Unlocking national treasures: the core scanning approach

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Abstract: Drill core is a vital resource for subsurface characterization and informs process understanding. However, it is expensive to collect and, as a result, the geoscience community increasingly relies on data from legacy core to address today's energy challenges. Many countries store geological materials collected over decades in national archives. In the UK, over 600 km of drill core is currently stored at the UK national core repository, which covers a breadth of the UK's geology, including those targeted for resources, energy and waste storage. The challenge is to maximize the value of these analogue archives and new core when deposited – improving access to materials and associated data, whilst simultaneously maximizing preservation to ensure optimized use, now and in the future. This paper summarizes the BGS approach to characterize drill core more efficiently and consistently using a multiple-technique core scanning approach set within a project-specific core scanning workflow to increase core data acquisition and complement traditional core characterization practices. Thus, creating a digital record of the core, preserving it beyond its physical lifetime and improving accessibility. This paper highlights the benefits and challenges of this long-term endeavour, especially in making the data open access and discoverable.

Much of the current understanding of the UK's subsurface results from onshore and offshore hydrocarbon and coal exploration datasets. These include seismic surveys, borehole images, geophysical wireline logs and drill cores collected over the past decades. Of these methods, only drill cores provide an opportunity to directly measure subsurface properties and are vital for ground truthing information derived from other methods and other scales. This makes their detailed and consistent characterization important to many subsurface studies (e.g. Andrews 2013; Monaghan *et al.* 2016; Stephenson *et al.* 2019).

The importance of core archives to ongoing subsurface usage is demonstrated by the existence of National Core Repositories, such as the National Geoscience Data Centre (NGDC) in the UK (https://www.bgs.ac.uk/), the Norwegian Petroleum Directorate Repository in Stavanger, Norway (https://www.npd.no/en/); and the South Australia Drill Core Reference Library in Adelaide (https://www.energymining.sa.gov.au/industry/geological-survey/drill-core-reference-library). Because of the high cost of drilling, many countries have legislation requiring the deposition of core and samples from research and commercial exploration with a national repository. In the UK, the Mining Industry Act 1926 requires the intention to drill any minerals boreholes deeper than 30 m to be notified to the NGDC. The Reporting and Disclosure of Information and Samples Guidance (NSTA 2021) made under the Energy Act 2016 Retention Regulations gives detailed specifications for the hydrocarbon well samples that must be submitted to the NGDC (pp. 21–25). Similar legislation is present in many other countries, e.g. Nigeria – Nigerian Minerals and Mining Act (2007).

National Core Repositories have three important uses:

(1) They underpin national reports, publications and maps, enabling existing observations to be repeated and therefore tested.
(2) They provide a resource for further research. Many research projects had insufficient funding for dedicated boreholes but can repurpose samples from existing archived material. This approach has the added benefit of progressively building on the existing characterization and research.
(3) They provide a resource for de-risking and therefore enabling commercial exploration. Owners of adjacent licences, or new owners of existing licences, can re-examine existing material at a fraction of the cost of drilling new.

Most of the drill core for the UK and UK Continental shelf (UKCS) is archived at the NGDC, co-located at the British Geological Survey (BGS) in Keyworth. There are currently over 600 km of core archived within the NGDC, covering a huge range of lithologies, depths, ages, conditions and regional areas (Fig. 1). However, much of the value of the resource is constrained by access, person time and the

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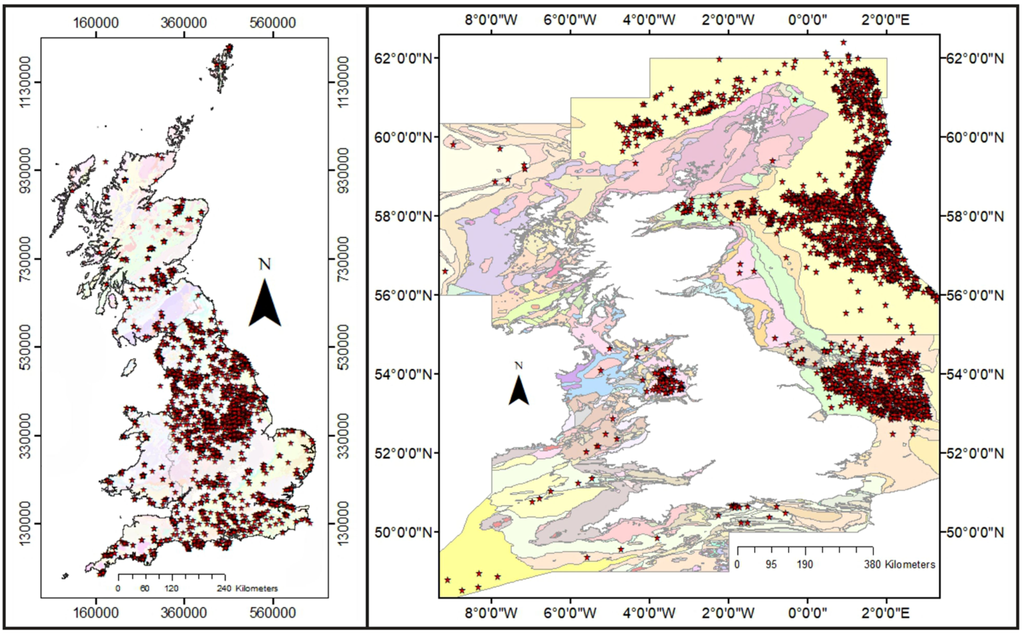

Fig. 1. Bedrock geology map showing the locations of boreholes across the UK where core is held by the NGDC. Left: Onshore boreholes, coordinates in British National Grid. Right: Offshore boreholes, coordinates in WGS1984. Source: contains Ordnance Survey data © Crown copyright and database right 2022.

availability of means to describe and characterize it efficiently and consistently. Current access to the core requires travel to the BGS Keyworth site and each user will have a different purpose for viewing and sampling core, resulting in competing demands and requirements. Even when sampling occurs or other core data are collected it is not always easy to find, integrate and rationalize the outputs. There is often a disconnect between continuous core and other subsurface datasets (i.e. wireline geophysics). Other studies have identified a paucity of both borehole geophysics and seismic surveys (Ireland *et al.* 2021). This leads to a lack of available datasets to correlate and consistently characterize the subsurface. To begin to address this point it is crucial that data collected from national collections conform to the FAIR data principles (Findable, Accessible, Interoperable, Reusable; Wilkinson *et al.* 2016).

Another aspect where challenges remain when dealing with drill core is the prioritization of data collection. For example, there may be tension between destructive analysis (sampling) and non-destructive analysis (logging). For some studies it becomes critical to rapidly sample the core after extraction to avoid drying out and/or alteration, i.e. claystone (e.g. Conil *et al.* 2018). Standard destructive rock core sampling and measuring methods can only be applied at low sampling resolution and they reduce the volume and quality of core available to be characterized by other means. Hence, those methods only provide a snapshot of the rock properties and are, at best, semi-representative of the whole volume of rock. These samples are, however, essential to understanding of rock behaviour such as unconfined compressive strength, porosity and permeability, hydro-mechanical behaviour, and fluid–rock interaction (e.g. Dobbs *et al.* 2018; Worden *et al.* 2020; Payton *et al.* 2021).

Despite this, drill core remains the only physical sample of the rock unit that can be analysed, tested and viewed providing vital information on rock properties and behaviour that will inform subsurface processes. Therefore, it is crucial to extract as much information as possible from core, especially considering the great investment and efforts needed to collect it in the first place. New technologies are exponentially increasing our abilities to log and analyse core and non-destructive analytical techniques are now widespread, providing us with means to efficiently, rapidly and consistently analyse any solid material with limited sample preparation at macro to micro resolution (e.g. Mees *et al.* 2003; Tappert *et al.* 2011; Vasiliev *et al.* 2011; Fresia *et al.* 2017; Shreeve *et al.* 2017; Croudace *et al.* 2019; Fellgett *et al.* 2019; Tuşa *et al.* 2019; Smith *et al.* 2020; Lee *et al.* 2021).

This paper discusses the importance of these non-destructive semi-automated tools to increase core data acquisition and complement traditional core characterization practices. It highlights the approach taken by the BGS to characterize core using a set of multi-property core scanning techniques within a defined core characterization workflow to maximize the utility of existing and new drill core. The core scanning workflows can be adapted to specific project needs and requirements, as demonstrated by the two case studies outlined in this paper. This approach will lead to an increased demand for access to the core and core-derived data, whilst also maximizing digital outputs, data availability and interoperability. It will help to provide the data needed to guide strategic core logging and sampling parties, and to bridge the gap between downhole logging and point sampling measurements.

The core scanning approach

Technologies for core scanning allow for non-destructive, consistent and relatively rapid core property analysis and high-resolution core imaging. The aim of these semi-automated tools is to improve acquisition and consistency of data from drill core. Core scanning provides a fast and straightforward way to begin assessing the core properties guiding investigations toward a more detailed analysis of target areas. Common analytical techniques (Table 1) include core photography, colour spectrophotometry, X-ray fluorescence (XRF) handheld and instrument systems, radiography, computed tomography (CT), hyperspectral core imaging and geophysical-property core logging systems mounted on track systems to ensure consistent sampling intervals and acquisition parameters.

During the past fifteen years, an increasing number of geological repositories have invested in core scan technologies. They fall into three broad subdivisions with differing strategic aims and drivers:

(1) Facilities digitizing cores to promote national and international investment in the country's mineral and hydrocarbon resources. Good examples of this are demonstrated in Australia and Sweden. Initiated in 2008, the National Virtual Core Library (NVCL), Australia, is the world's largest drill core mineralogical database, freely accessible to users anywhere in the world with over 192 km of scanned core. NVCL's hyperspectral image scans are available via the AuScope Discovery Portal (AuScope 2019). During 2014, the Geological Survey of Sweden (SGU) started a project to scan 200 km of drill core at SGUs drill core archive in Malå (total collection 3000 km from 18 000 boreholes). Included in the assignment is high-resolution optical photography and hyperspectral infrared imaging (Geological Survey of Sweden 2020). In Finland, a commercial operator has used a mobile XRF scanning laboratory in the Geological Survey of Finland's national drill core store in Loppi to scan some of the 3000 km of core for training and research purposes (IMA 2017). The stated intention is to digitize more core to attract investors to Finland.

(2) Facilities digitizing cores to provide data to assist research projects. Many core repositories and research institutes provide this service. Good examples include the British Ocean Sediment Core Research Facility (BOSCORF) and the International Ocean Discovery Program (IODP) Bremen Core Repository. BOSCORF hosts the UK's most comprehensive suite of core logging and scanning facilities alongside the national deep-sea core repository set up by the Natural Environment Research Council (NERC) to store and curate marine sediment cores collected by NERC-funded research projects. BOSCORF aims to preserve and log/scan sediment core routinely, making it available to scientists and thereby promoting secondary usage amongst the scientific community (https://boscorf.org/about);

(3) The IODP Bremen Core Repository (MARUM), established in 1994, currently holds more than 158 km of deep-sea cores from over 90 expeditions, and has a similar remit through collecting and preserving marine core for the international geoscience community (https://www.marum.de/en/Research/IODP-Bremen-Core-Repository.html).

(4) Commercial facilities providing services predominantly to private and industrial sectors, e.g. oil and gas, mining. Good examples include CoreLab and Geotek Limited. Corelab have laboratories in Houston, Calgary, Rotterdam, Aberdeen, Abu Dhabi and Kuala Lumpur and offer specialist reservoir assessment services including various laboratory instrumentation for the petroleum industry (https://www.corelab.com/). Geotek is a service consulting engineering firm specializing in high-resolution, non-destructive analysis of geological cores through the use of their Multi-Sensor Core Logger (MSCL) platforms (https://www.geotek.co.uk/services/core-loggingscanning/).

In 2018, a new state-of-the-art Core Scanning Facility (CSF) was setup at the BGS Keyworth site, co-located with the NGDC and other analytical laboratories at BGS. The CSF was initially envisioned in 2010 as part of the survey's long-term strategy

Table 1. *Core scanning techniques*

Analytical technique	What does it measure?	How ares the data used?
Photography	• High-resolution optical images • 2D and 3D • Tens of micrometres	• Digital record • Quality assessment • Stratigraphic correlation • Sedimentary logging
Spectrophotometry	• Absorbance, reflectance, and transmission of light • Millimetres	• Colour quantification • Sedimentary logging • Core-to-core correlation
Radiography and laminography	• Map of X-ray attenuation • 2D and 3D information • Tens of micrometres	• Structural characterization • Quality assessment • Heterogeneity • Discontinuity/engineering logging • Analysis of geological features • Dip and orientation of beds
Computed tomography	• Cross-sectional X-ray images • Nano- to micrometres	• Structural characterization • Quality assessment • CT analysis and simulations (e.g. pore space, grain segmentation, fluid-flow, fracture network)
Hyperspectral imaging	• VisNIR – visible and near-infrared (400–1000 nm) • SWIR – short-wavelength infrared (1000–2500 nm)	• Mineralogical characterization • Mineral mapping • Spectral analysis • Clay and carbonate content quantification
Ultraviolet fluorescence imaging	• UV – ultraviolet (100–400 nm)	• Hydrocarbon distribution • Fluorescent mineral identification
Thermal imaging	• IR – Infrared radiation (700–1000 nm)	• Hydrate distribution
X-ray fluorescence (XRF)	• Bench-systems or portable XRF • Elemental abundances • Profile and/or map scan • Sub-millimetres	• Geochemical characterization • Heterogeneity • Elemental ratios as proxies for depositional/environmental conditions • Elemental maps • Provenance assessment • Core-to-core correlation
Geophysical core logging	• Gamma ray attenuation • Acoustic velocity • Magnetic susceptibility • Resistivity and conductivity • Natural gamma spectrometry • Millimetres	• Geophysical characterization • Quality assessment • Lithological and textural determination • Core-to-log integration

for improving access to its information and data by digitization and online delivery. Whilst the high-resolution photographs of the UKCS cores taken in 2011–12 quickly became a significant resource for academics and commercial organizations, it was also clear that core scanning techniques could provide additional online datasets that would improve access and increase the utility of the core archive. The hyperspectral imaging of the core archive in South Australia is a good example of a national/state core repository achieving this objective (Stromberg *et al.* 2021).

The CSF was strategically placed within a wide range of laboratories and other facilities at BGS, many of which provide complementary analyses and outputs. The CSF facilitates the development of analytical datasets that enable core-derived data to be effectively integrated with geophysical borehole logs, seismic data, and visual descriptions derived from direct observation of core, which are available via the BGS Geoindex, UK Onshore Geophysical Library for onshore data and National Data Repository for offshore data. These continuous analytical outputs create a medium whereby other data collected through discrete sampling and analyses (e.g. mineralogy and petrology, mechanical properties) may be integrated with volumetric methods (i.e. seismic). This, in turn, enables researchers to move between the micro (<10^{-4} m) and the macro (>10^3 m) scale.

The CSF combines four main core scanning techniques to profile a set of multi-property core characteristics, including structural, geophysical, geochemical and mineralogical rock properties. These include a Geotek multi-sensor core logger standard (MSCL-S), a Geotek rotating X-ray computed tomography (RXCT) core scanner, a Geotek core workstation (MSCL-XYZ), and a Cox Analytical Systems Itrax MC core scanner. The large amount of consistent information that is retrieved from core and/or sample in a few minutes to hours using the CSF will make this facility a central resource which can interface with academic and commercial research projects and investments.

Case studies and associated core scanning workflows

Carefully designed core scanning workflows are created to maximize preservation of the core material to ensure optimized use and robust data extraction. These are aimed to fit with both non-destructive and destructive core characterization procedures and are greatly dependent on core condition.

Here we summarize two idealized core scanning workflows tailored for:

(1) newly acquired core with a requirement for full core characterization;
(2) legacy core archived at the NGDC with the requirement to understand the influence of core condition on core scanning.

An example project is provided for each workflow, with the UK Geoenergy Observatories (UKGEOS) Glasgow (Table 2) being use for recently acquired drill core and the Llanbedr (Mochras Farm) (Table 2) being used for legacy core stored at the NGDC. The presented workflows are adaptable as core scanning should always be tailored to the needs of users on a project-by-project basis.

Newly acquired core/UK Geoenergy Observatories Glasgow core scanning

In 2014, the UK Government announced £31 million to fund NERC/UK Research and Innovation (UKRI) world-class subsurface energy research test centres – the UK Geoenergy Observatories. When completed the UKGEOS facilities will comprise field-based observatory infrastructure in Cheshire and Glasgow, the CSF, and an open-data digital platform. Their remit is to independently monitor underground energy technologies, gather scientific evidence, support management and regulation, and develop innovative, exportable technologies and expertise (https://ukgeos.ac.uk/). As the proposed facilities will have a lifespan of more than 15 years there is a need to characterize any recovered core material in a consistent manner and ensure it is stored securely and readily accessible. This is where the CSF plays a significant role by maximizing the value of the core and preserving a record of its condition shortly after acquisition enabling future research.

The first fully cored borehole to be scanned in the facility was GGC01 from the Glasgow observatory (Table 2). GGC01 was drilled at the end of 2018, recovering 199 m of core that was comprehensively logged, scanned and analysed at the BGS. This was the only core collected for this facility and, once acquired, the analysis and sampling of the core had to be carefully managed to balance the requirements for destructive sampling against the need for long-term preservation and making the core and associated data publicly available for the wider research community (Monaghan *et al.* 2021*a*). The UKGEOS Glasgow core scanning workflow (Fig. 2) was designed with these considerations in mind. The objective of this workflow is to collect the largest amount of data consistently and systematically, at the highest affordable resolution, to enable the greatest retention of digital parameter data to enable understanding of the geological, geochemical and geophysical properties of the core.

The first step in the workflow is to ensure that the core is curated and databased in the NGDC immediately after the core arrives at the BGS Keyworth site. For GGC01, after curation the whole round core was then scanned for 2D radiography, geophysical property measurements and high-resolution optical images. This provided not just a baseline for core condition and recovery, but also ensured optimized geophysical core property data for correlation with geophysical borehole logs. Whilst scanning was ongoing, data and image processing was also

Table 2. *Borehole metadata*

Bore name	SOBI ref	BNG Easting (m)	BNG Northing (m)	Total depth (m)
Llanbedr (Mochras Farm)	SH52NE1	255 330	325 940	1938.38
UKGEOS GGC01	NS66SW3754	260 915	663 109	199

SOBI, Single Onshore Borehole Index; BNG, British National Grid.

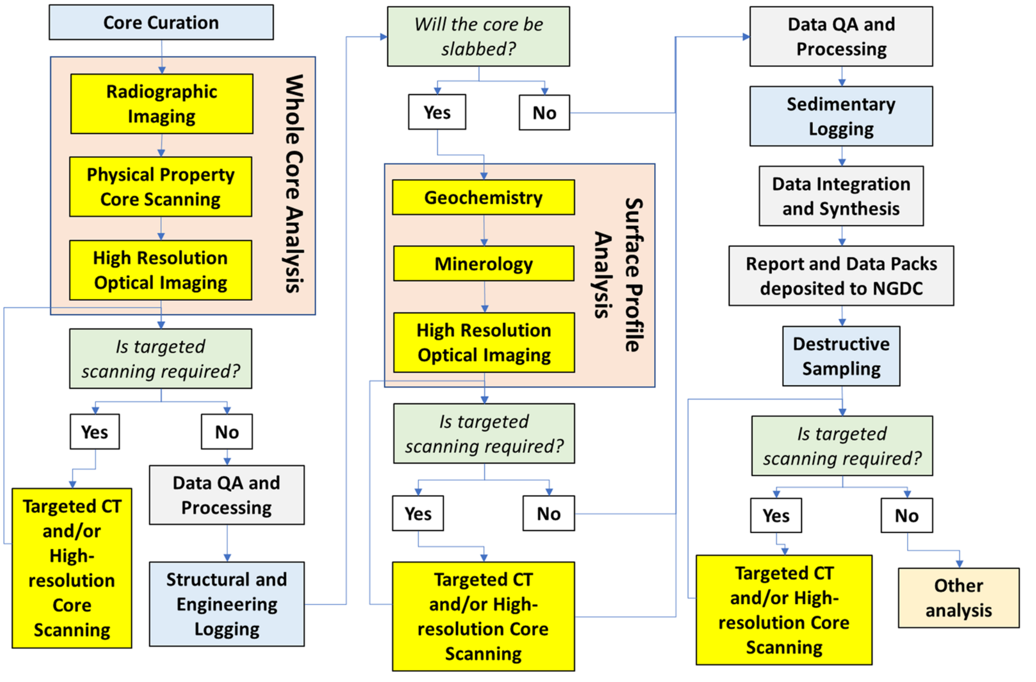

Fig. 2. Schematic core scanning workflow for newly acquired core. This diagram shows that various multi-property core scanning techniques (highlighted in yellow) can be easily integrated into existing core characterization workflows maximizing core data acquisition and consistency as well as complementing traditional analysis techniques by guiding investigations toward target areas.

undertaken. This included image processing (e.g. artefact correction, identification of technical problems), normalization and data quality assessment (QA; Fig. 2). Data and metadata were captured and stored in a centralized in-house database, which is specifically designed for the facility to obtain the relevant information that is needed to subsequently trace and access the data, enable rescans and link the data with other datasets. This prevents scanning data to becoming orphaned.

After the initial whole round core scanning, discontinuity and engineering logging were undertaken by BGS geologists utilizing the data collected during the first phase of core scanning (Fig. 3). This was particularly aided by the availability of the radiographic images collected at three angles (0°, 45°, 90°) which provided a detailed understanding of the internal structure of the core, such as core integrity, fracture network, mineralized veins, joints, inclusions and bedding planes.

Once this stage was completed there was a requirement to slab the core (cut the core along its length) to facilitate scanning techniques which required a flat surface for optimized analysis. These techniques included X-ray fluorescence (XRF), near-infrared (NIR) and high-resolution optical imaging. As with most surface profile analysis techniques, a flat and smooth surface greatly improves the quality of the scan data. In addition, a fresh cut surface is advantageous for sedimentary logging, making it easier to see and measure small-scale structures. But slabbing can be disadvantageous for destructive sampling as it can decrease available sampling volume. In discussion with the UKGEOS project team, the BGS Research and Design Engineering Workshop developed a new asymmetric slabbing and core scanning clamp (Fig. 4), which preserves a larger section of the whole round for subsequent subsampling whilst providing a flat surface for core scanning and sedimentary logging. This BGS key innovation was integrated into the workflow to ensure core scanning data are not lost over subsampled intervals.

After the surface profile core scanning, sedimentary logging was undertaken by BGS geologists incorporating the data collected during the second phase of core scanning. The high-resolution geochemical–mineralogical dataset could thereby be used to recognize small compositional changes, such as cement type, which cannot be assessed by eye (Fig. 5). The high-resolution optical and radiographic imagery at a resolution of up to 50 μm

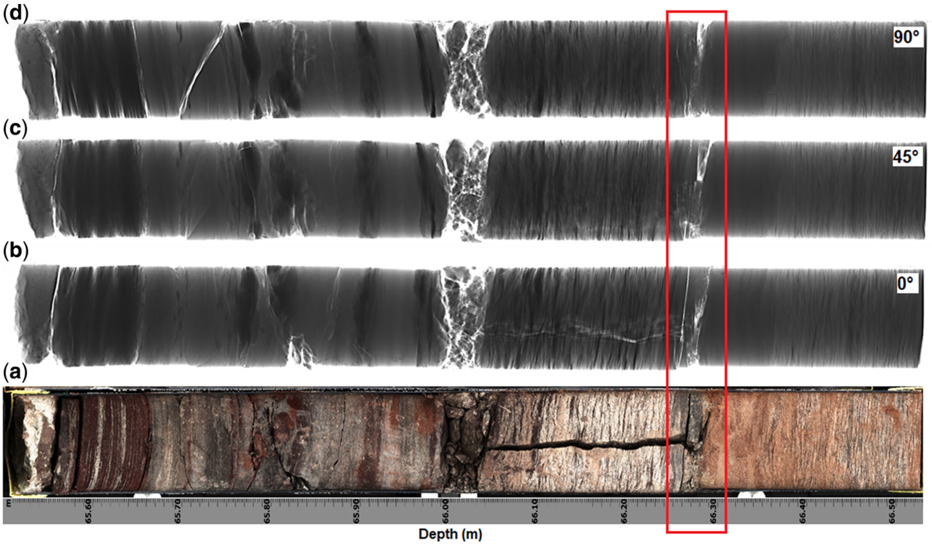

Fig. 3. (**a**) Scaled optical image and (**b–d**) X-ray radiographic images at 0°, 45°, 90° of UKGEOS Glasgow GGC01 whole round core at 65.5–66.5 m drillers' depth. The optical and radiographic imagery was used to assist discontinuity and engineering logging. Note the subvertical joint at approximately 66.3 m terminating abruptly at both ends against subhorizontal bedding planes. Source: Monaghan *et al.* (2021*a*).

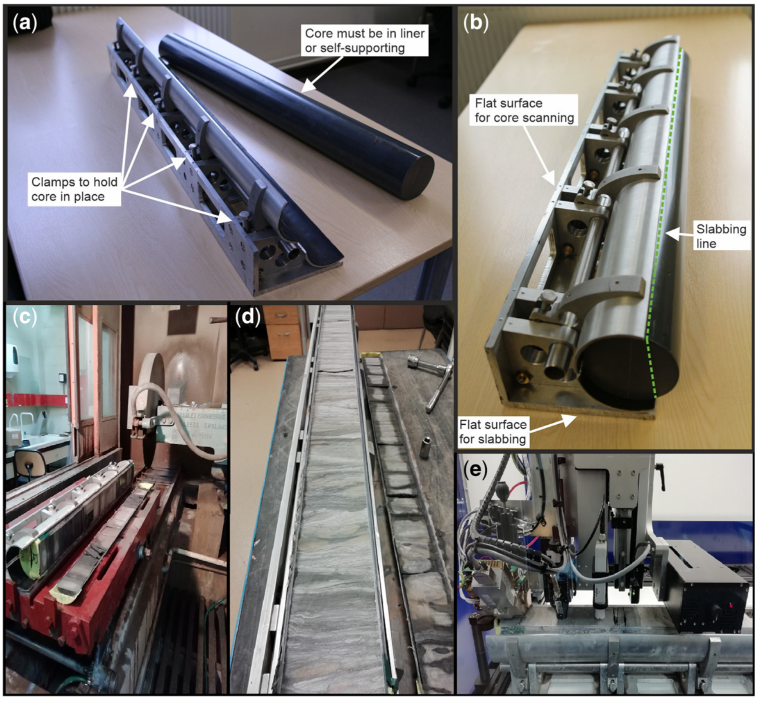

Fig. 4. (**a**, **b**) BGS core slabbing and scanning clamp design. The design of the clamp provides a secure surface for the core to be slabbed asymmetrically one-third to two-thirds, which preserves a larger section of the whole round for subsequent subsampling whilst providing a flat and intact surface for core scanning and sedimentary logging. (**c–e**) Once the core is slabbed the clamp is rotated 90° to allow for surface core scanning without releasing the core. This key innovation designed by BGS and integrated into the core scanning workflow maximizes data collection, data quality and preservation of the core material. Source: (a, b) from Monaghan *et al.* (2021*b*).

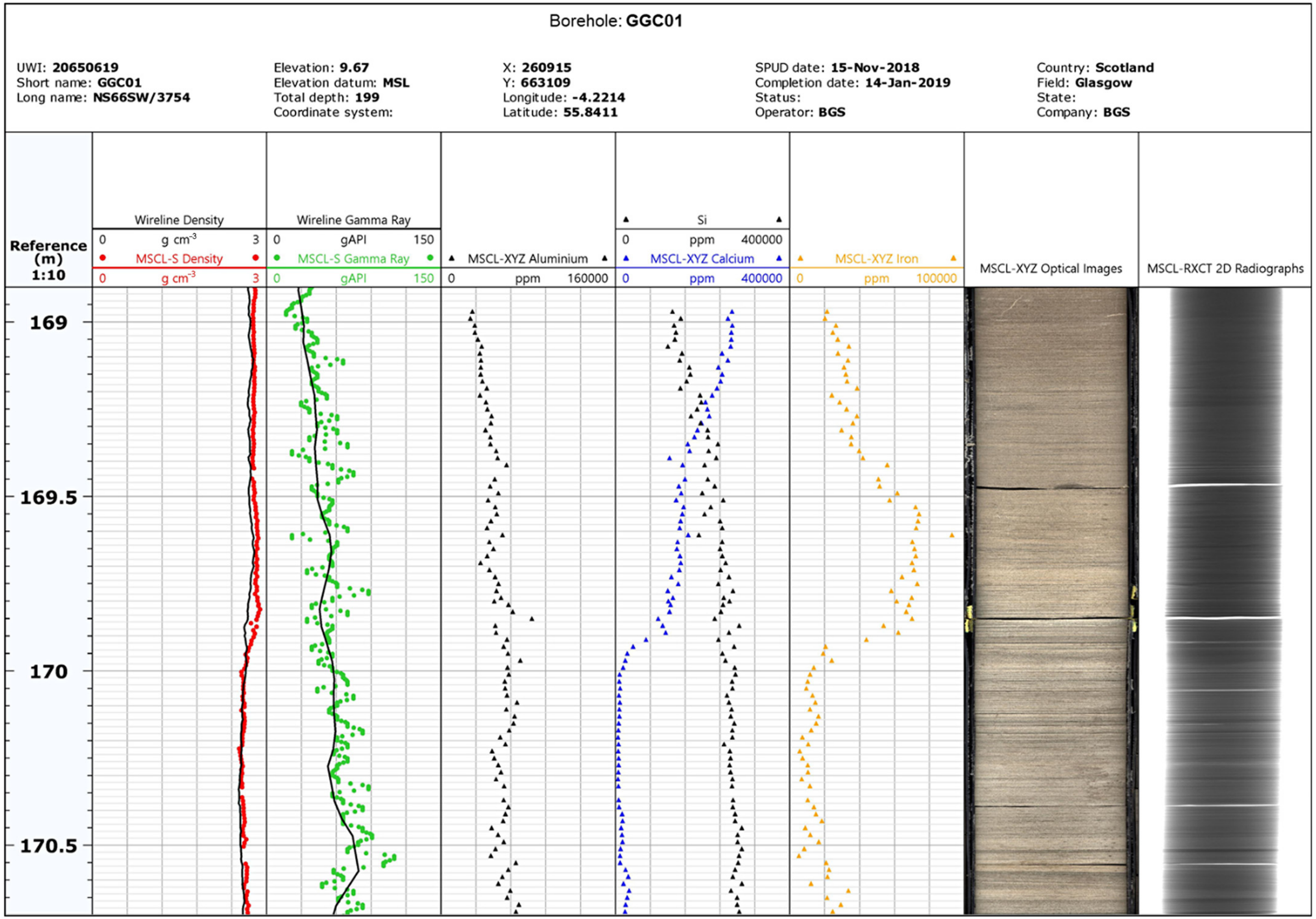

Fig. 5. Integrated visualization of wireline log data with geophysical, geochemical and structural core scanning data of channelized sandstone of UKGEOS Glasgow GGC01 core at 169–170.5 m. Note the compositional variability within a visually homogeneous rock unit. Source: image produced using Schlumberger Techlog version 2017.2.

captures sedimentary structures and stratigraphic boundaries to a standard higher than the current logging standards. This contributed to creating a more detailed sedimentary log for these cores than would be possible from core inspection without extensive destructive sampling (e.g. thin sections).

At any point within this workflow, areas of specific interest can be targeted for higher-resolution core scans and/or virtual three-dimensional (3D) reconstruction of the core/sample material to allow for an even more detailed assessment of the sedimentary architecture (Fig. 6) or other property characteristics such as porosity and permeability (Payton *et al.* 2021).

After core scanning was completed, the core scan data were matched to the wireline geophysical logs (Fig. 2, 'Data Integration and Synthesis'). This included comparing high-resolution optical images and radiographs as well as the physical property measurements to the borehole imaging, natural gamma ray and density logs collected by conventional geophysical logging (Monaghan *et al.* 2021*b*). Initially, fractures and distinct lithological boundaries in the core that were visible on the optical images and radiographs were directly matched to borehole images collected on wireline. For GGC01, the borehole images are acoustic amplitude and travel time false colour images (Paillet *et al.* 1990; Prensky 1999). This was used to create a depth shift for each core run. Once this shift had been applied, the density and gamma ray data from the geophysical logging and the core scanning were compared. This highlighted an area of the borehole where an additional depth shift was applied. For a detailed description, see Monaghan *et al.* (2021*b*).

The final step of this workflow (Fig. 2) was to create a comprehensive data pack and report, which were deposited in the NGDC (Monaghan *et al.* 2021*a*, *b*). These were published using an Open Government licence, thereby complying with UKRI's Open Access Policy and ensuring data conform to the FAIR principles. Through the assignment of a digital object identifier (DOI), access to the dataset and report is open and consistent. This allows the data to be reused and reapplied, adding value to the initial investment and effort used to create and collect it. The CSF has now used this mechanism to make data openly available for multiple boreholes from Glasgow and Cheshire (BGS Core Scanning Facility 2022*a*, *b*).

Legacy core/Llanbedr (Mochras Farm) core scanning

The Llanbedr (Mochras Farm) core from the Cardigan Bay Basin, North Wales, UK (Table 2) is a well-studied Early Jurassic rock succession. The material is stored as slabbed core within the NGDC. The *c.* 55-year-old core continues to be a valuable resource for the acquisition of fundamental datasets to understand palaeoclimatic/palaeoenvironmental conditions and change during the critical epoch of the Early Jurassic and may even serve as an analogue for present-day and future environmental transitions (Woodland 1971; Dobson and Whittington 1987; Copestake and Johnson 2013; Hesselbo *et al.* 2013; Ruhl *et al.* 2016; Xu *et al.* 2018; Deconinck *et al.* 2019; Hollaar *et al.* 2021; Ullmann *et al.* 2021).

For the Llanbedr (Mochras Farm) core to be successfully scanned, there was a need to understand core integrity and scanning quality for Jurassic mudrocks. Learnings from the scanning of this core were also needed to inform the scanning of core recovered from the drilling of a new research borehole in the Cheshire Basin at Prees, Shropshire, UK (Hesselbo and the JET Science Party 2021). The new dataset, combined with data generated from the legacy Mochras core, is intended to become the international standard for a high-resolution integrated stratigraphy of the Early Jurassic.

The core scanning workflow (Fig. 7) for the Llanbedr (Mochras Farm) core differs from the newly acquired core workflow due to the age of the core and its consequent degradation during storage. The condition of legacy cores is variable, particularly due to impacts from prior sampling, repeated handling and prolonged storage (e.g. Fellgett *et al.* 2022). Artefacts of poorly preserved core can include fragmentary core, encrustation with post-acquisition salt precipitation and/or (pyrite) decay products, or physical degradation of the core caused by it having dried out and shrinkage. This has an impact on both the volume and quality of core scanning that can be undertaken. This is particularly true for surface profile measurements, such as XRF and NIR, which require a smooth flat surface. As a result, legacy core has to be rigorously assessed and evaluated as part of the core scanning workflow; associated core logs, images, reports and existing data can contribute to this process.

For Llanbedr (Mochras Farm) core, existing core photographs taken in 2014 have been utilized to visually inspect the core's fragmentary state (Fig. 8; Ullmann, pers. comm., 12 December 2021). Depending on the number of fragments within each metre of core, a core fragmentation degree from 0 (low number of fragments) to 5 (high number of fragments) was assigned. A higher fragmentation degree will result in poor XRF data quality, with highly fragmented core, e.g. fragmentation degree 4 and 5, being unsuitable for XRF core scanning altogether (Fig. 8). From the fragmentation chart it became apparent that the majority of the Llanbedr (Mochras Farm) core remains relatively intact. As a result, a 150 m core interval (Fig. 8) of

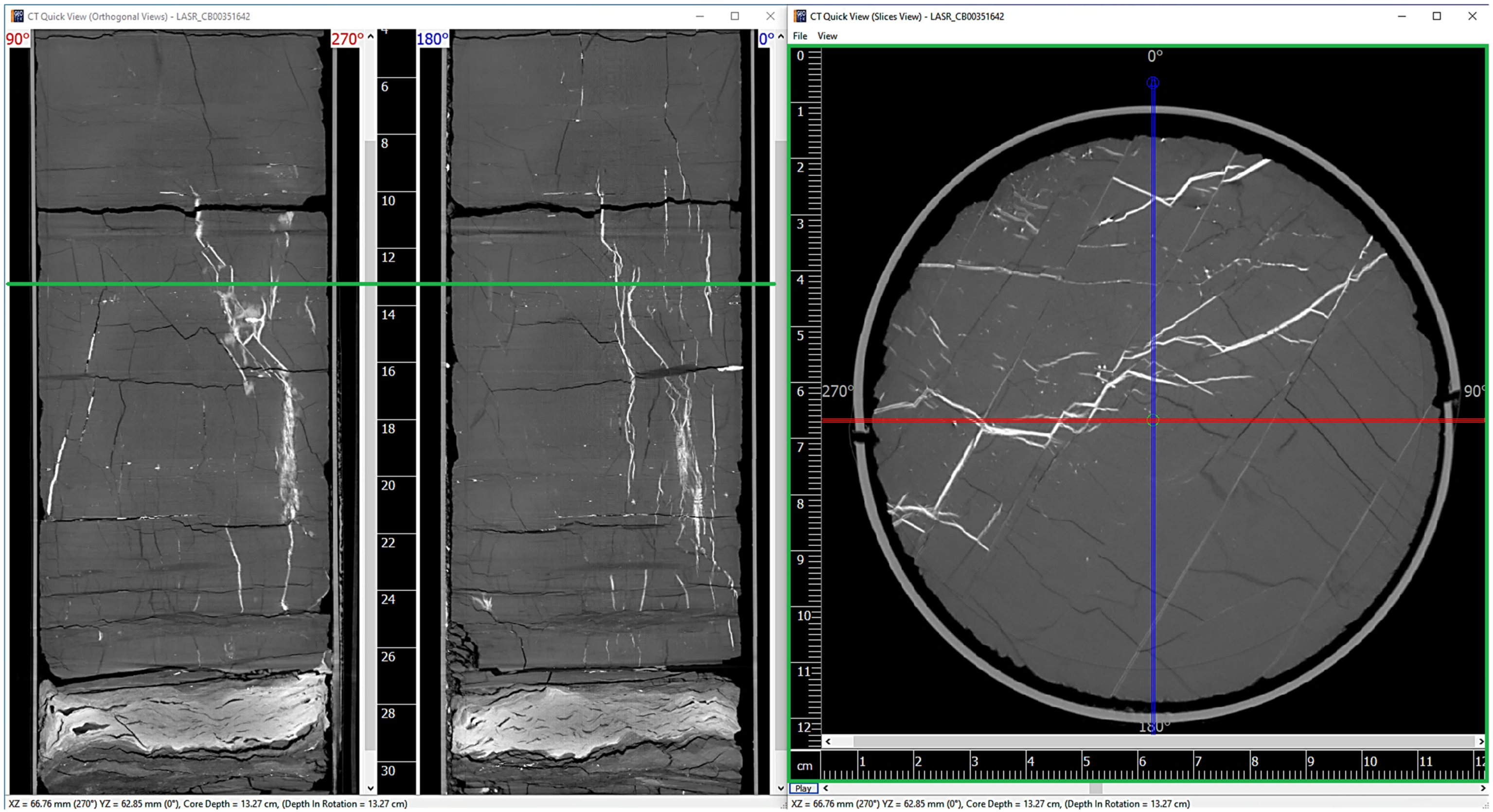

Fig. 6. A full 3D reconstruction of a typical coal bed of UKGEOS Glasgow GGC01 core showing numerous thin veins that have exploited the coal cleat system. The X-ray core imagery is viewed using the Geotek CTQuickView software. To the left: Orthogonal view through 0°–180° (indicated by a blue line on the right image) and 90°–270° (indicated by a red line on the right image). To the right: Slice view across the core indicated by a green line on the left two images.

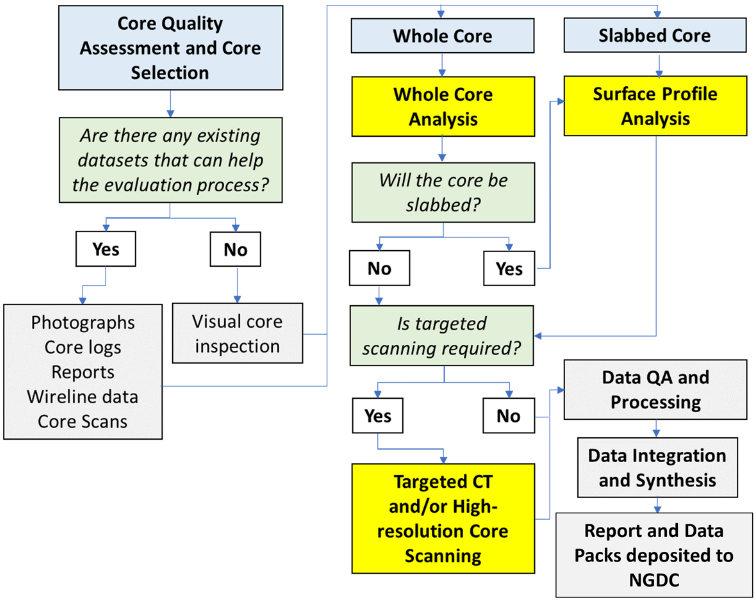

Fig. 7. Schematic core scanning workflow for legacy core. This diagram highlights that a detailed core quality assessment and selection is required prior to core scanning legacy core. The condition of legacy cores is variable and some of the core may no longer be suitable for specific core scanning techniques, e.g. surface profile core scanning, such as XRF and NIR.

the highest integrity could be identified and was subsequently scanned for XRF and optical imaging (Damaschke *et al.* 2021).

The newly acquired optical images taken in 2021 show that the condition of the Mochras core has changed compared to core photographs taken in 2014 (Fig. 9). This has two aspects, the first is that additional subsampling has further degraded the core since 2014, potentially compromising scanning. The second is a visual change in the colour profile of the images, which is a result of the changes in imaging technology.

Discussion

Project-specific core scanning workflows are a prerequisite of robust and consistent data collection. The workflows highlighted in this paper (Figs 2 & 7) are necessary to maximize data from legacy and new core, but also significantly add to and complement traditional core characterization routines.

For UKGEOS, the core scanning workflow has supported a comprehensive characterization of the subsurface at two separate research sites (Glasgow and Cheshire). It has aided in the planning and installing of field experiments both at surface and at depth, e.g. selection of depth intervals for packer testing and composition of gravel pack used to complete boreholes at the Cheshire site. For GGC01, the representative rock succession of the Carboniferous Middle Coal Measures was characterized at a detail that is almost unprecedented and could not have been achieved with traditional core characterization methods alone. Core scanning has assisted with discontinuity and sedimentological logging procedures as well as informed effective subsampling for mineralogy and petrology, and permeability and porosity testing. It enabled a detailed core–log integration, which is vital to correctly orientate the sample material in 3D space and upscale data accurately into the rock mass to better understand rock properties and processes. Some of which might be critical for understanding the difference between a conceptual location for decarbonization technologies and an economically viable one.

Reconstructing cores into their true geographical orientation and positioning them in 3D space also allowed subsamples to be referenced to true core depths. Thus, the collection of core scan data and matching these to wireline logs allow laboratory samples to be contextualized spatially. For GGC01, a workflow was developed to combine imaging of the borehole wall and imaging of the core to deliver this spatial reconstruction (Rogers *et al.* 2000). The core was acquired in 3 m lengths and then cut into nominally 1 m sections at the drill site. However, when inspected it was found that some core sticks

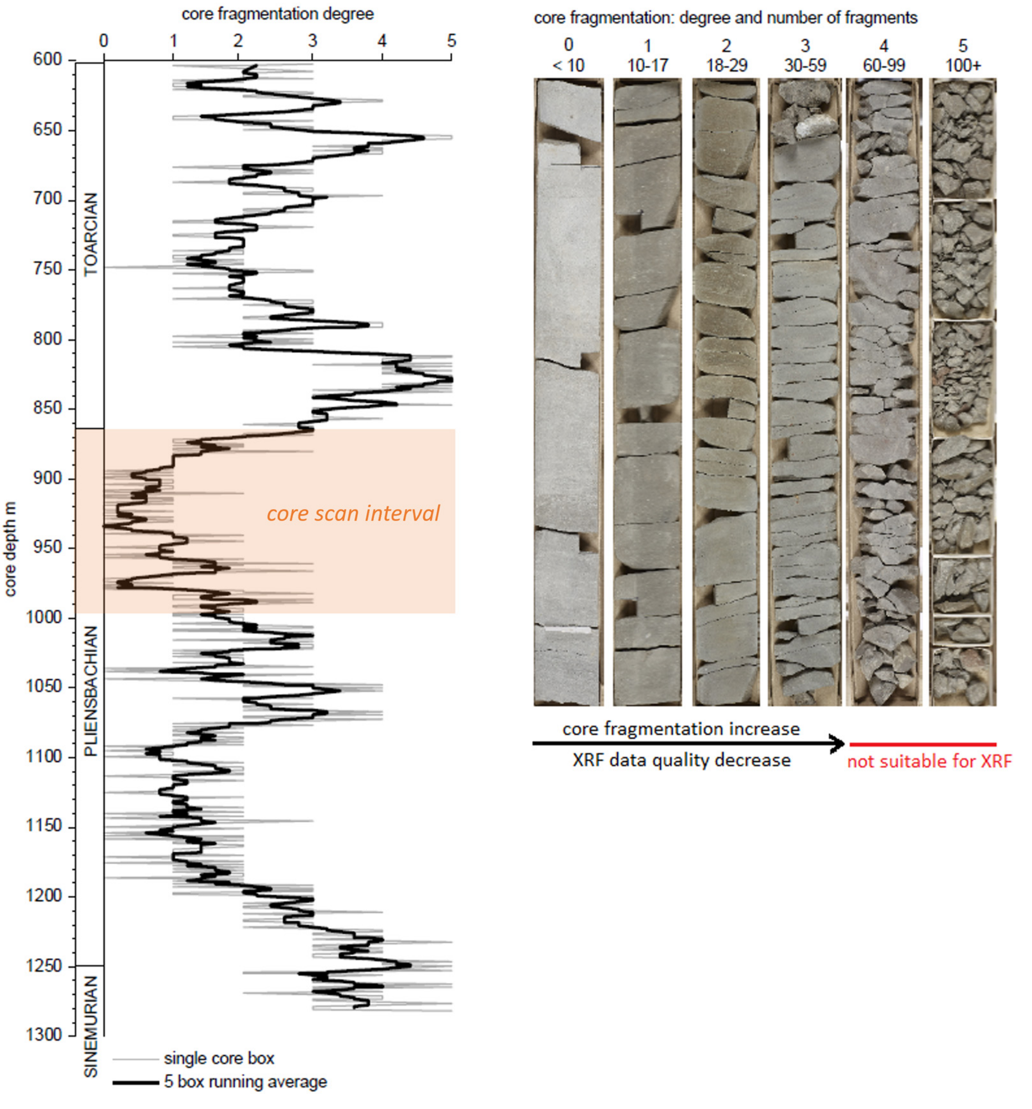

Fig. 8. Llanbedr (Mochras Farm) core fragmentation chart (Ullmann, pers. comm., 12 December 2021) used to identify and select suitable core sections for X-ray fluorescence (XRF) core scanning (*c.* 150 m of core selected; highlighted in orange). A core fragmentation degree was assigned depending on the number of fragments within each metre of core, with core fragmentation degree 0 (<10 fragments) to 5 (100+ fragments).

recorded as 1 m on the drilling logs were in reality as long as 1.3 m. This created apparent overlaps and gaps between the physical core lengths and the drilling logs. The physical comparison of borehole wall images and core images allowed the accurate reconstruction of the complete core section. Without the acquisition of both sets of image data this depth matching could not have been performed with the same degree of rigour. This technique is especially useful in zones of less than 100% core recovery where missing sections of rock within cored intervals, for example friable fault rocks, can make accurately locating the material in depth difficult. Undertaking this depth matching process prior to data delivery allows core derived data to be provided in both drillers' depth and wireline-equivalent depths. This allows users of the data to immediately and accurately upscale observations into a rock volume. As GGC01 is the only cored borehole for the Glasgow observatory, core scanning was therefore critical to the characterization of the facility to achieve volumetric parameterization. The 15-year

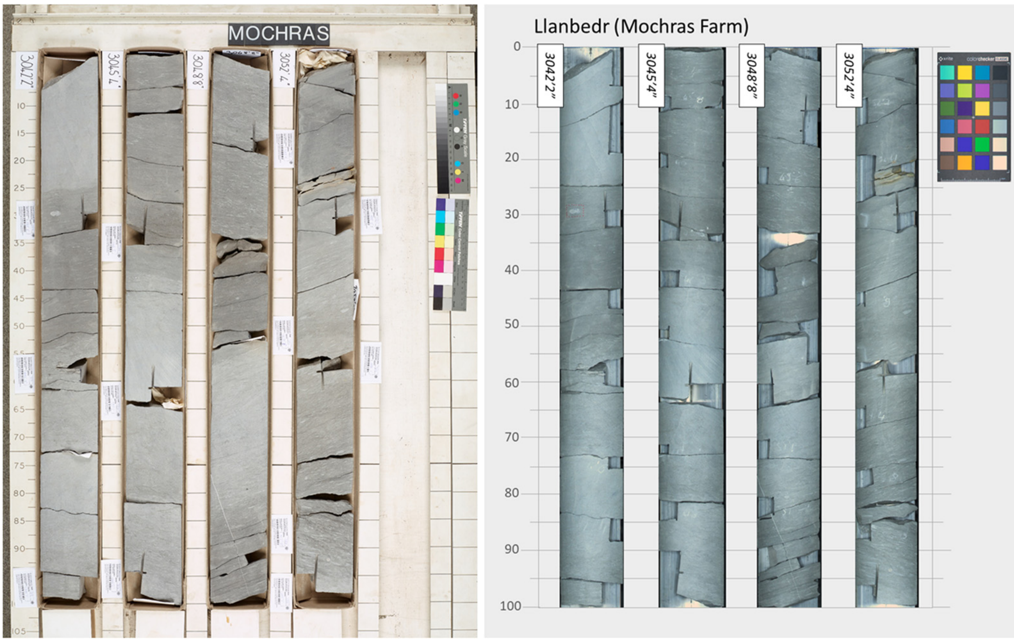

Fig. 9. Photographs of archived Llanbedr (Mochras Farm) slabbed core, borehole SH52NE/1, 3042 ft 2 in to 3055 ft 3 in, taken in 2014 (left) and in 2021 (right). Note the increased sampling and fragmentation state of the core over time and improved colour depiction.

lifespan of the UKGEOS facilities demands that as much information as possible must be collected from any core recovered, as well as preserving it to enable future research.

Benefits can also be demonstrated through the core scanning of legacy core, where scientific questions can be answered without the need to acquire expensive new core material (e.g. Holland *et al.* 2005; Fellgett *et al.* 2019; Hollaar *et al.* 2021, 2022). It can guide new research campaigns or target exploration of new frontiers (e.g. Hesselbo and the JET Science Party 2021; Kazak and Kazak 2021), as well as provide additional online datasets that improve access and increase the utility of an existing core archive. One example is the creation of new optical imagery that will shed light into the degradation of core over time whilst preserving a digital record. Another example is the creation of analogues of geophysical logging data for correlation studies where such data were not acquired at the time of drilling. For the Llanbedr (Mochras Farm) core, the core scanning workflow has highlighted the importance of assessing legacy core condition in relation to acquiring specific core scanning techniques and their data quality. This results in better time and resource management through targeted core scanning in intervals of greater core quality and, by extension data acquisition. The additional data that were obtained by XRF scanning of the Llanbedr (Mochras Farm) legacy core has expanded on existing datasets collected at lower resolution (10–15 cm; Ruhl *et al.* 2016), thereby increasing analytical resolution and scientific understanding, for example improved definition of astronomical time scales for the Early Jurassic Pliensbachian Stage (Hollaar *et al.* 2022).

The use of established core scanning workflows also promotes data security and reuse. Once acquired and securely stored within a data centre, core scan data become an archive that can be revisited and, if necessary, re-analysed and integrated with other datasets. This preserves information about the core, which can be accessed years to decades after the data are collected, potentially beyond the life of the physical core material. The breadth of information acquired during core scanning far exceeds that of traditional lab analysis. Collecting data on a near-continuous basis, compared to discrete ‘spot’ data collection, not only allows a user to understand the framework of these individual data points, but also benefits the understanding of the variability in rock properties and geological characteristics at multiple scales.

Predictions of subsurface behaviour often involve producing detailed, integrated models of the subsurface using as much data as available. This includes all data from seismic surveys at kilometre scale down to microscopic scales at micrometres to nanometres (10^{-6}–10^{-9} m), for example from scanning electron microscopy. Through depth-matching, core scanning data can be integrated with data obtained from wireline logging and other datasets at widely different scales. Such data systems are an important element for the integration of multiscale data. The data generated by the CSF will be a key component in creating a seamless flow of otherwise separate data at a range of scales. This is exemplified by the UKGEOS core scanning workflow, which bridges data gathered at basin, field and lab scales. Integrating datasets at different scales facilitates different disciplines to collaborate and integrate ideas and thinking on studies that span different rock properties and scales.

The co-location of the CSF with the NGDC contributes to flexible and efficient core handling logistics thereby maximizing throughput and return on investment whilst minimizing core movement. It also offers a unique opportunity to test new and enhanced core scanning techniques through the variety of available core material, thereby increasing collaboration and opening up additional research opportunities, for example, through digital rock physics or destructive testing (Fellgett *et al.* 2019; Payton *et al.* 2021). The recent world-wide pandemic has demonstrated that it may be difficult to physically interact with core, increasing the need for alternative digital solutions. Core scanning data can enable remote investigations and provide benefits by turning physical rock core archives into digital ones and thus, creating new platforms for collaboration and innovation. More digital datasets improve the extraction and efficiency of sharing of scientific information, as well as promoting data science techniques such as machine learning. Machine learning approaches are increasingly being used in Earth Science to automate the analysis of images to assess core condition (Fellgett *et al.* 2022) through to the identification of lithology (Hill *et al.* 2021; Martin *et al.* 2021) and mineral abundances (Tuşa *et al.* 2020).

Despite the great advances in the field of core scanning techniques, challenges remain. There is a requirement for the development of visualization tools to optimize the validation and interpretation process, as well as for sharing best practices and standardized calibration procedures across BGS laboratories but also externally through a national/international core scanning community network to gather reliable and reproducible core scanning results (e.g. Durance *et al.* 2014; Löwemark *et al.* 2019). Many of the current core scanning techniques generate vast amounts of data, yielding up to terabytes of data, which can overload traditional archiving systems. Although it is possible for individual users to discover, visualize and process these large digital core imageries via powerful PCs using specialist software (i.e. iPoint by Perigon Solutions Ltd, PerGeos by Thermo Fisher), these can be costly to obtain/maintain, as well as rely on specific domain data and set workflows built for specialized users. In order to lower the barriers to access these data for all users, in the case of core scan data from UKGEOS, these have been made available through the free to use, web-based, core scan image viewer (https://ukgeos.ac.uk/). This data delivery service strives to fulfil the FAIR data principles and was co-designed by BGS scientists and digital user experience (UX) designers from a user-first approach. The viewer was released through the UKGEOS Digital Science Lab, an open, public, beta-testing environment to encourage end-user engagement in the future improvements to the service.

Digital data, software and samples are key factors that underpin research and ultimately scholarly publications, and there are increasing expectations from policy makers and research funding organizations that they will be Open and FAIR. As a UKRI research facility, all publicly funded data from the CSF conform to UKRI's Open Access Data Policy, whereby data are made openly available within two years of collection. The CSF encourages other users, non-UKRI academic and commercial, to follow this approach; however, decisions are often made on a case-by-case basis where the Intellectual Property Rights are with the customer. Open, accessible, high-quality data, software and samples are critical to ensure the integrity of published research and to facilitate reuse of these inputs in future scientific efforts. Adherence to the EU directive INSPIRE (Infrastructure for Spatial Information in Europe) becomes gradually more enforced by national legislations, affecting also the data lifecycle in Earth and Environmental Sciences. Journals are changing policies to improve the integrity and reproducibility of research by mandating openness of both data and software connected to publications. National, European and global initiatives and institutions are developing increasing services around Open and FAIR data, covering curation, distribution and processing. An inclusive, integrated approach to Open and FAIR is required, with consistent policies, standards and guidelines covering the whole research data lifecycle, addressing also legal frameworks, e.g. for intellectual property and licensing. At the same time, the research community needs to further develop a common understanding of best practices and appropriate scientific conduct adequate for this new era and could still better share tools and techniques.

Conclusion

Core scanning data add fundamentally to scientific data acquisition and consistency derived from rock cores. Core scanning provides the critical data that are needed to understand the influence of small-scale geological features upon large-scale rock properties and geological processes. Both newly drilled core and legacy core from archives are the only physical record of the subsurface at depth to which scientists have access. Understanding and maximizing the value of this archive are fundamental to identify key properties to characterize and predict subsurface behaviour.

This paper has outlined workflows for extracting more information from cores while preserving their physical integrity by non-destructive sampling using a multi-property core scanning approach in combination with traditional characterization techniques. Whilst core scanning is not a new approach, we have shown that the integration of multiple core scanning techniques within a project-specific workflow results in a powerful new discovery tool that can be used to maximize the acquisition of geological core property data and also bridge the gap between field- and lab-based studies. Core scan data enable the scientists to target precise pieces of core for digital and physical sampling necessary to address research questions and to inform subsequent planning and implementation of the scientific and analytical work. Continuous data allow an understanding of the context of individual data points and improve the understanding of heterogeneous rock properties and geological characteristics at multiple scales. Once physical sampling is performed on core, the samples are usually damaged or destroyed so no more data can be extracted.

In addition, many lithologies decay with time due to drying, rendering legacy cores unsuitable for many possible future sampling requirements. Data from core scanning can be stored in perpetuity and can be applied to address new and evolving challenges, as well as repurposed as needs and technologies change; thus, contributing to the current digital transformation. The UKGEOS project is an exemplar for publishing Open Data in perpetuity so that these can be utilized by multiple users from various scientific disciplines. This is a model that the CSF promotes across all projects. Such sets of geological subsurface data will be highly relevant to informing the use of the geosphere in delivering transition to NetZero and other relevant environmental change research. The large investment needed to acquire core and ever-increasing use of directional drilling techniques are resulting in less drill core being collected and therefore higher demand for legacy core samples and data from competing users. The application of core scanning data is versatile and data can be used for various different studies. In addition, the availability of consistent, continuous high-resolution digital data, such as core scanning data, will enable the use of new techniques such as machine learning, help advance preservation of and access to core data, and create new platforms for collaboration and innovation.

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Author contributions **MD**: conceptualization (lead), data curation (lead), methodology (lead), writing – original draft (lead), writing – review & editing (lead); **MWF**: conceptualization (supporting), methodology (supporting), writing – original draft (supporting), writing – review & editing (supporting); **MPAH**: writing – original draft (supporting), writing – review & editing (supporting); **CJW**: writing – original draft (supporting), writing – review & editing (supporting).

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Data availability The UKGEOS Glasgow dataset, including images, are available for download under Open Government Licence V3.0 from the UKGEOS website, https://ukgeos.ac.uk/data-downloads

The Llanbedr (Mochras Farm) core scanning dataset is available under NERC EDS National Geoscience Data Centre https://doi.org/10.5285/c09e9908-6a21-43a8-bc5a-944f9eb8b97e.

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