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The GIK-Archive of sediment core radiographs with documentation

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Abstract. The GIK-Archive of radiographs is a collection of X-ray negative and photographic images of sediment cores based on exposures taken since the early 1960s. During four decades of marine geological work at the University of Kiel, Germany, several thousand hours of sampling, careful preparation and X-raying were spent on producing a unique archive of sediment radiographs from several parts of the World Ocean. The archive consists of more than 18 500 exposures on chemical film that were digitized, geo-referenced, supplemented with metadata and archived in the data library PANGAEA®. With this publication, the images have become available open-access for use by the scientific community at https://doi.org/10.1594/PANGAEA.854841.

1 Introduction

During the late 1950s, the new field of marine geology was developed in Germany at the Geologisch-Paläontologisches Institut und Museum (Geological-Palaeontological Institute and Museum) at Christian-Albrechts-Universität zu Kiel (GIK), since 1998 known as Institut für Geowissenschaften (Institute of Geosciences). With the commission of the new German research vessel *Meteor* in 1964 and its maiden voyage in the Persian Gulf, GIK developed new techniques and assimilated existing methods to recover sediments from the ocean floor (e.g. Seibold, 1958; Werner, 1998). A simple but efficient gravity corer with a 12 cm diameter barrel and up to 1.5 t lead weight (*Schwerelot*) was constructed by the company Hydrowerkstätten Kiel. Piston coring technology was applied in the 1970s with the Kiel version of the former Kullenberg corer (Kullenberg, 1947). A vibrocorer supplemented the set of devices for sampling harder sediments. High-volume coring technology was performed by the kasten corer (*Kastenlot* by Kögler, 1963) with a rectangular size of 15 cm × 15 cm and length of 6.4 m for clay-like sediments. In the 1970s, a larger version recovered cores of 30 cm × 30 cm and lengths of 12–15 m, weighing up to 3.5 t. Besides the most commonly deployed gravity and piston corers, the kasten corer is also used due to its well-known ability to recover undisturbed and continuous sedimentary sequence for providing sufficient material to fulfil numerous interdisciplinary sampling demands.

To obtain an undisturbed sediment surface from the sea floor for the investigation of the sediment–water interface, the spade box corer was added to the suite of sampling devices (Reineck, 1963). The corer ensures that the pristine sediment succession is collected from the top of the seafloor surface. It was first employed for sampling deep-sea sediments during the *Meteor* cruise 25 in 1971. An extended large version of the spade corer with a box size of 50 cm × 55 cm was developed by Scripps and USNEL (United States Naval Electronic Laboratory) (Farris and Crezée, 1976). This type was modified and rebuilt by Wuttke GmbH (Henstedt-Ulzburg) to become the German *Großkastengreifer* (GKG). Since its first deployment in 1980 on RV

Meteor during cruise M60 (Thiel, 1982), it has been in use on most expeditions of German marine research vessels.

Schwerelot, *Kastenlot* and *Großkastengreifer* became valuable devices recovering large volumes of high-quality sediments, always providing sufficient material for X-ray sample preparation even for multiple sets of radiographies. For more than five decades, doctoral dissertations and publications of GIK have included radiograph interpretations, as described, for example, in Exon (1972), Werner (2002), Winn (1974, 2006), Wetzel (1979), Löwemark (2001), Hinz et al. (1971), Whitaker and Werner (1981), and Winn and Averdieck (1984).

2 Application of X-ray techniques in sedimentology

In radiography, the structural heterogeneity or homogeneity of an object is made visible by the different attenuation of X-rays on a photographic negative film. The resulting image is referred to as a *radiograph*, with the key quality parameters blackening, contrast and resolution. In the late 1990s, positive films were also exposed and interpreted. Applications of radiography are best known from medical and industrial studies, for example to verify the welding quality of steel products.

X-ray imaging on marine sediment cores was initiated at GIK around 1960 by means of a self-constructed device, which simply consisted of an X-ray source located in a shielded cabinet. In the early 1970s, the Faxitron cabinet X-ray system was invented by physicist Joseph Edmonds Henderson at the Applied Physics Laboratory, University of Washington (Faxitron, 2017). In 1974, Hewlett-Packard took over the product for use in manufacturing silicon chips. GIK applied the professional technology of the Faxitron model type 43855 (10 to 110 kV, 3 mA, size 84 cm × 55 cm × 51 cm, weight 176 kg) to the study of sediment slabs taken from marine sediment cores. Its use finally resulted in a comprehensive collection of large-format radiography (Werner, 1998). In marine geology, the Faxitron became the most frequently used device in X-ray imaging. The technology and preparation procedures of GIK as described below were subsequently adopted by various other sedimentology laboratories in Germany.

2.1 Preparation and exposure

Marine sediment cores are archived in segments of 1 m in length for convenient handling and cut longitudinally in two halves for further processing. (This is not required for box and kasten cores, where samples are taken from the outer side.) After photography and a visual lithological description of the sediment sequence (structure, texture, colour), the "work" half is sampled for various analyses, with the preparation of X-ray slabs being the first step of the sampling workflow (Grobe, 1986; Fig. 1). It was common practice first to prepare sediment slices for radiographs and use the exposure as a guide for further sampling, in particular across strongly bioturbated sections. The remaining "archive" half is sealed in airtight D-tubes for future investigation. As a common practice in geological repositories worldwide, the core segments are archived in repositories at +4 °C.

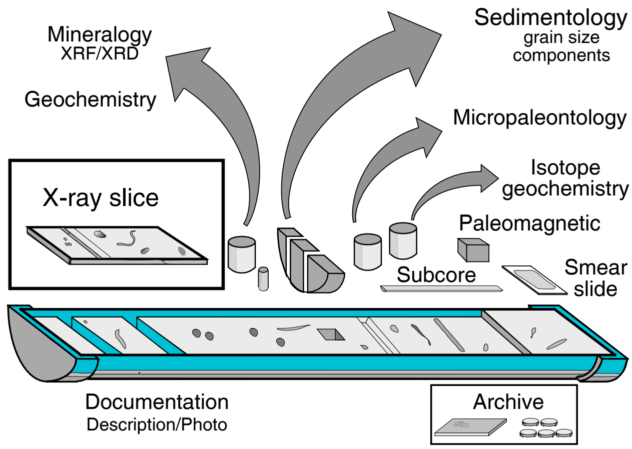

Figure 1. Standard sampling workflow for the investigation of sediment cores as developed at GIK. The first step during the sampling sequence was the preparation of sediment slabs for X-ray imaging along the core profile.

To ensure optimum quality of the X-radiograph, sediment slices have to be prepared with the utmost care so as not to destroy the original sediment structures and to avoid artefacts. The surface of the longitudinal core half is smoothened with a wet glass plate, eliminating the grooves and furrows on the sediment surface usually caused by larger sediment particles. A hard Plexiglas® lid measuring 25 cm × 10 cm × 1 cm is pushed gently into the level surface of the working half to provide support and stability for the sediment slab (Fig. 2). Core label, depth interval and an arrow pointing downwards in the direction of penetration of the coring device are then marked on the lid (in reverse chronological order, in contrast to the convention at other research institutes and programmes, such as the International Ocean Discovery Program). A kasten core typically prepared for the sampling of X-ray slabs is shown in Fig. 3. The slab within the lid is separated from the remaining core by pulling a nylon line up-core behind the plastic lid, thereby using the two sides of the lid orientated parallel to the core axis as guides. The slab is carefully lifted with a cheese knife and removed from the core. The slit may be moistened if the slab tends to adhere to the main sediment core. The slices in the lids are vacuum sealed in polyethylene lay-flat tubing after evacuation of the enclosed air. The equipment used for the preparation is shown in Fig. 4. It is important to note that the X-radiograph technique is non-destructive and that – after X-raying – the sample material could be used for further analyses.

Figure 2. Sediment slab (25 cm × 10 cm) stabilized in Plexiglas lid ready for X-raying. Top of core is to the left.

Figure 3. Sediment core taken with a kasten corer (30 cm × 30 cm) prepared with Plexiglas lids to remove the samples for X-raying.

X-ray film is coated on both sides and thus has higher sensitivity and contrast compared to film used in light photography. For exposure the film type Structurix D 4 manufactured by Agfa-Gevaert was chosen. The film is not sensitive to red light and thus can easily be handled in a darkroom under low-light conditions. The film is cut into 25 × 10 cm strips and stored in black film covers. Each 25 cm long slab is exposed to the X-ray beam with the slab surface not covered by the lid facing the X-ray source (Fig. 5).

The characteristics of the X-radiation determine the quality of the sediment images, with the wavelength being the most important factor. High energy will produce "harder" radiation with shorter wavelength while lower energy will result in radiation with longer wavelength. Due to the soft composition of unconsolidated sediments, a spectrum of longer wavelengths and thus "weaker" radiation is preferred to produce images with a moderate contrast (Werner, 1975).

Exposure times depend on sediment type and are mostly controlled by grain size and compaction, the thickness of the slab and the strength of the radiation. A 1 cm thick slice has to be exposed for a time span from 3 (soft clay) to 20 min (high sand content) at a voltage of 30–35 kV and an electrical current of 3 mA. Identification of the core ID and the depth interval on the negative is assured by putting corresponding lead letters and numbers on the film during exposure. The film is developed in a darkroom for 3 min by using the devel-

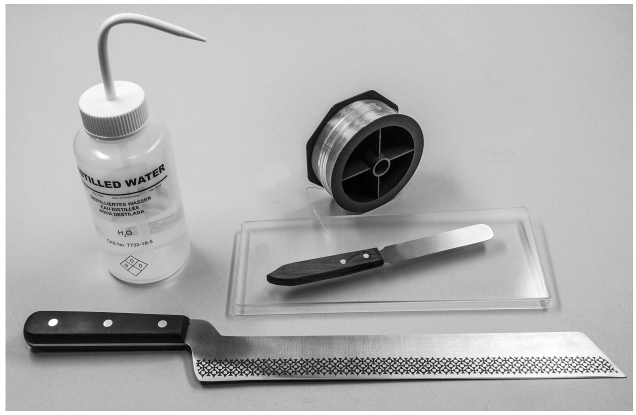

Figure 4. Equipment used for the preparation of sediment slabs for X-ray imaging comprise fishing line, distilled water, cheese knife, spatula and special Plexiglas lids for support of the sediment slab. Lids used for preparation measure 25 cm × 10 cm × 1 cm (Bensberger Kunststoffwerk Lappe GmbH). Lay-flat tubing and sealing device (not shown) are used to protect the sample from drying.

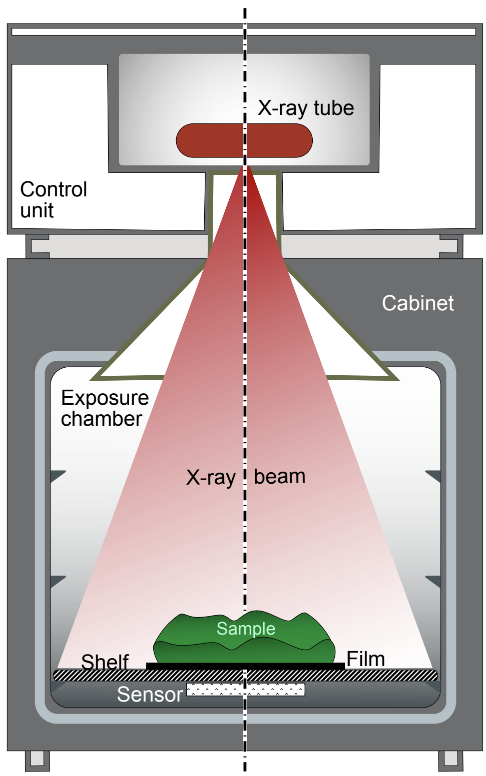

Figure 5. Schematic drawing of an X-ray device of the FAXITRON series (Hewlett-Packard), which has an upper chamber for the X-ray tube with a control unit and an exposure chamber below (Faxitron X-ray Corporation, 1975). X-ray cone is shown in red. Both are fully lead shielded allowing for operation under normal laboratory conditions without special protection of registration. The sensor below the sample shelf can be used to set automatic exposure times. In modern digital operation mode, shelf, film and sensor are replaced by a scanner sensitive to X-ray beams.

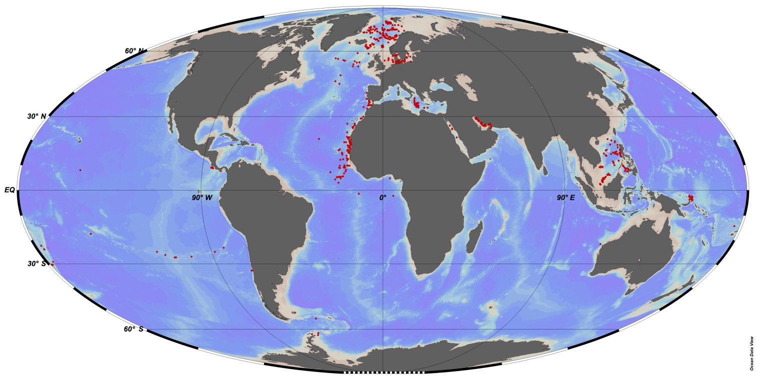

Figure 6. Map showing the locations of marine sediment cores, from which X-radiographs were obtained as part of the GIK-Archive. The cores were collected between 1965 and 2000 on a total of 93 expeditions. The cores are listed in table in https://doi.org/10.1594/PANGAEA.875415.

oper G124 and the fixer G335 (Agfa), washed for 20 min in distilled water and dried. A detailed description of the procedure can be found in Werner (1975).

Over 50 years of marine geological research at GIK, a suite of 1355 sediment cores with a total length of 3547 m were investigated (Fig. 6). More than 18 500 sediment slices were prepared for X-ray imaging and exposure. Between 2010 and 2014 the images were transferred to the PANGAEA department at the Alfred Wegener Institute for Polar and Marine Research, Bremerhaven (AWI). They were digitized at a resolution of 600 dpi by a transmitting light scanner (Microtek ScanMaker 9800XL). The X-radiographs, photos and descriptions were supplemented with the metadata of the corresponding cores including position, water depth, sampling device, expedition, date/time, ship, etc. The resulting collection of 1355 datasets was combined into a single parent dataset, which is available at https://doi.org/10.1594/PANGAEA.854841.

2.2 Analysis of images

Besides the documentation by light photography, X-radiography became a standard imaging technique in marine geology to complement and support the visual description of sediment profiles, which comprises the detailed logging of the lithological composition of the sediment, its texture and sedimentary structures (Bouma, 1969). In particular, radiographs reveal details of structures, such as bioturbation and graded bedding, diagenetic modifications and large internal components (e.g. fossils or dropstones) which are not discernible in normal light photography.

The dominant control on beam attenuation is bulk sediment density (Holyer et al., 1996), which in turn is affected by grain size, mineralogical composition, abundance of biogenic components and physical parameters such as water content, porosity and compaction. Thus radiographs can be used to determine a whole range of various sediment properties. During examination of the images, some specific points need to be considered. These are described in brief in the following examples of typical sedimentary textures as shown in Fig. 7.

Structures that may be unrecognizable to the naked eye include boundaries of strata, non-conformities, fine lamination, graded bedding and most importantly – bioturbation (Werner, 1968; Winn, 1974; Wetzel, 1979). *Lebensspuren* are the most common structures in marine sediments which allow the identification of the species and the reconstruction of paleoecological and paleoenvironmental conditions (Löwemark, 2001). The resulting taxonomy of palichnology is the basis for its identification and classification (Bromley, 1999; Seilacher, 2007). Sedimentological sequences formed by distinct processes (e.g. deposition by turbidity or contour currents) and their evolution over time are also part of this structural group. Features such as base and top boundaries, type, thickness, frequency, rhythms and cycles indicate facies differentiation and changes.

Physical properties can be identified by the brightness of the negatives, as well as by internal structures such as layering (e.g. ash layers), lamination, bedding planes, cross-bedding, current ripples or sorting. By using a magnifying glass while investigating the X-ray image, individual grains with a size of > 1 mm can be classified in terms of grain shape and composition. Support of a high-resolution sedimentology is given in the millimetre to centimetre scale, including large components such as mud clasts or gravel grains, e.g. as ice-rafted debris (Grobe, 1987; Principato, 2004). Any gravel fraction reveals itself by the distinct appearance of each individual grain.

Extracted high-resolution greyscale curves were correlated with physical parameters (colour, gamma-ray density, magnetic susceptibility, grain size; St-Onge et al., 2007; Kowalczk, 2005). There is a clear relationship between grain size distribution and brightness/blackening of the film. Sandy to clay-like sediments are composed of just a few minerals (quartz, feldspar, clay minerals, carbonates), all of which have a similar specific grain density of 2.6 to 2.8 $g\,cm^{-3}$. Diatomaceous oozes may result in nearly black X-radiograph negatives because of the low density of opal. Thus, differences in brightness result mostly from changes in grain size rather than from a heterogeneous distribution of minerals. Water content, density and porosity are the major factors governing greyscale values; porosity increases from coarse-grained to fine-grained sediments. The sediment density and thus the brightness of the image negative increases with core depth because the compaction results in reduced pore space and water content.

Minerals may result from diagenesis including authigenic pyrite, zeolite, or the rarely formed porcelanite (Gerland et al., 1997). Heavy minerals such as pyrite and other iron sulfide as well as iron oxide minerals can easily be identified by their high brightness/X-ray attenuation and their specific grain shapes and internal structures. However, dark grey features visible in negatives can be areas with an extremely high water content, plant fossils, wood or even small voids. In cases where the samples were stored for a longer period, new minerals may have formed through chemical processes in the sediment (e.g. as per Fig. 6g).

Artefacts reflecting the post-depositional disturbance of the original sedimentary structure must be identified within the core. These effects can have various causes which should always be considered while investigating and interpreting the images (Skinner and McCave, 2003). During the coring process and recovery, especially with a gravity, kasten, piston or vibrocorer, the mostly soft and often "soupy" sediments from near the seafloor surface (i.e. at the core top) may flow, resulting in a loss of the original structure. In some instances it is not even possible to prepare a sediment slab suitable for X-radiography from the upper decimetres of the core. Coring disturbance caused by the piston or gravity coring process may result in "pseudo-tectonic" features (e.g. faults, fractures, sediment mixing, "flow-in") which are predominantly observed at the bases of longer piston and gravity cores. In particular, gravity coring can cause micro-faulting within the sediment and result in an artificial shortening of the sediment column (Fig. 6c). Especially in clay-like sequences, even pseudo-hiatuses can occur when parts of a sediment section succession allow the core barrel to pass but are squeezed out and thus not recovered. In addition, the outer edges of a core segment may show downward bending of layers in close proximity to the core liner, which results from the friction between the liner and the sediment when the core barrel penetrates the seabed.

Further effects visible in radiography might include the following: if the sediment slice is not properly sealed in lay-flat tubing it may dry out and produce drying cracks, which can, however, be clearly identified. If a sediment slice has a variable thickness, the brightness of the X-radiograph will vary throughout the sample. If the sediment contains larger particles, the marginal areas around the particle may be disturbed during the preparation. Regular stripes and patterns observed also on an X-radiograph are usually the result of insufficient smoothening of the slab surface and reflect tracks from the cutting wire. The projection also has to be taken into account during analysis: structural elements of a three-dimensional slice are projected in two dimensions onto the film. A 1 cm thick slab sample for X-raying does not work well for gravel- and pebble-rich sediments (such as diamic-

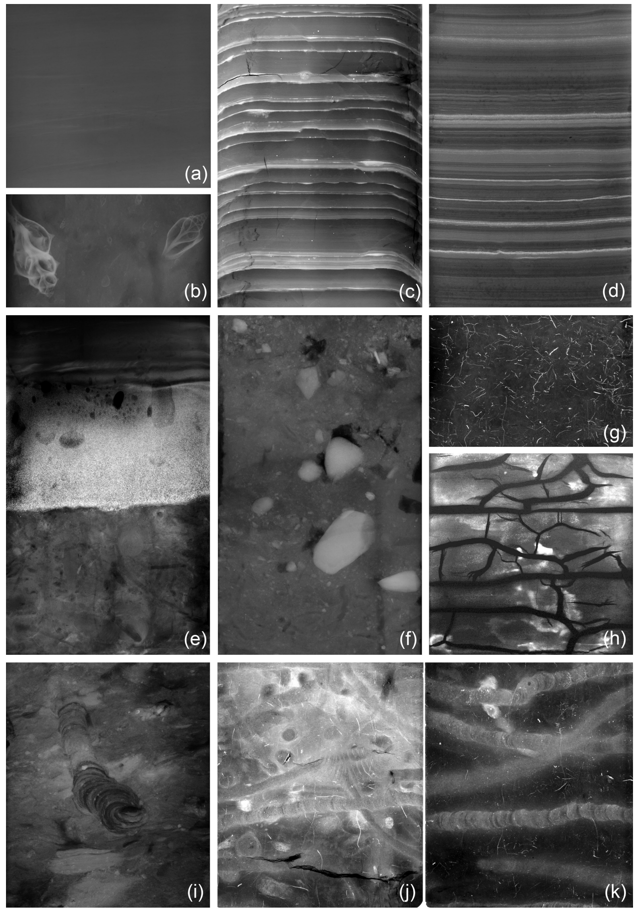

Figure 7. Examples of various X-radiographs from the GIK-Archive. Each has a width of 10 cm. **(a)** Homogeneous clay-like sediment, Mediterranean Sea, https://doi.org/10.1594/PANGAEA.720925; **(b)** fossil molluscs, Persian Gulf, https://doi.org/10.1594/PANGAEA.720253; **(c)** interbedded strata with artificial down-bending of layers and fault lines as a result of gravity coring, Baltic Sea, https://doi.org/10.1594/PANGAEA.690661; **(d)** laminated sediment, Red Sea, https://doi.org/10.1594/PANGAEA.720616; **(e)** turbidite with graded bedding, South China Sea, https://doi.org/10.1594/PANGAEA.720737; **(f)** gravel as ice-rafted debris, Norwegian Sea, https://doi.org/10.1594/PANGAEA.720368; **(g)** pyritized lebensspuren, West Atlantic – off Senegal, https://doi.org/10.1594/PANGAEA.705737; **(h)** artificial cracks from drying out of an unprotected sediment slab, https://doi.org/10.1594/PANGAEA.705491; **(i, j, k)** examples of bioturbation, Baltic Sea off Flensburger Förde, https://doi.org/10.1594/PANGAEA.705626 and African continental slope, https://doi.org/10.1594/PANGAEA.705737.

tons), and thus X-raying of half cores works better for those sediments. However, X-raying of half cores has its own problems, especially overlaps and projection issues.

3 Archiving

The X-radiographs archived at GIK were taken from 1355 globally distributed sediment cores recovered on 93 voyages of the German research vessels *Wattenberg*, *Alkor*, *Littorina*, *Poseidon*, *Meteor* and *Sonne*, mostly on expeditions between 1964 and 2000 (Fig. 4). For the list of cores with metadata, please refer to https://doi.org/10.1594/PANGAEA.875415, linked as "Further details" to the parent set. RV *Sonne* cores collected on behalf of the Preussag manganese nodule project and BGR-led (Bundesanstalt für Geowissenschaften und Rohstoffe, Hanover – Federal Institute for Geosciences and Natural Resources) cruises to the equatorial and South Pacific were also sampled and analysed. Most of the remaining material is available in the core storage of GIK and at the Lithothek of GEOMAR Helmholtz Centre for Ocean Research Kiel.

Image digitization and archiving

More than 18 500 exposures of X-radiographs were digitized using two A3-format scanners, model Microtek ScanMaker 9800XL, at a resolution of 600 dpi and stored in JPEG format with moderate compression to generate file sizes for convenient Internet download times. Not all images were post-processed and thus some may still be underexposed. Brightness, lucidity and contrast can be corrected as required for investigation with any image processing software. The full information is in each image due to the high-resolution scan of the fine-grained film. Images were uploaded to PANGAEA and stored in a database. One dataset includes all images of one core. Metadata and additional documentary files including core descriptions and photos were added, if available. The metadata cover core ID, latitude and longitude, water depth, recovery, coring device and date/time when the core was taken. The label of the expedition linking to the cruise report (if published) is also provided. Each dataset starts with a "Citation" tagged line, consisting of the name of the principal investigator(s), a standard title "Documentation of sediment core GIKxxxxx-x", year of electronic storage and thus public availability, and the source institute (in this case always set to GIK). The DOI as a persistent link to the dataset is a mandatory part of any modern citation. If the images were already used in publications, the corresponding references can be found under the "Related to" field. Selected examples of images from this collection are presented in Fig. 7.

4 Data availability

The GIK-Archive of radiography is available at https://doi.org/10.1594/PANGAEA.854841.

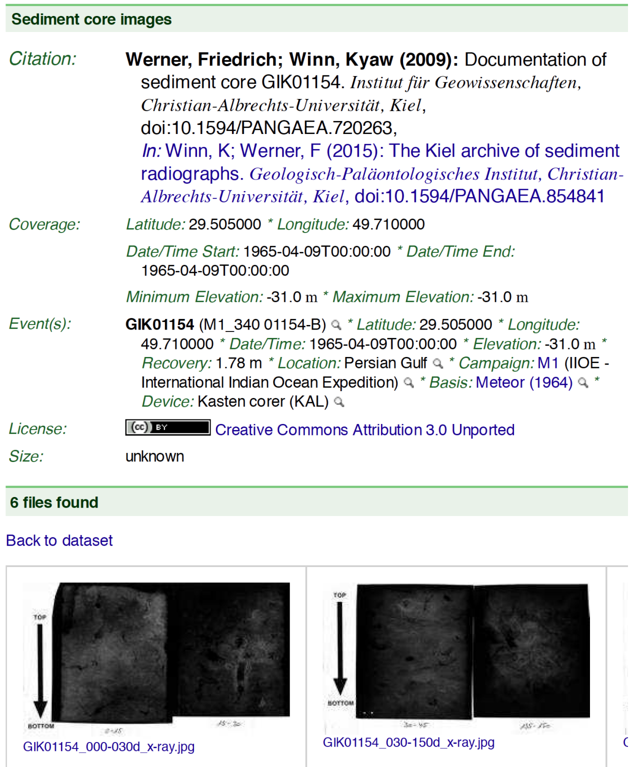

Figure 8. Example of the standard metadata header provided by PANGAEA from dataset https://doi.org/10.1594/PANGAEA.720263. Starting with the citation, comprising author(s), year, title, source and DOI. Citation is followed by the georeference in space and time and links to further references or reports. For this collection, images of each core location have their own data subset. The total of 1355 data subsets of this paper are grouped together in one "parent" dataset (https://doi.org/10.1594/PANGAEA.854841). At the end of the metadata header, each image is shown as a thumbnail and can be downloaded either individually or as part of a compilation of all images in a single zip archive.

With the establishment of polar research through the foundation of the Alfred Wegener Institute for Polar Research (AWI) in 1980 in Bremerhaven, the methods of sediment core sampling and analysis developed at GIK were utilized and adopted by the department of marine geology at AWI (Grobe, 1987). All geological sample material taken aboard RV *Polarstern* was archived in an institutional core repository, administered by a database. Between 1987 and 1997, this system was further developed, in part driven by an initiative of the German National Climate Project of the BMFT in 1994. It finally became an archiving and publishing system for data from earth system research, namely PANGAEA® – Data Publisher for Earth and Environmental Science (Diepenbroek et al., 2002). Technically PANGAEA is a relational database (RDB) with geo-reference in time and space for a consistent storage of analytical and observational data. A storage system (tape robot) for files and binary objects such as images assists the RDB. For single items or collections of files, only the metadata are stored in the relational tables of the data model, including stable links to the image files on tape (Fig. 8).

PANGAEA provides its content not only for direct download from its website (http://www.pangaea.de) but also for data harvesting. Besides standard search engines, the image datasets are also distributed via web services through library catalogues, e.g. WorldCat and a number of portals (listed at http://wiki.pangaea.de/wiki/Portal). Most images of a core can be found easily via the PANGAEA query window or even via an Internet search engine by using the (unique) core label as a search phrase. The requested dataset is usually listed among the first search results.

Metadata of PANGAEA are routinely mirrored in DataCite (reference http://data.datacite.org), which is the central entry portal for citable research datasets on the Internet. This information is also stored in the catalogue of the German National Library of Science and Technology (reference TIB), co-inventor of the data DOI and co-founder of DataCite. Since 2004, PANGAEA has provided its content for OAI-PMH harvesting (Open Archives Initiative – Protocol for Metadata Harvesting). The current operator is OCLC (https://www.oclc.org) with WorldCat (https://www.worldcat.org), which incorporates the content of repositories following the OAI standard and thus also includes the metadata of the PANGAEA content.

5 Conclusion

With this publication, the complete digitized archive of more than 18 500 radiographs from the World Ocean has been made available to the scientific community. This dataset is publicly available under the CC-BY 3.0 licence (https://creativecommons.org/licenses/by/3.0/) with a persistent identifier (https://doi.org/10.1594/PANGAEA.854841) as the Supplement to this publication.

Although X-ray imaging is a method well-suited to supplementing the documentation of sediment cores, this technology has been increasingly neglected in some parts of the scientific community because it is time-consuming and new high-resolution analytical techniques (e.g. multi-sensor core logging, X-ray fluorescence and colour scanning) have been continuously introduced and gained priority over the last couple of decades. In addition, digital X-ray images of sediments can now be taken very quickly both on-board and in the lab (e.g. with the ITRAX XRF scanner; Croudace et al., 2006). For the old FAXITRON models a digital X-ray scanner is now available to fit in (NTB, 2005). The time of analogue X-ray imaging of sediments is over and will now continue with digital X-ray devices and X-ray computed tomography (CT) systems (e.g. Freifeld et al., 2006).

Competing interests. The authors declare that they have no conflict of interest.

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This article with its supplementary image collection is dedicated to co-author Friedrich Werner, head of the sediment core sampling laboratory and core curator at GIK for more than 40 years, who passed away in 2012.

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