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Industrial X-ray computed tomography studies of lake sediment drill cores

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Abstract: An industrial X-ray computed tomography (CT) system was used for the study of sedimentary and deformation structures in weakly consolidated late Pleistocene and Holocene lake sediments. CT analysis revealed details of structures that could not be detected by X-ray radiography or visual core logging. Examples include sand dykes, dropstones and plant remains, which are potentially important in palaeoseismological and palaeoenvironmental research. The CT images also help to discriminate between drill core artefacts and natural structures. X-ray tomography was also used for the determination of physical properties, particularly for bulk density measurements based on calibrated grey-scale values.

X-ray computed tomography (CT) is a technique that is increasingly used for geological investigations (Denison et al. 1997; Ketcham & Carlson 2001). A general outline of its principles and application is given by Moore (1990), Wells et al. (1994) and Kak & Slaney (1998). CT allows the observation and analysis of internal structures without the need for manual serial-sectioning of samples, which is time-consuming, destructive and not appropriate for valuable specimens. Industrial CT systems are the preferred instruments for analysing large geological objects with high X-ray attenuation coefficients, because high-energy radiation can be used and a high spatial and contrast resolution is offered. In this paper, results are presented for the application of industrial CT for the study of lake sediment drill cores from northern Switzerland.

Method and scanner specification

The CT system of the Swiss Federal Laboratories for Materials Testing and Research (EMPA) is a medium-sized device that is particularly suitable for investigating geological samples. The 450 kV X-ray tube has the capability to penetrate up to 20 cm of sedimentary rock. The tube is highly stable and has a small optically effective focal plane. The achievable spatial resolution of the CT scanner is in the range of 0.5% to 1% of the object diameter. To minimize radiation scattering within the object and to achieve a high signal-to-noise ratio, the X-ray beam is collimated to a 2 mm thick fan.

The line detector consists of 125 cadmium–tungsten scintillators. A detector collimator made of tungsten reduces diffuse scattering reaching the scintillators and improves image quality. The collimator aperture can be set vertically and horizontally. A small horizontal aperture provides a high spatial resolution. The vertical opening determines the thickness of the investigated slice.

The object manipulator can handle samples that are up to 40 cm in diameter, 60 cm in height and 25 kg in weight. During the measurement, the object is rotated several times over 360° (fan beam mode). The higher the required spatial resolution the more rotations are needed to fill the gaps between the detector channels. If the object diameter is larger than the line detector, which is 25 cm long, the sample has to be moved back and forth several times in order to obtain the required projections (parallel beam mode). For image reconstruction, fast Fourier transformation (FFT) algorithms are used (filtered back projection).

The selection of acquisition parameter was different for the scans that are reported in the different parts of this paper: Lake Seewen (dropstone study) - 450 kV, 2 mA, no filter, 0.20 x 0.50 mm detector aperture, 600 x 800 pixels, 0.15 x 0.15 mm pixel size; Lake Seewen (sand dyke study) - 400 kV, 2.25 mA, 1.5 mm brass.
filter, 0.35 x 0.50 mm detector aperture, 800 x 500 pixels, 0.15 x 0.15 mm pixel size; Lake Bergsee (density study) – 150 kV, 6 mA, no filter, 0.35 x 0.75 mm detector aperture, 360 x 240 pixels, 0.25 x 0.25 mm pixel size.

Investigation of lake sediment drill cores

Two lakes in the Basle region, Lake Seewen in northern Switzerland and Lake Bergsee in southern Germany, were sampled. The drill core samples, with a diameter between 5 and 10 cm, were taken as part of a palaeoseismological research project searching for deformation features (seismites) related to strong pre-historical earthquakes, occurring in Holocene and late Pleistocene lake deposits. Earthquakes may create characteristic soft-sediment deformation structures, sand dykes and fractures or changes in physical properties of the sediment such as bulk density.

In addition to visual logging of the core samples, X-ray CT was used to identify features that are not visible to the naked eye. The core samples were first split parallel to the long core axis for visual logging and then scanned by X-ray radiography, followed by X-ray CT analysis. X-ray radiography was used as a first pass technique because it quickly and inexpensively provides information about the internal structure of the core samples and also helps to define intervals that are most interesting for CT investigations. All CT images presented in this paper are slices of half-cores scanned perpendicular to the long core axis.

Grey-scale value graphs along selected lines in CT images were used to clarify the nature of recognized features (Fig. 1). This is possible because grey-scale values are closely related to density, especially for sediments with a nearly uniform composition. Because EMPA’s industrial CT is not calibrated to Hounsfield Units, the (arbitrary) absolute grey-scale values are not indicated on Figure 1. The qualitative grey-scale curves help to clarify the nature of objects and their origin. The short lines A–B, C–D, E–F and G–H in Figure 1 mark the positions along which the grey scale values were determined, which are presented in the curves A–B’, C–D’, E–F’ and G–H’. The dark grey object along line A–B in Figure 1 showing grey-scale values in curve A–B’, which are lower than those of the surrounding silty sands but higher than those of air, is a piece of wood. In contrast, the white feature along line C–D, marked by higher grey-scale values in curve C–D’ and thus by a higher density than the surrounding silty sand, is a rock feature.
fragment embedded in fine-grained lacustrine deposits. The dark grey inclusion along line E–F could be an enrichment of plant chaff in a sandy clay silt layer, but the grey-scale curve E’–F’ identifies it as a hole, with a grey-scale value close to that of air. It is most likely an artefact, because layers with low cohesion are preferred sites of failure during core recovery or handling. Line G–H transects a sand dyke, which again was the site of a core failure creating a crack that follows the sand fill of the dyke, characterized by a high density and low cohesion.

Example 1: dropstones

Detailed investigation of the Lake Seewen sediments revealed several examples of mainly angular rock fragments with a size of up to 3 cm, embedded in the fine-grained lake deposits (Becker et al. 2000). Figure 2 shows three CT images with examples of angular, (a), or weakly rounded, (b), rock fragments, seen as light patches with a diameter of up to 13 mm, in a matrix of silty clay. The smaller, slightly rounded components indicate transportation of the fragments over short distances before deposition in the lake. In addition to the dropstones, large plant remains can be seen as dark patches in slice (b) and especially in slice (c).

The presence of large rock fragments in fine-grained lake deposits is not possible under normal lacustrine hydraulic conditions. However, transport of fragments of all sizes is possible by floating ice or wood. The occurrence of large rock fragments can therefore be related to: (i) the melting of icebergs derived from glaciers in an ice-dammed lake; (ii) the melting of the ice of a seasonally frozen periglacial lake covered with rock debris by spring floods or slope failures; or (iii) the decay of tree trunks and root bales that float on the lake surface.

Most of the dropstones in the Lake Seewen cores occur in late Pleistocene deposits and only a few (small) stones occur in the Holocene sediments. Because the Lake Seewen area was not glaciated during the Würm ice age, the most plausible origin of the dropstones is related to deposition of rock debris on the ice-covered surface of the seasonally frozen periglacial lake. However, transportation in root bales cannot be excluded, as indicated by the frequent co-occurrence of plant remains and dropstones.

Example 2: sand dyke

Figure 3 shows the most prominent sand dyke in the Lake Seewen cores. Visual logging of the core sample reveals a 52 cm long, vertical feature, which widens upward from about 1 mm to 4 mm width (Fig. 3, left hand column). It has an associated yellowish-brown alteration zone, which is most prominent in the upper half of the.
Fig. 3. Photograph (left), X-ray radiograph (centre) and representative CT images (right) of a drill core split along the long core axis, showing a 52 cm long sand dyke in lake deposits.
dyke where it is up to 30 mm wide, becoming narrower and less pronounced at depth. The sand dyke consists of pure calcareous coarse silt to fine sand. It rises from a 5 cm thick layer of silty sand to silty clay sand and passes upward through silty sands and sandy clay silts, which contain some dropstones and plant remains. The weakly developed layering in the surrounding lake deposits shows no offset across the sand dyke. The dyke changes in character when it reaches a thin silty sand layer at 23.5 cm, where it shows a lateral offset of about 2 cm reaching a maximum thickness of 8 mm about 4 cm above this level, at the highest point of its occurrence in the core. Below the continuation of the dyke, the silty sand layer shows a reduced thickness (Fig. 3).

In the X-ray radiogram (Fig. 3 central column) the onset of the dyke is clearly visible as a white line starting abruptly at 75.6 cm. In the middle of the core section, the dyke appears to split into branches, whereas in the upper section it can be hardly recognized except at the top left side of the core. X-ray radiogram reveals the layering of the surrounding lacustrine deposits, with also some dropstones and plant fragments.

Additional information about the structure of the sand dyke was obtained by CT scanning. 147 slices were scanned perpendicular to the long core axis, nine of which are shown in Figure 3 (right hand column, slices (a) to (i)). The sand dyke first clearly appears as a short, thin white line at the top left margin in slice (g), although a light grey inclusions in slice (h) could correspond to a lower occurrence. The sand dyke becomes wider from slice (f) to (c) and turns counterclockwise by about 25° in slices (d) and (e). In slices (a) and (b) the dyke is wider, less well confined and split into two branches. Slices (h), (g) and (b) show dark grey structures, corresponding to slightly irregular sand layers in cross-sections that are nearly parallel to the bedding.

The section of the dyke between 52 and 57 cm was scanned in some detail for 3D visualization (Fig. 4). 101 slices with a spacing of 0.5 mm were recorded, using a scan time of 11 minutes. The reconstruction shows dropstones and twigs, as well as layering disturbed by minor core drag along the tube walls. The sand dyke is a prominent feature, traversing the whole width of the core sample before it is cut abruptly by the core casing.

The CT slices and the 3D visualization show that the sand dyke is a planar structure and not a cylindrical de-watering or de-gassing tube (Guhrman & Pederson 1992; Neumann-Mahlkau 1976), or a root canal. The core casing cuts

Fig. 4. 3D visualization of a 5 cm high section of the core sample shown in Figure 3. The image has been created using the volume rendering technique.
the dyke abruptly and there is no relationship with the slight disturbance of the sediments near the edge of the core. We therefore conclude that the dyke is a natural feature rather than an artefact. The orientation of the dyke shows only minor variations, which is also observed for other sand dykes in the Lake Seewen cores (e.g. Fig. 2). Such a consistent orientation is another argument in favour of a geological origin (Rodriguez-Pascua et al. 2000). The dyke is rooted in a sand-rich layer, which shows peculiar structures that are similar to those described by Anketell et al. (1970) for unstratified sediments. As indicated by radiocarbon dates and pollen frequencies (Becker et al. 2000, 2002), the sand dyke was formed in an environment with low to normal sedimentation rates. It formed in a very shallow lake environment, as demonstrated by the occurrence of tube-like carbonate concretions (Magny 1992) and by the gastropod fauna. In addition, there are no indications of sub-aquatic slumps in the layers topping the sand dyke or a sudden increase in water level during emplacement of the sand dyke.

It is believed that the sand dyke has not formed from top to base as a Neptunian dyke: (i) the very 'clean' dyke fill containing only sand and coarse silt may indicate that clay and fine silt particles were washed out; (ii) the dyke is very narrow and shows no grading of the sediment fill; (iii) a sufficiently large source of sand is lacking at the top of the sand dyke; and (iv) the base of the sand dyke is connected to a sand-rich layer. Therefore, it is believed that the sand dyke was formed by the upward injection of sand facilitated by liquefaction and fluidization processes. A sudden increase of pore-water pressure in the water-saturated lake deposits, to a point which equals the confining pressure may have caused liquefaction of the sand layer at a depth of 76 to 81 cm. This caused instabilities in the sand layer, recorded by the irregular sediment structures around 76–76.5 cm and resulting in the injection of a sediment suspension into the overlying sediments. The increase of the width of the dyke from base to top may be explained by erosion or by a decrease in density of the confining sediments closer to the former water-sediment interface. However, it is believed that the dyke did not reach the former lake bottom. As soon as the density of the surrounding lake deposits reached the density of the water-sand suspension in the dyke, the injected silty sand started to intrude laterally, creating sill-like sand intrusions or sand pockets only a few centimetres below the water/sediment interface. Evidence for a sill-like intrusion is found in the increase in thickness of the thin sandy layer where the sand dyke shows a 2 cm lateral offset close to the top (Fig. 3, left column). Furthermore, patchy sediment structures can be seen where sand intruded laterally (Fig. 3, slice (b)), similar to those in the sand layer at the base of the dyke (Fig. 3, slices (g) and (h)). Alternatively, it is possible that the sand dyke could not pass through sediments along the former lake bottom, which were completely root ridden. However, there is no evidence in the sediments that would support this idea.

We believe that the formation of the sand dyke can be most easily achieved by strong earthquake shocks, which increases pore pressure in the slightly cohesive sand deposits at the base of the sand dyke to such a level that liquefaction can take place and, in addition, facilitate the opening of cracks for sand injection due to shearing. Contemporaneous structures such as mushroom structures, disrupted layers and fractures in the Lake Seewen deposits, together with the sand dyke described here, further confirm the occurrence of a strong prehistorical earthquake of a magnitude between $M \geq 5.5$ and $M \leq 6.5$ (Becker et al. 2002).

**Example 3: density determination**

Following Orsi et al. (1994) and Amos et al. (1996), CT data were used to determine the density of almost purely organic sediments (gyttja) to establish a high resolution density profile for the deposits of Lake Bergsee, southern Germany (Fig. 5). 3905 slices were recorded, with a slice distance between 2 and 5 mm and a 3 min scan time. The quality of the slices can be seen in Figure 5. The resolution is low and not really suitable for the investigation of structures, but it is sufficient for density determinations. For every slice, the average of the grey-scale values of 16 counting squares was determined for the undisturbed central part of the slice. For every core section the density of the sediments were determined conventionally by the Geotechnical Institute at ETH using a 5 cm thick sample. These density values were used to calibrate the grey-scale values for each core section.

The diagram in Figure 5 shows an example of the density determination for an approximately 9 cm long profile along a typical core section. The average density for all counting squares is indicated, as well as the maximum and minimum density. Slice 1 is a typical example of an almost homogeneous core section. Slices 2 to 4 include some single mineral grains and holes,
Fig. 5. Density profile of an approximately 9 cm long core section using calibrated grey-scale values determined by CT analysis (top), and four representative CT images (bottom), showing the effects of single mineral grains (white) and holes (black) on the density curves of a largely homogeneous organic lake deposit (grey).

recognized as light and dark patches, which influence the reported maximum or minimum densities. Because only few of these features occur, they do not strongly affect the average density values. No significant variations or trends in average density of the gyttja are recognized.

These measurements were carried out because gyttja, with its weak jelly-like consistency and very high water content, may have a structure that is susceptible to collapse following earthquake shocks. However, a general increase of the density which might have indicated such changes could not be found in the Lake Bergsee deposits.

Conclusions

Industrial CT has been applied to the investigation of sedimentary and deformation structures in lake drill cores. CT analysis, which is entirely non-destructive, is especially suited for the study of soft-sediment structures of this type.
It preserves (expensive) drill core samples for additional investigations and it is also a rapid method compared with classical methods based on thin section preparation.

High resolution CT images reveal various types of sedimentary structures in drill cores, which can be used for a palaeoenvironmental and palaeoseismological analysis of lake deposits. They also help to discriminate between drill core artefacts and natural structures, which is of special interest in palaeoseismological investigations using drill core samples. For the determination of physical properties of sediment samples, CT images with a lower resolution can be used. Calibrated grey-scale values supply continuous information about density variations in extremely thin core sections, which is a type of information that cannot be obtained by conventional geotechnical methods. In addition, the CT images supply direct information about the origin of the density changes, which is an advantage compared with classical methods of density determination for core samples using gamma ray radiography.

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