Earth science needs (Alves et al., 2015; Duliu et al., 2003; Iovea et al., 2006; Paziresh et al., 2016; Remeysen & Swennen, 2008).

These DECT techniques require the properties of the incident X-ray beam spectra, but this information is difficult to calculate (Remeysen & Swennen, 2006). However, in the 2000s, medical physicists developed DECT methods that did not require spectral information, facilitating the analysis (Bourque et al., 2014; Landry et al., 2013). Martini et al. (2021) applied for the first time one of these techniques, specifically the stoichiometric calibration, in the field of geology in order to identify common minerals.

This paper aims to test this method developed by Martini et al. (2021) on a non-consolidated, fine-grained sediment core from an Arctic varved lake (South Sawtooth Lake). The analysis conditions of this case study are much more complex than those reported in Martini et al. (2021) who tested the method on individual minerals that have a very simple chemical composition. In comparison, the sediment sample analysed here contains a variety of minerals, has a complex geochemistry, porosity and granulometry. The reason for testing the DECT technique on the South Sawtooth Lake sediment resides in the fact that this sedimentary record allowed a long annually resolved palaeoclimate reconstruction over approximately the past three millennia (Lapointe et al., 2020). The sediment consists of clastic varves that are interrupted by rapidly deposited layers (RDLs) caused by occasional summer rain events (Lapointe et al., 2019). The goal of the present work was to test the capacity of the stoichiometric calibration method for dual-energy CT to discern clastic varves from RDL in a non-destructive way and to discuss its potential use in other sedimentary settings.

2 | MATERIALS AND METHODS

2.1 | Core from South Sawtooth Lake

South Sawtooth Lake is located on the Fosheim Peninsula in the Eastern Canadian High Arctic and contains a varved sequence that has already been studied in several research works (Francus et al., 2008; Lapointe et al., 2019, 2020; Lewis et al., 2005).

The sediments from the distal basin are particularly interesting because they contain a robust 2900 years long palaeoclimate record (Lapointe et al., 2019). At this site, two main facies are present. First, clastic varves as defined by Zolitschka et al. (2015). This facies results from snowmelt in the watershed and is characterised by medium to fine silts grading into a clay cap. This facies can be less than a millimetre thick, but can be as large as a few centimetres (Francus et al., 2008). Second, grain-supported sand-rich-laminae (RDL) occasionally interrupt the clastic varves succession. Their thicknesses varies between 0.1 and 13 mm. From their stratigraphic position, between the base of silt graded beds and their caps, it was established that they result from debris flows from the slope surrounding the distal basin and are triggered by rare summer rain events (Francus et al., 2008). Their chemical composition is different from the clastic varves, that is, richer in carbonates, as the lithology of the surrounding slopes is different from the rest of the watershed. The 2m long section investigated here is core SS12-12-3-2P that was collected in 2012 using an Uwitech piston corer. Analyses have been performed on the intact archive half of the core.

2.2 | Medical CT scanner

The medical CT scanner used in this work is a Siemens Somatom Definition AS+128 (Siemens healthcare GmbH, Erlangen, Germany; Figure 1), located at the Institut national de la recherche scientifique (INRS), Centre Eau Terre Environnement (ETE), Québec City, Canada.



FIGURE 1 Siemens somatom definition AS+128, INRS, Centre ETE, Québec City, Canada. An example of sediment core being scanned is located in the gantry centre.

T.	A	B	L	Е	1	CT acquisition	parameters
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X-ray voltages	70 and 140 kV
Pitch factor	0.55
Current	495 mA
Beam collimation	12 mm
Detector	Stellar ^{Infinity} generation
Images acquisition mode	Spiral mode
Reconstruction method	ADMIRE
Reconstructed images	512×512 pixels
Voxel size	$0.1 \times 0.1 \times 0.6 \text{mm}$
Grey-level scale	Extended scale, or 2 ¹⁶ grey levels
Reconstruction filter	D45s

The instrument and the acquisition parameters are the same as the ones used in Martini et al. (2021) and are summarised in the following Table 1.

2.3 | Characterisation method

The stoichiometric calibration protocol used here is briefly outlined below, but details can be found in the original publication (Martini et al., 2021). The method consists of accomplishing two successive calibrations: the first one characterising the effective atomic number Z_{eff} and the second one, the electron density ρ_e . First, the effective atomic number Z_{eff} and electron density ρ_e of a set of standard samples with known composition are calculated (Azevedo et al., 2016; Bonnin et al., 2014):

$$Z_{\rm eff} = \sqrt[\beta]{\sum_{i}^{N} f_i Z_i^{\beta}} \tag{1}$$

$$\rho_e = \sum_{i=1}^N \frac{Z_i}{A_i} \rho \tag{2}$$

In Equation 1, f_i is the fractional mass of element *Z* in the compound. The exponent β is a function of photon energy, sample materials, instrument and specific analytical settings (Alves et al., 2015; Azevedo et al., 2016; Landry et al., 2013) and can vary between 2.94 and 3.8 (Bonnin et al., 2014; Spiers, 1946). In Equation 2, A_i is the atomic mass of the element Z_i , and ρ is the material mass density (g·cm⁻³) (Azevedo et al., 2016; Manohara et al., 2008).

Second, these standard samples are scanned, according to acquisition conditions described in Table 1, at 70 and 140 kV, and the two materials normalised linear attenuation coefficients (μ_{low} and μ_{high}) are calculated from Hounsfield units (*HU*), a relative scale tied to the attenuation of materials, following Equation 3 (Boespflug et al., 1995; Watanabe, 1999):

$$\mu = \frac{\mu_{\text{sample}}}{\mu_{\text{water}}} = \left(\frac{\text{HU}}{1000}\right) + 1 \tag{3}$$

Third, the Z_{eff} calibration procedure described in Martini et al. (2021) was performed, plotting the linear attenuation coefficients (Equation 3) ratio and the calculated Z_{eff} (Equation 1), obtaining a second-order polynomial data-driven empirical model.

$$Z_{\rm eff} = a + b \cdot \left(\frac{\mu_{\rm low}}{\mu_{\rm high}}\right) + c \cdot \left(\frac{\mu_{\rm low}}{\mu_{\rm high}}\right)^2 \tag{4}$$

Finally, ρ_e calibration is achieved by plotting the ratio between measured μ (Equation 3) and standard samples ρ_e (Equation 2), normalised by water electron density ($\rho_{e water} = 3.34 \text{ E}+23 \text{ e}^{-1} \text{ cm}^{-3}$) and Z_{eff} determined in Equation 4:

$$\frac{\mu_{\text{low or high}}}{\frac{\rho_{\text{e}}}{\rho_{\text{e water}}}} = d + e \cdot Z_{\text{eff}} + f \cdot Z_{\text{eff}}^2$$
(5)

Again, the data-driven empirical model is a secondorder polynomial. Here, the μ value used in Equation 5 can equally be those obtained at low or high energy; it is also possible to use both equations to calculate ρ_e and average the outcomes.

The calibration materials, and consequently the two sets of coefficients, are the same as the ones in Martini et al. (2021) (Figure 2). These equations are used to calculate both Z_{eff} and ρ_e for each voxel of each CT slices (see below).



FIGURE 2 Coefficients related to Equation 4 on the left and to Equation 5 on the right with the respective calibration curves (from Martini et al. 2021).

2.4 | Selection of the region of interest

A single CT scan slice is perfectly perpendicular to the length of the sediment core and can include several layers. Indeed, coring operations deform the originally horizontal parallel varve layers because the friction of the tube being pushed into the relatively soft sediment sequence deforms the sediment near the edge (Gallmetzer et al., 2016).

Figure 3A shows the comparison between the highresolution picture of the half-core surface and a CT coronal view (i.e., orthogonal to the core length) that was built stacking together the orthogonal slices from a volume within the half core using the software *SedCT* (Reilly et al., 2017). Figure 3B shows a screenshot of *SedCT* interface, where the core orthogonal axial slice is masked in white, and the red line pinpoints the depth at which the CT coronal view was assembled.

The visible layers in the core picture and the CT image do not match perfectly because the core surface is irregular and has been manually smoothed to obtain a 'clean surface', erasing somehow the desiccation cracks visible only in CT images that are assembled from an area located a few millimetres deeper than the core surface.

Hence, to mathematically subsample a single varve among the several layers present in only one slice, a region of interest (ROI), where Z_{eff} and ρ_e are measured, needs to be defined along the core (Figure 4). The ROIs are about $2 \times 2 \text{ mm}$ (i.e., $10 \times 10 \text{ pixels}$) and were selected using *ImageJ* software in a central zone as close as possible to the surface so that these outcomes can be better compared with the geochemical measurements made at the surface of the core as described in Section 2.5. Z_{eff} and ρ_e were calculated for each pixel of each CT scan ROI slice and then were averaged to obtain one value per slice. Subsequently, these averages will be used to report measurements.

2.5 | μ-XRF

The ITRAX core scanner (Figure 5) located at INRS-ETE, Québec City, Canada, was used to measure the elemental variations along the core surface using the parameters outlined in Table 2. Chemical analysis, performed before the tomographic acquisition, was acquired at a similar resolution than the CT scans in order to facilitate their comparison with DECT inferred properties. Prior to measurements, the surface of the core was gently scraped to present the needed smooth surface to the detector (Cuven et al., 2015).

The acquisition parameters used here are summarised in Table 2. Each energy dispersive spectrum was reevaluated using Cox Analytical RediCore[™] software (Löwemark et al., 2019) and then elemental data were normalised by incoherent (related to Compton scattering) and coherent (related to Rayleigh scattering) ratios to take into account the matrix, mainly water content and density variations within the sediment (Kylander et al., 2011).

2.6 | Statistical analysis

The *R* commander package of the software *R* (Fox, 2016) was used to compute the Pearson correlation coefficient *R*

В

Image Location (%)

10 cm

90

100



603

FIGURE 4 ROI selection in a CT scan slice of South Sawtooth core where the deformation caused by coring process is visible and several varves are present. The ROI selection was performed using



ITRAX core scanner, INRS, Centre ETE, Québec

TABLE 2 µ-XRF acquisition parameters.

Tube	Molybdenum
Resolution	600 µm
Exposure time	12 s
Voltage	40 kV
Current	10 mA
Count per second (CPS)	≈40,000

FIGURE 3 (A) High-resolution picture of the half South Sawtooth core surface versus a CT coronal view. (B) White mask of an axial slice of the core; the red line indicates the depth at which the CT coronal view was assembled with SedCT.

and the respective pairwise *p*-values between the Itrax and DECT measurements. Then, the Matplotlib Python library was used to compute and plot box-and-whisker diagrams of the DECT measurements on the different sedimentological facies.

RESULTS 3

Figure 6A shows the Z_{eff} and ρ_e profiles laid over the CT coronal view of the core. A zoom into a smaller section illustrates the variations at the varve scale; the profiles are interrupted where there is a fracture (i.e., no value) and their trends generally follow varve boundaries. In the CT images, lighter grey values indicate higher X-ray attenuation due to the heavier/denser material. Yet, Z_{eff} and ρ_e profiles have higher values in these light intervals. The Itrax core scanner detected several elements

from the surface of the core. Figure 6B shows the Ca profile that is of interest because of the rich carbonate content of the RDLs. The enlarged section shows that

FIGURE 6 (A) Z_{eff} and ρ_e profiles overlapped on the CT coronal view. (B) Ca profile normalised by inc/coh (yellow curve) detected by Itrax.

the Ca trend closely follows the varve boundaries. This is even clearer in the case of the thick RDL layers; the signal increases in the carbonate-rich layer, it decreases where there is a fracture and it increases again in the lowest part of the RDL.

The Pearson correlation coefficient R between Itrax and DECT inferred Z_{eff} and ρ_e along the entire core profile, and the respective pairwise *p*-value ranges are presented in Table 3.

Because the desiccation cracks make the alignment of the two datasets difficult to complete, some remarkable and well-defined clastic varves (23 layers) and RDLs (15 layers) were visually identified and selected as archetypal samples to perform the comparison between μ -XRF and DECT. Clastic varves were split into two categories, based on their granulometry, fine-grained and coarse-grained.

Figure 7 shows an example of the layers that were used for this analysis in the upper part of the core: the white vertical line represents the point where the ROI was chosen and the coloured horizontal lines (coarse-grained clastic varves in light blue, fine-grained clastic varves in fuchsia and RDL in green) point to the exact layer that was used for this analysis.

The Pearson correlation coefficients and the respective pairwise *p*-value ranges performed on these 38 clearly identified layers are presented in Table 4. Then, Z_{eff} and ρ_e of each ROI voxel were represented in a box-and-whisker diagram in order to verify that the three facies, that is, coarse-grained clastic varves, fine-grained clastic varves and RDL, can be identified based on their DECT properties (Figure 8).

Figure 9 shows the image of a thin section and the Z_{eff} (blue) and ρ_e (red) profiles; the lower part is characterised by thick RDL (green) where Z_{eff} is low and ρ_e is high. This RDL is overlain by a succession of fine-grained clastic varves (fuchsia), having slightly higher Z_{eff} values, while the ρ_e profile drops to the lowest values. Finally, the coarse-grained clastic varve (light blue) at the top is characterised by the highest Z_{eff} values and increasing ρ_e values. Figure 8 and previous Figure 9 show that the combination Z_{eff} and ρ_e values measured using DECT are different for the three main facies.



	Ca	Cr	Cu	Fe	Inc/Coh	К	Mn	Ni	Pb	Rb	Si	Sr	Ti	Zn	Zr
$ ho_{\rm e}$	0.33 ***	0.13 ***	0.05 **	0.23 ***	-0.33 ***	-0.11 ***	0.24 ***	0.17 ***	0.07 ***	-0.07 **	0.24 ***	0.17	0.35 ***	0.23 ***	0.16 ***
$Z_{\rm eff}$	0.25 ***	0.1 ***	0.08 ***	0.31 ***	-0.22 ***	-0.01	0.19 ***	-0.04 *	0.06 **	0.03	0.08 ***	0.11 ***	0.28 ***	0.21 *	0.03

Note: Pairwise *p*-values are represented by stars: *<0.05; **<0.01; ***<0.001; otherwise the *p*-value is >0.01. The shading is related to the correlation value, the darker the shading, the better *R*.





FIGURE 7 Layers that have been chosen to be individually analysed. The vertical white line represents the point where the ROI was chosen, then coarse-grained clastic varves are in light blue, fine-grained clastic varves in fuchsia and RDL in green. The ruler on the left measures centimetres.

4 | DISCUSSION

4.1 | DECT and chemical elements

Dual-energy X-ray computed tomography allowed the three main facies to be distinguished based on their Z_{eff} and ρ_e , but it was not possible to infer their exact chemical composition. Indeed, the Pearson correlation coefficient *R* calculated on the entire core (Table 3) is relatively weak except for those of Ca, Ti and Inc/Coh versus ρ_e and Fe versus Z_{eff} that are above 0.3, and most of them are highly significant with *p*-values <0.0001.

The negative correlation between ρ_e and the ratio Inc/ coh of the Itrax is meaningful because the latter is an indicator of the density of the sediment matrix (Croudace et al., 2019; Fortin et al., 2013). The relatively high correlation values of Ca, Ti and Fe with ρ_e and/or Z_{eff} can be explained by the fact that these elements are abundant (Lapointe et al., 2019) in the South Sawtooth Lake sediments and are well detected by the Itrax.

The relatively weak correlations can be explained by several factors: first, it is impossible to perfectly align the two profiles because of the desiccation cracks and the slight changes due to the scraping of the surface in preparation for the Itrax analyses. Several attempts to realign the two datasets using the QAS software (Kotov & Pälike, 2019) were unsuccessful and hampered by the high frequency change in sediment elemental composition because of the varved nature of the sediment. Second, the Itrax is used to measure the geochemistry at the surface of the sediment, whereas CT scanning is a 3D technique, so there will always be a mismatch between the analysed spots, entailing a difficult comparison. Moreover CT scan images can be affected by beam hardening, an artefact which affects the attenuation profile, creating high-attenuation and low-attenuation artefacts on the sample; it is caused by preferential attenuation of low energy photons biasing the reconstructed image quality mainly at the phase interfaces (Di Schiavi Trotta et al., 2022). In this case, beam hardening was relatively mild. Third, the core is very long and the more than 45,000 data points are driving the calculated R to lower values, even if the *p*-values are excellent. Indeed, the correlation is inversely proportional to the amount of data (i.e., the highest possible correlation is between only two points, defining a linear relationship) and this effect is illustrated by the higher R values obtained with a reduced set of points in Table 4 (Benesty et al., 2009). In order to improve the comparison between DECT and Itrax analyses, and to reduce misalignment between the two datasets in the future, it is suggested that CT scans are performed on unopened fresh cores, with the XRF analysis conducted immediately to avoid any shrinkage or motion of the sediment within the core liner.

As illustrated in Figure 8, the three different sedimentological facies can be discriminated by a combination of the two properties measured and calculated using DECT. Coarse-grained clastic varves have the highest mean Z_{eff} of the three facies probably because they are richer in elements with high atomic number. They also have a high average ρ_e value that is generally proportional to mass density, a characteristic in line with high *HU* values observed on single-energy CT images of this facies. Titanium and Si

	Coarse-grain varves	ed clastic	Fine-grain varves	ed clastic	RDL		
	ρ_e	$Z_{e\!f\!f}$	ρ_e	$Z_{e\!f\!f}$	ρ_e	$Z_{e\!f\!f}$	
Ca	0.43 ***	0.19 *	0.04	-0.23 *	0.19	0.48 ***	
Cr	0.16	0.09	0.008	-0.01	-0.08	0.26	
Cu	-0.0001	-0.04	-0.23 *	-0.005	0.11	0.16	
Fe	0.37 ***	0.45 ***	0.26 *	0.14	-0.28 *	0.21	
Inc/Coh	-0.27 **	-0.15	-0.29 **	0.19 *	-0.31 *	-0.06	
K	0.09	0.19 *	-0.44 ***	0.16	0.19	-0.007	
Mn	0.37 ***	0.17	0.14	-0.19	0.08	0.48 ***	
Ni	0.19 *	0.12	0.19 **	-0.28 *	0.11	-0.26	
Pb	0.0647	0.07	0.09	0.16	-0.11	0.13	
Rb	-0.03	0.15	-0.16	0.13	-0.02	0.21	
Si	0.36 ***	0.24 *	0.29 **	-0.24 *	0.21	-0.31 ***	
Sr	0.009	-0.16 *	0.38 ***	-0.24 *	-0.24	-0.06 ***	
Ti	0.36 ***	0.14 *	0.46 ***	-0.14 **	-0.27 *	0.19 ***	
Zn	0.16	0.03	0.007	0.003	0.21	0.37 **	
Zr	0.44 ***	0.11	-0.01	-0.31 **	0.47 *	0.29 *	

TABLE 4 Correlation matrices between Itrax and DECT results on selected sedimentological layers.

Note: Pairwise *p*-values are represented by stars: *<0.05; **<0.01; ***<0.001; otherwise, the *p*-value is >0.01. The shading is related to the correlation value, the darker the shading, the better *R*.



FIGURE 8 Z_{eff} and ρ_e box-andwhisker diagram of coarse-grained clastic varves (light blue), fine-grained clastic varves (fuchsia) and RDL (green). ρ_e is expressed in e^{-1} cm⁻³.

(R=0.36) are often linked with clastic input (Balascio & Bradley, 2012; Kylander et al., 2011; McWethy et al., 2010) in Arctic settings devoid of diatoms. Moreover, as reported in Lapointe et al. (2020), Ti is a proxy for summer temperature at South Sawtooth Lake and its good correlation with CT properties may be an opportunity to use DECT for palaeoclimate reconstructions. Calcium and Fe also

have a strong correlation with ρ_e in coarse-grained clastic varves (R=0.43 and 0.37, respectively); these elements are reported to covary with Si and Ti in Lapointe et al. (2020), and hence are also related to the detrital input. While Zr is present in trace amounts in the sediments, hence not responsible for driving the mean Z_{eff} and ρ_e values to higher values, it is interesting to note that Zr has a good



FIGURE 9 Thin section sampled in the upper part of the core where the Z_{eff} (blue) and ρ_e expressed in e cm⁻³ (red) profiles are overlapped. Vertical bars on the left shows the limits of the different facies (green, RDL; fuchsia, fine-grained varves; light blue).

correlation (R = 0.44) with ρ_e in the coarse-grained clastic varves facies (Table 4), but this correlation does not occur in fine-grained clastic varves. Manganese is more difficult to interpret because it can be influenced by changes due to redox reactions (Lapointe et al., 2019).

Fine-grained clastic varves have the lowest ρ_e (Figure 8) and this result is consistent with the low-attenuation values seen in the low *HU* values of the CT scans. Titanium is better correlated with Z_{eff} in this fine-grained facies than coarse-grained clastic varves. This is in line with the observations made with Itrax and scanning electron microscopy (SEM) analysis (Lapointe et al., 2019) of sediments from South Sawtooth Lake that shows a maximum Ti content in medium silt layers. Potassium is negatively correlated to ρ_e , and this is surprising because this element is linked to the clay cap of these clastic varves (Cuven et al., 2010; Lapointe et al., 2019).

The RDLs have a small average Z_{eff} value, similar to that of the fine-grained clastic varves, but higher ρ_e values

similar to those seen in the coarse-grained clastic varves. Again, high density values are also registered by HU values in these layers. More intriguing is the low Z_{eff} value in the RDLs because these layers are rich in carbonates and the theoretical Z_{eff} of calcite (15.07) is higher than quartz (11.56). The presence of carbonates is confirmed by the good correlation between Ca and Z_{eff} (R=0.48). A possible explanation for the low average Z_{eff} values of the RDL resides in the heterogeneity of this sedimentary layer; the carbonate presence could increase the Z_{eff} value, but since the measurement are averaged within ROI over the layer, the presence of minerals composed of lighter elements should contribute to lowering the overall Z_{eff} . This facies is also probably to have a larger porosity because of its coarser grain size (Francus et al., 2008).

The lowest ρ_e encountered in fine-grained clastic varves could be counterintuitive and contrary to the fact that a volume filled with smaller grains entails fewer intergranular spaces or a lower porosity, and therefore



FIGURE 10 Boundary between RDL and fine-grained clastic varves acquired by scanning electron microscopy. The intergranular space of RDL is not empty but filled with finer sediments.

TABLE 5 Classification of the three different facies based on the first and third quartile values (Figure 8) of Z_{eff} and ρ_e .

Facies	$Z_{e\!f\!f}$	$\rho_e (\mathrm{e}^- \cdot \mathrm{cm}^{-3})$
Coarse-grained clastic varves	11.49–11.99	5.42E+23-5.65E+23
Fine-grained clastic varves	11.22–11.61	4.74E+23-5.26E+23
RDL	11.08-11.53	5.38E+23-5.75E+23

should be denser. However, here the larger intergranular space of RDL is not empty but filled with other smaller grains, explaining the lower density of the fine-grained clastic varves as illustrated in Figure 10, where the bound-ary between RDL and fine-grained clastic varves has been acquired by SEM.

4.2 | Facies identification

The possibility of distinguishing the three facies based only on DECT was tested using only the voxel values comprised of the first and third quartiles of the boxplot in Figure 8 (Table 5). The result of this classification is outlined in Figure 11 on a section of a sediment core. Each point corresponds to a voxel on which this calculation has been performed (Figure 11); about 6% of the voxels are identified as coarse-grained clastic varves, about 62% as fine-grained clastic varves and about 16% as RDL. Moreover, about 14% is empty and these gaps represent the whiskers and the outliers visible in the boxplots of Figure 8.

This facies classification based on the DECT method can be accomplished in 3D as well. First, the grey values of the slices were segmented according to the values in Table 5 and then the slices were stacked (Figure 12). Again, the inner empty parts (in black) are the whiskers and the outliers visible in the boxplots of Figure 8.

It is also possible to build up the entire volume of the segmented facies by stacking all the slices. Figure 13 shows the 3D reconstruction of a core section (on the right) where the different sedimentological layers are clearly visible and reflect the reality of the high resolution picture (on the left side).

Recognising the three facies might be of interest for palaeoclimate reconstructions, but the application of this technique to other fields of Earth science is not excluded. In this example, RDLs are interpreted as summer rain events, rich in Ca. As reported in Lapointe et al. (2019) an increase in grain size and Ca content over the last few hundred years would be due to an increase in summer rainfall, an interpretation consistent with progressive climate

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FIGURE 12 Stack of slices for the 3D volume reconstruction where the three different facies are identified according to DECT values reported in Table 5. Coarse-grained clastic varves are in light blue, fine-grained clastic varves in fuchsia and RDL in green.

heavier elements on the values of Z_{eff} and ρ_{e} . Applying the DECT technique on artificial samples with controlled granulometry, porosity and mineralogy should allow the complexity of natural samples to be better understood.

CONCLUSION 5

Dual-energy CT stoichiometric calibration is here applied for the first time on a sample as complex as a varved sediment core. This sedimentary sequence contains three main facies, that is, fine-grained clastic varves, coarsegrained clastic varves and grain-supported sand-richlaminae RDLs. The DECT allowed the three main facies of this core to be distinguished based on their unique combination of Z_{eff} and ρ_e . Significant correlations were found between these two properties and some elements measured by µ-XRF at the same resolution, but it was not possible to infer the exact chemical composition of the facies. Stoichiometric calibration DECT has the advantage of being quick, entirely non-destructive and possible in

grained clastic varves (fuchsia) and RDL (green) identified from the statistical property values of first and third quartiles from box-andwhisker diagram, overlapped to a core section. The ruler on the left measures centimetres.

warming. However, using the Ca profile acquired by the Itrax alone does not allow a Ca peak to be definitively defined as a RDL because it is also associated with coarse grained varves. The RDL characterisation is relevant for palaeoclimate studies at this site, and this task seems to be possible with DECT.

This DECT approach to identifying sedimentary facies is in its infancy because several questions remain. For instance, in this example, there are opposing effects between grain size and the presence of minerals with







FIGURE 13 High-resolution picture where the three facies are highlighted on the left and segmented facies in 3D on the right. Again, the facies are identified according to DECT values reported in Table 5, and coarse-grained clastic varves are in light blue, fine- grained clastic varves in fuchsia and RDL in green. The ruler on the left measures centimetres.

3D. In this test sample, the identification of RDL has interesting prospects as this facies was not unambiguously identified by other scanning techniques such as singleenergy CT scans and μ -XRF. It has an interesting palaeohydrological signature that could be useful in future palaeoclimate studies. Although this method is still in its infancy and more tests are required to better explore the combined effects of porosity and grain-size variations on the outcomes of DECT, this paper paves the way for a

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new approach in sedimentological studies.

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DATA AVAILABILITY STATEMENT

The Python codes allowing the performance of the DECT profiles of Z_{eff} and ρ_{e} (Figure 6) and the 3D volume reconstruction where the three different facies are identified (Figure 12) are available at the Dataverse repository: https://doi.org/10.5683/SP3/RRS4DO.

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