The UK National Geological Repository: a case study in innovation

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Abstract: The UK National Geological Repository (UKNGR) is the largest collection of British geoscience samples, with 16 m 'specimens', including 600 km of drillcore. Samples are available for study/subsampling by commercial organizations and researchers. Data, reports and publications must be returned. Raw data are available after 2 years.

The scientific method requires published results to be repeatable, necessitating the archiving of samples. Re-purposing samples for new research saves money and time and thereby reduces risk. The National Geological Repository (NGR) has cost over £200 bn to collect and the cost of a single deep cored borehole would be outside the funding of most research projects, so the operation of an NGR makes financial sense. Many of the boreholes have been extensively characterized, so new research can build on the wealth of published data.

The NGR has been at the forefront of international efforts to utilize digitization and the World Wide Web to improve the impact of the collections. Geographical information system (GIS) access was provided to the onshore borehole collection in 2000, and GIS access and text searching were added to the other collections over the next 10 years. This was followed by high-resolution images of the UK Continental Shelf (UKCS) cores, petrological thin-sections, and images, stereo anaglyphs and 3D-digital models of British-type fossils.

The UK National Geological Repository (UKNGR) is part of the British Geological Survey's (BGS) National Geoscience Data Centre (NGDC) which is one of the Natural Environment Research Council's (NERC) Environmental Data Centres. NERC is one of the constituent research councils within United Kingdom Research and Innovation (UKRI) and is listed on InfraPortal, the UK's Research and Innovation Infrastructure Portal (InfraPortal 2022). The BGS was effectively founded in 1835 as part of the Ordnance Survey, following discussions between Col. Colby (Master-General and Board of Ordnance), the professors of geology at Oxford and Cambridge and the President of the Geological Society of London (Bailey 1952). It became independent with the passing of the Geological Survey Act 1845, and subsequently changed its name (with various reorganizations) from the Geological Survey of Great Britain to the Institute of Geological Sciences (IGS) and then to BGS. For simplicity and continuity throughout this paper, it will be referred to as 'the Survey'.

This paper will outline the present scope of the collections, emphasizing their holistic nature, with geochemistry, mineralogy and petrology, and biostratigraphy collections closely related to the borehole core and sample collections. It will discuss the relative size of the collections, including comparisons with other UK geoscience collections, and illustrate their unique character in underpinning the British stratigraphy and economic geology. Scottish mineralogy and petrology collections, and biostratigraphy collections, are held in the George Bruce Building, part of the Lyell Centre, Heriot-Watt University, Edinburgh. English, Welsh and overseas mineralogy and petrology, and biostratigraphy collections, plus all borehole and wells samples, and all UK Continental Shelf (UKCS) samples, are held in Keyworth, Nottingham.

Finally, this paper will show how the early adoption of online databases and digitization has opened up national and international access to the collections, and has contributed to the smarter working necessary to address the new challenges that many collection organizations are facing, whilst complying with new initiatives such as FAIR (Findable, Accessible, Interoperable and Reusable) Data.

Scope of the BGS collections

The overall size and scope of the National Geological Repository (NGR) collections is given in Table 1.

The question is often asked as to how many specimens the NGR contains. It is clearly impossible to compare 1000 m of drillcore from one borehole with a micropalynological slide or bottle of micropalaeontological residues that could contain a thousand

From: Neal, A., Ashton, M., Williams, L. S., Dee, S. J., Dodd, T. J. H. and Marshall, J. D. (eds) 2023. *Core Values: the Role of Core in Twenty-first Century Reservoir Characterization*. Geological Society, London, Special Publications, **527**, 333–353.
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Table 1. Summary of the main collections within the National Geological Repository and the National Geoscience Data Centre

Geological materials	Boreholes	Number of wells and boreholes with retained samples	>23 500
		Total length of drillcore	>600 km
		Total number of individually registered borehole samples	>1 000 000
		Total number of washed cuttings samples	>6 000 000
	Min & Pet	Total number of mineralogy and petrology samples	>1 000 000
		Petrological thin-sections	*c.* 300 000
	Biostrat.	Fossil specimens	*c.* 5 000 000
		Micropalaeontological slides	*c.* 250 000
		UKCS (non-hydrocarbon) samples	*c.* 50 000 boxes
		Total 'Equivalent specimens'	**16 m**
Paper		**Paper records, maps, notebooks, site investigation reports, borehole logs, etc.**	**17.5 linear km**

UKCS, UK Continental Shelf.

individuals. Counting slides or containers of powders or residues as single specimens, and considering continuous drillcore as 40 cm lengths (typically the maximum length for an individual registered borehole sample), the total size of the collection is around 16 million specimens, making it the largest collection of UK geoscience samples. It is almost half the declared geological samples in the UK (Smith *et al.* 2022). It could also be quantified as very approximately 12 000 tonnes.

To place the BGS collections in context, they are similar in size to the Earth Science collections of the Natural History Museum (NHM), but the NHM's scope is worldwide whereas the Survey collections are very largely from the UK. The NHM collections are the results of centuries of donations, purchases and specific expeditions, whereas the Survey collections provide a more systematic coverage of Britain. Whilst the NHM has specimens collected from boreholes, the Survey collections are more systematic and widespread, and the hydrocarbon archive is virtually complete. The Survey collections clearly form a systematic NGR for Britain.

Onshore borehole collection

The onshore borehole collection, which includes hydrocarbon wells, but also many mining, coal, hydrogeology and general exploratory wells drilled by or for the Survey, includes material from over 15 000 boreholes and wells, and over 200 km of core. Their locations are shown in Figure 1. Of particular current significance are 22 km of core drilled and donated by Nirex (originally the Nuclear Industry Radioactive Waste Executive) in 2000.

The registered borehole specimens, numbering more than a million, are typically from the earlier boreholes, and can range from one or two specimens from an entire borehole to almost the entire borehole

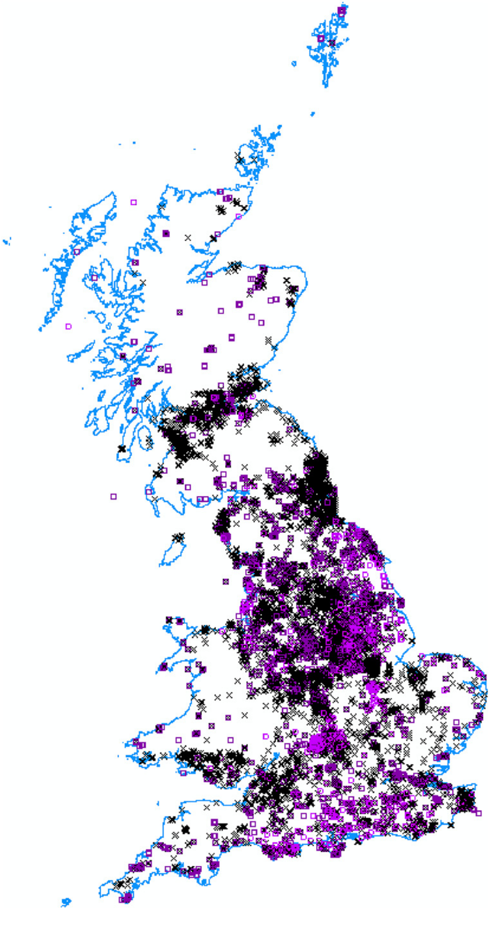


Fig. 1. Geographical information system plot showing the positions of British onshore boreholes with samples in the National Geological Repository collections. Source: contains Ordnance Survey data © Crown copyright and database right 2023.

broken up into several thousand individually registered samples.

The collections are housed in three core and sample repositories. The cores and samples are now curated into 1.8 mm thick board boxes, kraft lined both sides, with heavy duty brass or corrosion-resistant staples. The boxes are stacked on 1 m-square wooden pallets, with 40 cm steel cages, and the pallets placed on standard warehouse pallet racking. Boxes, pallets and locations all carry barcodes and are linked in the *Borehole Materials Database*. The caged pallets are accessed using a VNA forklift ('Very Narrow Aisle, Man Up Forklift', commonly known as the 'Hi-Racker') and transferred to the Examination Laboratories with standard counterbalance electric forklifts, or even pallet stackers or manual pallet trucks.

The main aim is to design out as much manual handling as possible. The former Gilmerton core store was based around core boxes on shelves, some of which required bending and twisting to access. Picking 200 to 300 boxes, sometimes heavy, off the shelving, wheeling them across the store on a flatbed trolley, and then laying them out for examination, before reversing the entire process, was a physically demanding job.

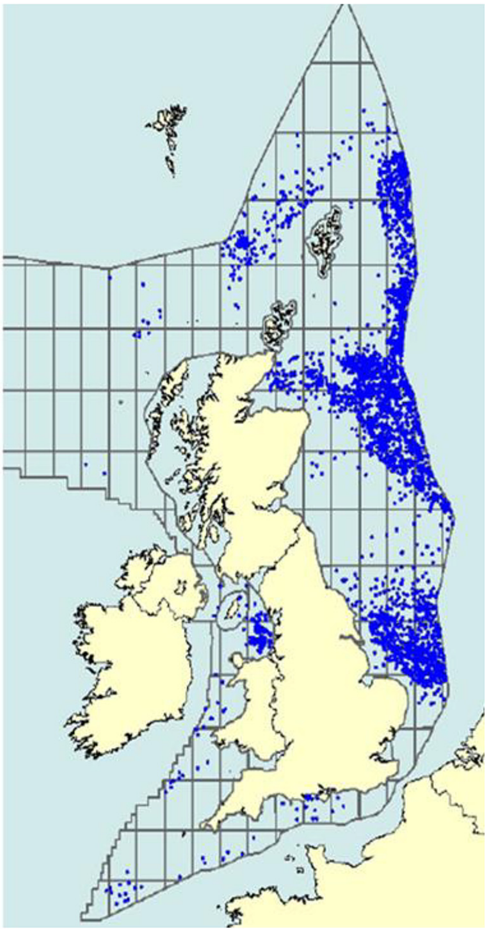


Fig. 2. Geographical information system plot showing the positions of UK Continental Shelf offshore hydrocarbon samples in the National Geological Repository collections. Source: contains Ordnance Survey & NSTA data © Crown copyright and database right 2023.

Offshore UKCS hydrocarbon wells

Offshore, the UKCS hydrocarbon well samples ('seaward') now include material from over 6700 wells, with an estimated 290–300 km of drillcore and 4.5 million cutting samples in 165 000 boxes. Their locations are shown in Figure 2.

The earlier UKCS southern North Sea cores, mostly split into approximately 40 cm lengths and held in 'London-style' lidded wooden or plastic sample boxes – the 'E' Collection – generally represent all of the original core and are considered as drillcore.

Marine samples and cores (non-hydrocarbon)

The offshore (non-hydrocarbon) collection includes large numbers of seabed samples, grab samples, vibrocores and gravity cores. There are also some drilled boreholes through the seabed. Their locations are shown in Figure 3. It is largely the result of the regional survey of the UKCS carried out between 1968 and 1986, funded by the Department of Energy of that time. It also includes many samples collected by or for the UK Hydrographic Office, and some important donations of geotechnical samples, including many from windfarm site surveys. Some samples have been cut and X-rayed and some have been subject to particle size analysis (Hollyer and Wheatley 2000).

Other collections: the value of the holistic approach

Other collections include mineralogy and petrology, which is biased towards Scotland because of the more varied metamorphic and igneous rocks present. A consequence of this is the relative rarity of fossils in the Scottish Highlands. Biostratigraphy (palaeontology) collections are biased towards England and Wales because of the dominantly sedimentary nature of the rocks, and the geochemistry collections are nationwide. Distributions of these collections are shown in Figure 4.

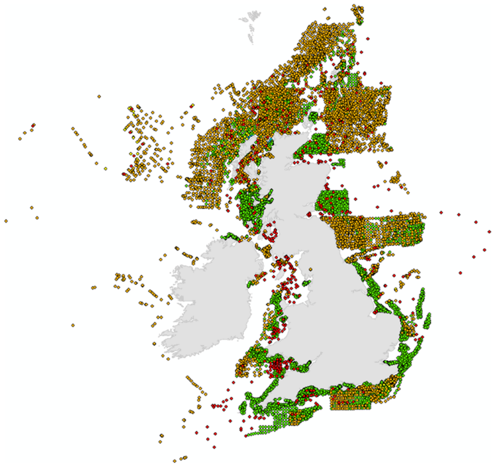


Fig. 3. Geographical information system plot showing the positions of UK Continental Shelf non-hydrocarbon samples in the National Geological Repository collections. Source: contains Ordnance Survey data © Crown copyright and database right 2023.

The borehole, well, marine, petrology, biostratigraphy and geochemistry collections, when combined with logs, field maps and notebooks, and published maps, memoirs, reports and publications, form a holistic resource. For example, holding onshore hydrocarbon wells and other boreholes together has proved advantageous. Onshore hydrocarbon wells are generally the deepest boreholes, but for speed and therefore cost, they tend to core the potential reservoirs, with the other units being represented by cuttings. Generally, source rocks, if present, are represented by cuttings. This has proved a problem now that the well samples are being re-examined for shale gas potential, and instead it has been necessary to study the BGS stratigraphic boreholes that had cored the shale for fossils for biostratigraphical age determinations. These samples have become a critical resource, and an application never anticipated when the boreholes were originally drilled many decades earlier.

Biostratigraphy (palaeontology) collection

The Survey generally refers to its palaeontology collections as biostratigraphy collections to emphasize their importance for dating rather than taxonomy. The collections are dominated by invertebrates and microfossils, with relatively few vertebrates – other than those acquired for display in the former Museum of Practical Geology. The majority of specimens are stored by locality, although a reference collection of about 250 000 specimens – the Museum Collection, or Type and Stratigraphic Collection – is arranged by stratigraphy, then by taxonomic groupings and finally alphabetically by genus. This collection includes around 30 000

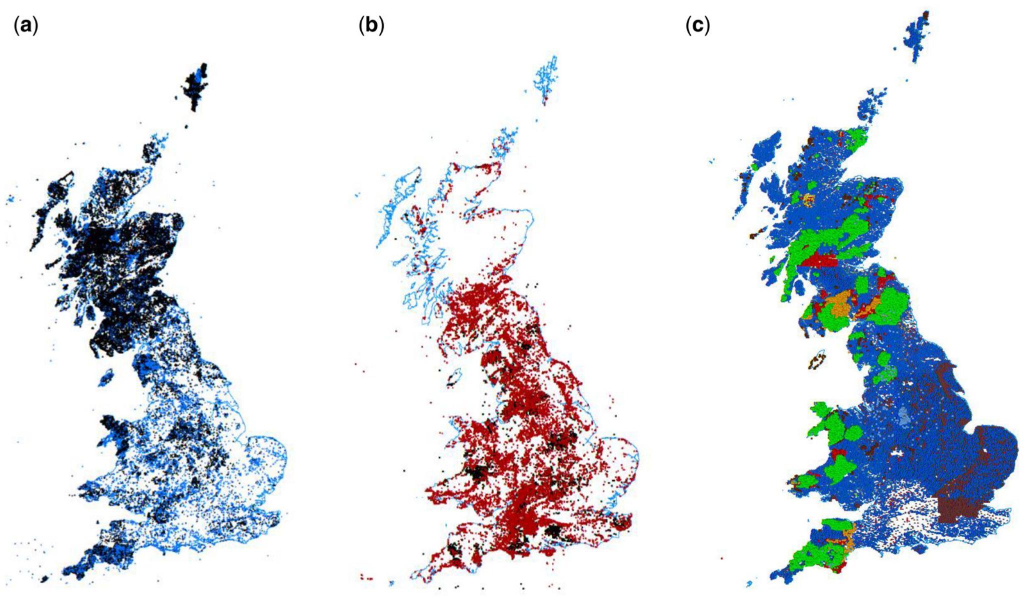


Fig. 4. Geographical information system plot showing the positions of the National Geological Repository samples in the onshore mineralogy and petrology (**a**), palaeontology (**b**) and geochemistry (**c**) collections. Source: contains Ordnance Survey data © Crown copyright and database right 2023.

typed, figured and cited specimens, of which approximately 7500 have actual type status. They are stored in wooden drawers with close-fitting glass lids. A typical drawer is illustrated in Figure 5. These then slot into over 200 wooden cabinets with tight-fitting wooden doors, providing very stable environmental conditions that have helped preserve the collection since 1935.

The Collections team has occasionally carried out larger exercises, including the moulding of 140 m^2 of Ediacaran fossiliferous bedding surfaces from Charnwood Forest, Leicestershire – the largest such exercise at the time. On Saturday 10 March 2007, the Leicester Literary and Philosophical Society, Section C, held a '*Charnia* at 50' symposium, celebrating 50 years since the (re-?)discovery of *Charnia masoni* in 1957 by three local school boys, including Roger Mason. Speakers included Guy Narbonne from Newfoundland and James Gehling from Australia (Ford 2006). During a field trip on the Sunday, Guy Narbonne was asked why there were thousands of fossils on some of the key Newfoundland coastal bedding planes, yet there were apparently only three on the similar-sized bedding plane that had yielded *Charnia masoni.* Guy replied that the Charnwood bedding plane had 160 years of moss, algae and lichen, and that it should be cleaned and then more closely studied.

With support from Natural England and the landowners, BGS Collections moulded approximately 1 m^2 of bedding plane in 'The Outwoods', including two specimens of *Cyclomedusa davidi.* This was followed by the 'Memorial Crags' bedding plane in Bradgate Park, which demonstrated clearly that many more fossils could be distinguished on moulds and casts with strong low-level illumination, than on the outcrop in typical natural lighting. Next, the 140 m^2 of bedding planes in the type locality of *Charnia masoni* were cleaned and moulded. The project was part funded by Natural England and carried out by Dave Williams of GeoEd Ltd, together with BGS staff. The resulting casts, when correctly illuminated, displayed over 1000 fossils, including several new taxa. They have underpinned several PhDs in Cambridge and Bristol and have contributed significantly to the revitalization of the study of the Ediacaran biota (e.g. Kenchington *et al.* 2018; Dunn *et al.* 2022). The casts are all available for *bona fide* study. Examples of two areas of the casts are shown in Figure 6.

Mineralogy and petrology collections

The historic display mineral collection from the Museum of Practical Geology was transferred to the NHM when the Survey moved to Keyworth in 1985, together with the gemstones and meteorites. The Survey retained its systematic collection of petrology hand specimens and thin-sections as well as its research collection of minerals.

The collections include a number of rocks collected by Charles Darwin with his original labels – 797 in the case of the 'cellular porphyry' illustrated in Figure 7. Darwin collected around 4000 rock

Fig. 5. A typical drawer containing type, figured and cited fossils. Note the edge of the tight fitting glass lid that assists the maintenance of environmental stability.

Fig. 6. Example casts of Ediacaran biota from Charnwood Forest, obtained as part of the 2008 moulding exercise.

specimens on his Beagle voyage, and number 797 came from Ascension Island, towards the end. The number is actually 3797, because Darwin used different coloured labels for the thousands: white from 1 to 999, red for the 1000s, green for the 2000s, and yellow for the 3000s. The label is actually faded yellow.

The Survey has two specialist collections of hazardous minerals. The former Atomic Energy Division Collection of Radioactive Minerals is now housed in a specially designed store. Figure 8 illustrates the contents of a typical tray.

The mineralogy and petrology collection also includes a specialist asbestos mineral collection, which has been fully decontaminated and imaged and is now correctly double bagged and safely held in a secure store. A typical specimen, chrysotile from South Africa, is illustrated in Figure 9. Both of these collections are exceptional in the UK and in demand by specialist researchers, trainers and consultants.

Fig. 7. Darwin specimen of ‘Cellular porphyry’ from Ascension Island. Specimen registration number UK.BGS.MR8755. Darwin number (3)797.

Fig. 8. Typical tray from the former Atomic Energy Division Collection of Radioactive Minerals, including monazite sand samples.

Geochemistry collection

We have good geochemical sample coverage for the whole of Britain (Fig. 4), originating from several Survey programmes.

The Mineral Reconnaissance Programme. The Mineral Reconnaissance Programme (MRP), sponsored by the Department of Industry (Dunham 1973), compiled geological, geochemical, geophysical, mineralogical and metallogenic information on prospective areas in Britain. Work was carried out at various scales, from regional reconnaissance surveys or appraisal, to the drilling of a geochemical or geophysical anomaly. Projects were multi-disciplinary and used a combination of tried and tested methods, together with innovative techniques arising from research and development programmes. Between 1972 and the end of the programme in 1997, 146 MRP reports had been issued covering localities across the UK. Over 12 500 rock samples were analysed for a variety of major and trace elements, mainly by X-ray fluorescence (XRF).

The Geochemical Baseline Survey of the Environment and the Tellus surveys (Ireland, Northern

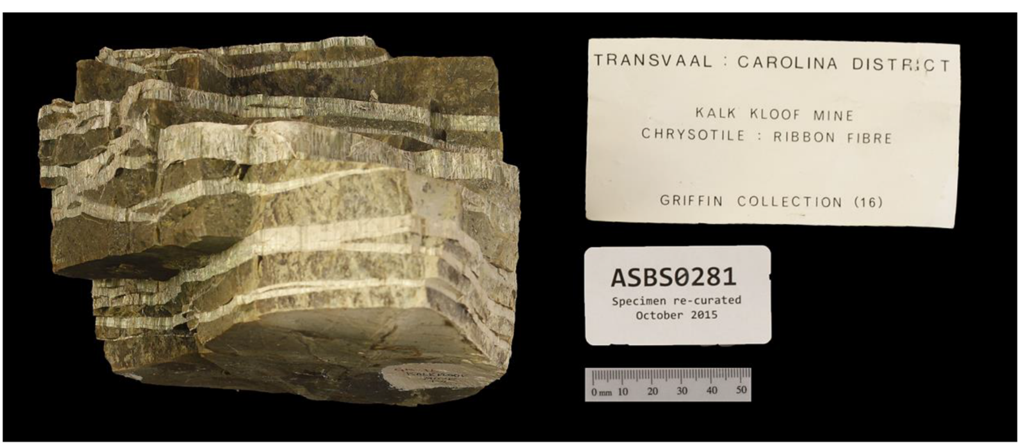


Fig. 9. Typical specimen from asbestos mineral collection. Registration number UK.BGS.ASBS0281 Chrysotile ribbon fibre, Kalk Kloof Mine, Carolina District, Transvaal, South Africa.

Ireland and SW England). The MRP also collected stream sediment samples and the −150 micron fraction of samples were analysed for a variety of elements including Ag, As, Au, Ba, Bi, Ca, Ce, Cu, Fe, Mn, Mo, Ni, Pb, Sb, Sn, Sr, Ti, U, V, W, Zn and Zr. Similarly, a panned heavy mineral concentrate was collected from the <2 mm sediment fraction and analysed for the same elements. This work then formed the Geochemical Baseline Survey of the Environment (G-BASE) Programme, with an average sampling density of one site per 1–2 square kilometres. Water samples and later soil samples were also collected, analysed and archived. Similar surveys, coupled with airborne geophysics, were then carried out as the Tellus projects.

Outreach and visits

The NGR has regular visits by individuals and groups to view the Keyworth Corestore in operation, including:

- foreign geological surveys, ministries of mines, minerals and hydrocarbons, and regulators;
- UK government officials and authorities;
- companies and organizations with an interest in geoscience;
- funding bodies;
- academics and university departments;
- geological societies and clubs;
- other groups and societies; and
- public open days.

The NGR maintains permanent displays illustrating key examples of core, including hydrocarbon reservoirs, aquifers, coal, minerals and biostratigraphical fossils. The exhibit also includes a tray of washed and dried cuttings in glass tubes. There are also current displays of building stones, an early collection of Antarctic rocks, a collection of Ascension Island and Galapagos volcanic rocks presented by Charles Darwin, and examples of Ediacaran fossils from nearby Charnwood Forest.

Accessing the collections for research and teaching

The Survey hosts a range of research visitors from commercial companies through academics, postdocs and PhD students to members of the public with *bona fide* projects. The facilities are also used for teaching workshops for professional groups, companies and final year undergraduate or MSc students (Fig. 10).

History of the collections

Museums

The Geological Survey was founded in 1835 by Henry Thomas De la Beche (1796–1855). De la Beche had lived in Lyme Regis when young, and his association with Mary Anning and other dealers and collectors had kindled an interest in palaeontology (Sharpe 2020). He joined the Geological Society of London and eventually began a survey of the rocks of Devon and Cornwall. Working with the mining community, he began to realize that a geological map of the UK and a collection of representative specimens would aid the development of the mineral industries. De la Beche then persuaded the

Fig. 10. Typical university teaching workshop visit for training in core logging and interpretation. Source: British Geological Survey, image no. P612721.

government to finance the work through the Ordnance Survey, and the Geological Survey was formed. In July 1835, De la Beche suggested to the Chancellor of the Exchequer that as the Survey was now collecting 'Specimens of the Application of Geology to the useful Purposes of Life', a museum was needed to illustrate the mineral productions of the country, and show their commercial value (Hunt and Rudler 1867). In 1837, the Geological Survey was allocated apartments in No. 6 Craig's Court and the Museum of Economic Geology was established. It grew quickly, and by 1839 Richard Phillips (1778–11 May 1851) was appointed as Curator.

The Geological Survey Act of 1845 provided the Survey with a legal framework, and transferred it from the Board of Ordnance to the Office of Woods, Forests, Land Revenues and Buildings. The Craig's Court museum was full and the Survey needed administrative offices, so arrangements were made in 1845 to construct a new museum and offices. The resulting Museum of Practical Geology, which ran from Piccadilly through to Jermyn Street, was opened by Prince Albert on 12 May 1851. Unlike many modern museums, it had all the 'crown jewels' on display in specimen-rich galleries (Fig. 11).

The museum continued until 1935, but during the 1920s structural problems became evident. The original construction had been prolonged and difficult, because during the installation of the foundations, a number of cesspits from the previous tenement buildings on the site (Derby Court) had to be removed. Whether due to the weight of rock and the compromised foundations, or possibly to Zeppelin damage during World War I, or even due to the nearby construction of the Piccadilly Underground line during the early twentieth century, the iron roof beams cracked and the glass panels fell out. Wooden scaffolding was installed to secure the roof and the museum was closed to visitors, although staff were still required to attend (Fig. 12).

A new site was then identified in South Kensington, between the Natural History, Science and Victoria and Albert Museums, and close to Imperial College and the Royal School of Mines. The Geological Museum was built, and the collections were moved there in 1935. The Museum of Practical Geology was demolished and replaced by a departmental store, which is now the flagship Waterstones bookshop.

Borehole department

The Geological Survey Act of 1845 (Fig. 13), as well as providing the legal framework, gave the survey right to access the land and to collect samples for the process of making geological maps. A series of other legislation and regulations, particularly the Mining Industry Act 1926, as amended by the Mines and Quarries Act 1954 and the Science and Technology Act 1965, imposed a requirement for anyone proposing to drill a borehole or shaft to a depth of more than 100 ft (30 m) for the purpose of searching for or getting any minerals, to notify BGS of the intention, and to keep records of the rocks encountered and samples or core, the latter for at least 6 months. BGS then has the right to visit, take copies of the logs and subsample the cores.

A good example is Hardstoft 1 (BGS registration number: SK46SW/1), the first onshore oil well,

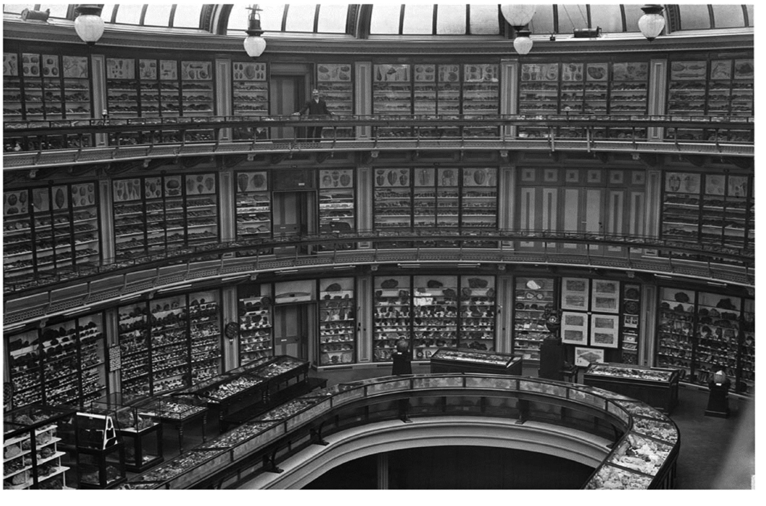


Fig. 11. Interior of the Museum of Practical Geology, Jermyn Street, London. Source: British Geological Survey, image no. P640481.

Fig. 12. Main floor of the museum with wooden scaffolding to support roof whilst cracked ironwork was inspected. Source: British Geological Survey, image no. P640471.

where the log shows that bags of samples were examined at Pearson's Yard in Chesterfield between Friday, 6 December 1918 (Fig. 14) and 7 May 1919 with the vertical section being drawn by C.D.C. (probably Clement Dyke Cooke (1884–1971) who was appointed a Draughtsman (First Class) in June 1919) on 28 November 1919. The well was subsequently deepened in 1938–39 by the D'Arcy Exploration Company Ltd, when an early 'composite log' was produced (Fig. 15).

All early hydrocarbon and petroleum exploration in the UK was done under the Mining Act 1926 and subsequent acts. Over the years, a significant collection was assembled from boreholes and surface outcrops, and the borehole logs were all geospatially indexed and plotted up to produce an important archive that was used by Survey staff whilst surveying and interpreting individual map sheets.

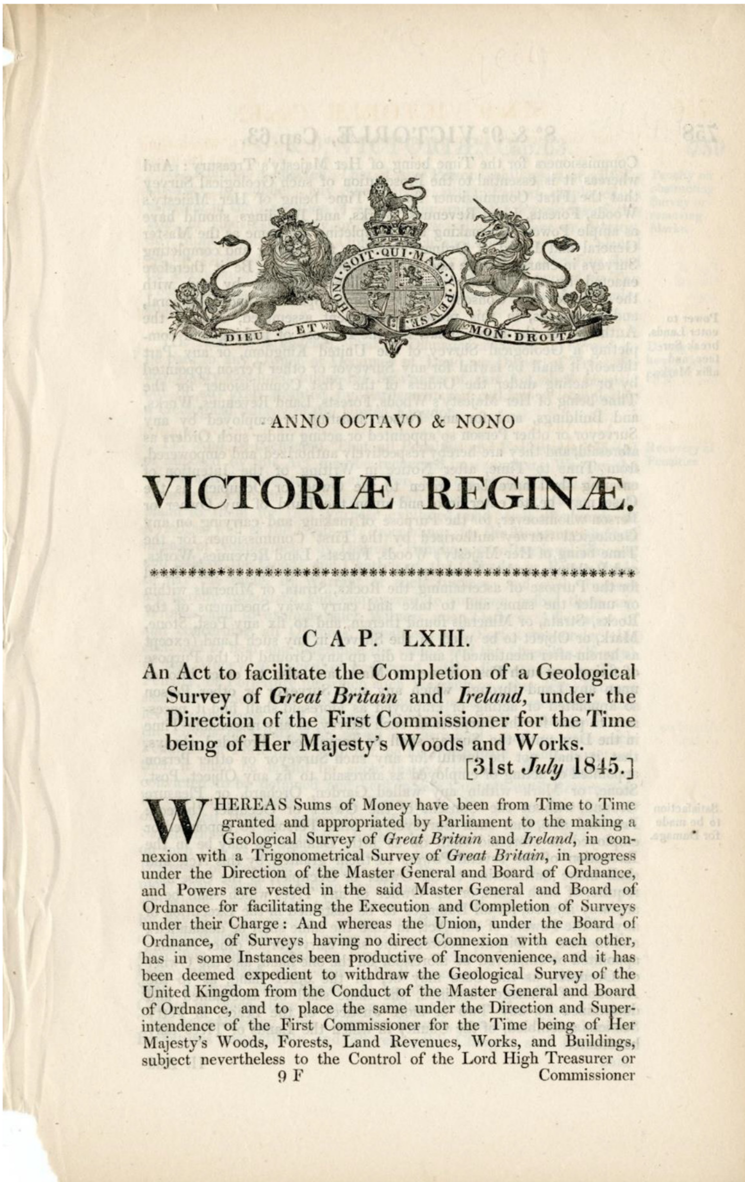
The borehole collection can trace its origins back to the mid-1940s, after an earlier attempt in the 1920s. Figure 16 illustrates a probably typical core workshop from 1945, taken in a yard behind the Geological Museum, South Kensington. There are probably five geologists with hammers, pens and notebooks, and logs (and college scarfs and pipes), plus a similar number of technicians.

There was nowhere suitable in the Survey's premises to store complete sticks of core, so short representative sections and hand specimens demonstrating significant features were extracted, designated as 'Registered Borehole Samples', and archived into the Survey's standard lidded wooden rock trays (Fig. 17). Register entries were made including registration numbers (commencing with B1), borehole names and sample depths. Generally, the lithology or lithostratigraphic unit was recorded, and sometimes the date and Survey Officer(s) responsible, plus the storage location (Fig. 18, Sample B1 was from the Keuper Marl of the Altcar Borehole, Lancashire, 50 k sheet 83 (Fig. 19)). A comment has been added later: 'shaly w. gypsum veins', but unfortunately (and unusually), there is no record of the depth. It seems most likely that these samples are from the Altcar BH (SD30NW108), referenced by Morton (1896).

There is evidence that the early part of the Borehole Collection was assembled in the Museum of Practical Geology before the move to South Kensington. It is possible that the closure of the museum to the public allowed some staff time to organize and consolidate collections of individual borehole specimens into a single collection ahead of a potential move to new premises. The early samples (B1–B5041) are entered in a leather-bound register titled 'MUSEUM OF PRACTICAL GEOLOGY: INVENTORY OF BORING SPECIMENS'.

Thereafter separate register sheets were used. Specimens B1–B1600 are entered in a characteristic copperplate script but thereafter a range of handwriting styles are present. A few of the first 1600 specimens are dated: B1440 is given as June 1926.

Most of the boreholes were examined for macrofossils to derive biostratigraphical dates, so there was an added incentive to break the cores up. Boreholes drilled by the Survey were generally fully cored because of the interest in the fossils to date the rocks. Hydrocarbon wells tended to be mostly



ANNO OCTAVO & NONO

VICTORIÆ REGINÆ.

C A P. LXIII.

An Act to facilitate the Completion of a Geological Survey of *Great Britain* and *Ireland*, under the Direction of the First Commissioner for the Time being of Her Majesty's Woods and Works.

[31st *July* 1845.]

WHEREAS Sums of Money have been from Time to Time granted and appropriated by Parliament to the making a Geological Survey of *Great Britain* and *Ireland*, in connexion with a Trigonometrical Survey of *Great Britain*, in progress under the Direction of the Master General and Board of Ordnance, and Powers are vested in the said Master General and Board of Ordnance for facilitating the Execution and Completion of Surveys under their Charge: And whereas the Union, under the Board of Ordnance, of Surveys having no direct Connexion with each other, has in some Instances been productive of Inconvenience, and it has been deemed expedient to withdraw the Geological Survey of the United Kingdom from the Conduct of the Master General and Board of Ordnance, and to place the same under the Direction and Superintendence of the First Commissioner for the Time being of Her Majesty's Woods, Forests, Land Revenues, Works, and Buildings, subject nevertheless to the Control of the Lord High Treasurer or

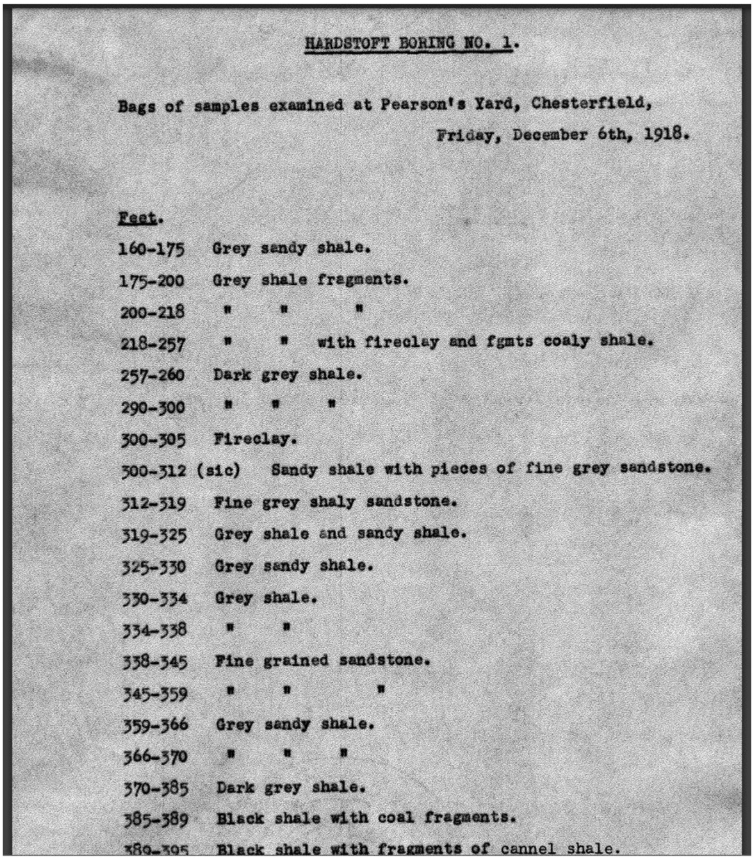
9 F Commissioner

Fig. 13. The title page of the Geological Survey Act 1845. Source: British Geological Survey, image no. P815508.

cuttings (recovered rock chips from the drill bit) for speed and economy. Unwashed cuttings tended to be held in canvas sample bags to allow the material to dry out slowly, whereas cuttings that had been washed and dried in the laboratory were historically in glass tubes and more recently in brown paper envelopes (Fig. 20).

In Summer 1959, the Survey opened an office in Leeds and transferred the staff there from its offices in Newcastle and Manchester, which were then closed. Some staff based in London, but also working in the north of England, were also transferred. All collections and records pertaining to the north of England were transferred, or in some cases copied. Cores and other samples were stored in the Kippax Rock Store, a former food storage warehouse constructed in 1942 (Simpson 1982).

Because of the size of the store, core could be held in 1 m-long boxes as it was received, with no need to break it up and just keep the highlights (Fig. 21). The early hydrocarbon material from the southern North Sea was held here.



HARDSTOFT BORING NO. 1.

Bags of samples examined at Pearson's Yard, Chesterfield,
Friday, December 6th, 1918.

Feet.	
160-175	Grey sandy shale.
175-200	Grey shale fragments.
200-218	" " "
218-257	" " with fireclay and fgmts coaly shale.
257-260	Dark grey shale.
290-300	" " "
300-305	Fireclay.
300-312 (sic)	Sandy shale with pieces of fine grey sandstone.
312-319	Fine grey shaly sandstone.
319-325	Grey shale and sandy shale.
325-330	Grey sandy shale.
330-334	Grey shale.
334-338	" "
338-345	Fine grained sandstone.
345-359	" " "
359-366	Grey sandy shale.
366-370	" " "
370-385	Dark grey shale.
385-389	Black shale with coal fragments.
389-395	Black shale with fragments of cannel shale.

Fig. 14. The first page of the record of samples from Hardstoft 1 Boring, December 1918.

In the late 1970s, the headquarters of the Survey were moved from the Geological Museum, South Kensington to the site of the former Mary Ward College, Keyworth, near Nottingham. The central directorate moved in the late 1970s, together with an increasing number of scientific and administrative staff. The deconsecrated former chapel was used as a temporary core store, before a purpose-built core and collections facility was opened in 1985, together with a palaeontological museum. A similar petrological museum had been planned, but was never built. During 1985–86, the collections held in London, Leeds and Newcastle were transferred to Keyworth, before the offices were closed, and the museum transferred to the NHM.

The southern North Sea hydrocarbon cores and samples were not transferred to Keyworth, but instead they joined central and northern North Sea hydrocarbon well samples that had previously been stored by the Survey in Scotland, at a newly established Department of Trade and Industry (DTI) core store at Gilmerton, which opened in 1984 on the southern side of Edinburgh. The Gilmerton core store was actually a converted Renault show room and garage, and would have been familiar to many hydrocarbon geologists (Fig. 22). By this time, the petroleum legislation had established regulations defining the scope of core and cuttings to be deposited with the DTI archive as a licence condition. PON9 and PON9b (Petroleum Operations Notices 9 and 9b (onshore)) made under the Petroleum Act 1998, and the Retention Regulations (and associated guidance) and Disclosure Regulations (and associated guidance) made under the Energy Act 2016 formally define the requirements.

In practice, where core is taken, the current requirement is for:

> 'A complete longitudinal section comprising at least one quarter of the core from exploration wells and one half of the core from development wells. If the core diameter is less than 7.6 cm (3 inches) the OGA (Oil and Gas Authority, now North Sea Transition Authority) collection at the NGR should also receive at least one half of the core from exploration wells'
>
> (Oil & Gas Authority 2019).

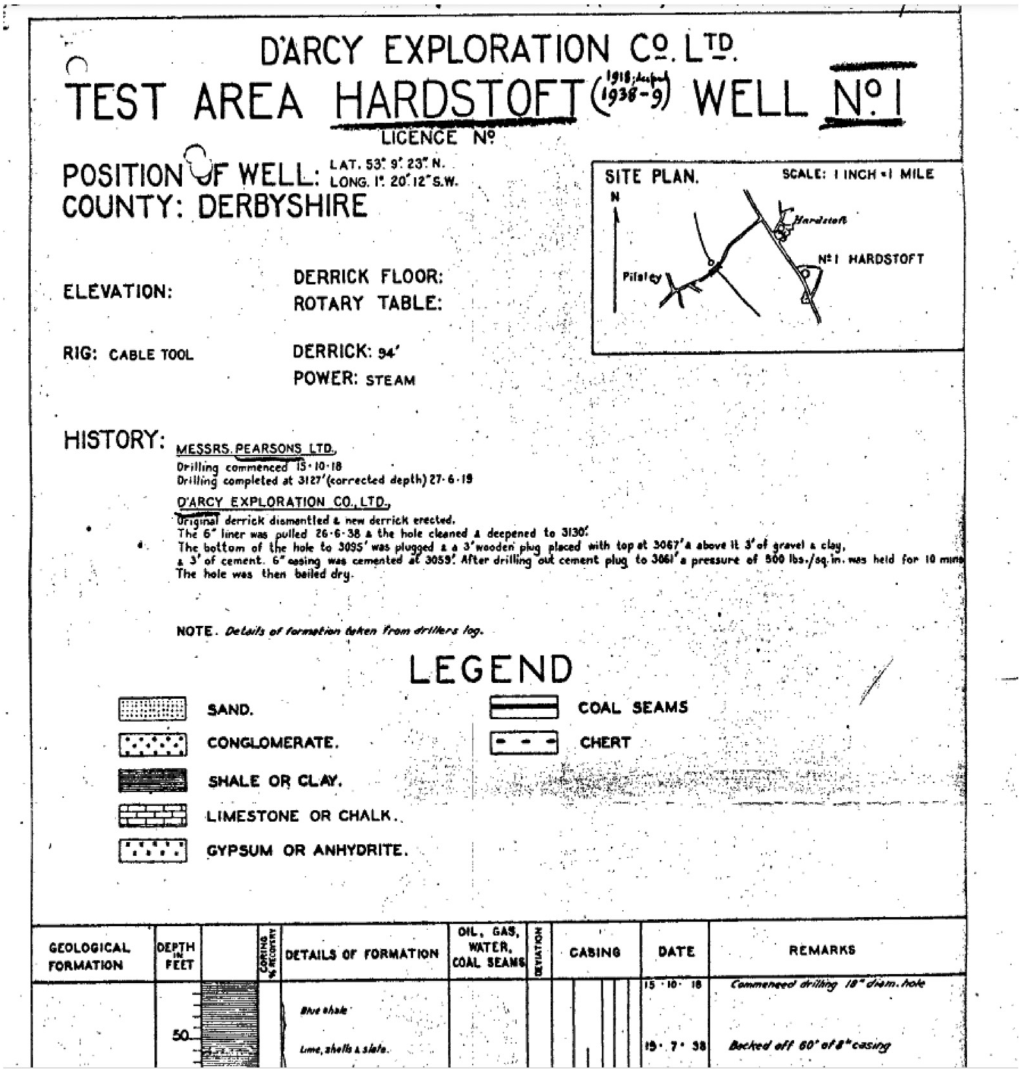


Fig. 15. The first page of composite log of Hardstoft 1 Boring, produced when the well was deepened in 1938–39 by D'Arcy Exploration Company Ltd.

The core is to be 'Routinely reported no later than 6 months from the date of completion of the wellbore (the 'regulatory completion date') as recorded in WONS (Well Operations Notification System)' (Oil & Gas Authority 2019). The main core cuts are illustrated in Figure 23.

For all wells, a full set of washed and dried cuttings is submitted, with a minimum of 100 g from each sample. A maximum of 6 months after the date of completion of the wellbore, as recorded in WONS, is allowed (Oil & Gas Authority 2019).

Consolidation of core stores at Keyworth

In 2009, the Survey decided it could improve the efficiency and effectiveness of the core store operation by transferring the material then held in Edinburgh, at Gilmerton and at Loanhead, to Keyworth to form a centre of excellence for core storage and research. There was an immediate outcry from many of the Gilmerton users who were based in Aberdeen and found Edinburgh a convenient location. As key reasons against the move, they cited potential damage to fragile sediments, such as the

Fig. 16. Examining core samples in the courtyard of the Geological Survey Museum, South Kensington. Source: BGS (British Geological Survey) Stubblefield Collection, *c.* Nov 1945. BGS image no. P537719.

poorly consolidated Forties sands, and access delays during the transfer.

When the Gilmerton cores had been curated into cardboard boxes, there was no anticipation of any future moves, and empty spaces were not filled with packers. Consequently, a complete examination of the core box would be required, with empty spaces being filled with Plastazote® (an inert conservation-

Fig. 17. A typical Survey rock tray containing Registered Borehole Specimens.

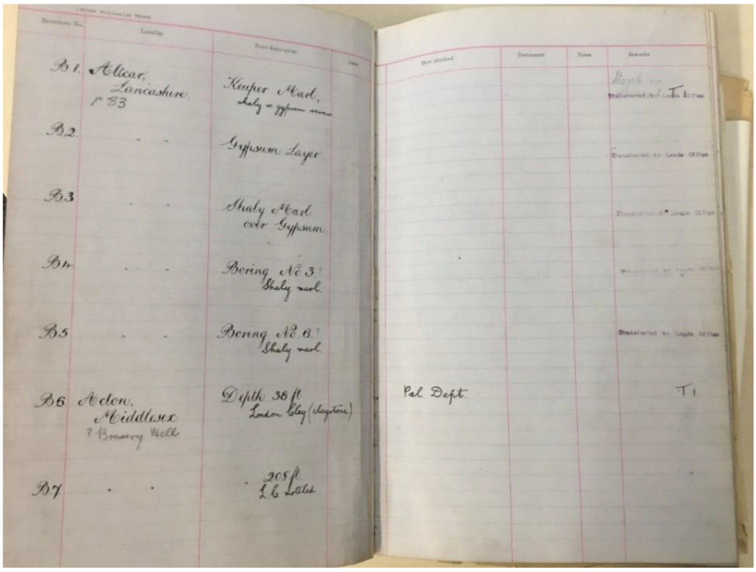


Fig. 18. Museum of Practical Geology, Inventory of Boring Specimens. Register entries for B1 to B7. No date, but possibly *c.* 1925.

grade foam) or 'scrunched-up' acid-free tissue. As it was necessary to open every box, then it would be the ideal opportunity to photograph every core. If high-resolution images of every core could be taken, without slowing down the packing process, and the images made freely available, it would be an added benefit to the move and should gain extra support. The plans were announced at a consultation meeting, when it was mentioned that the estimated processing time would be between 1.0 and 1.5 minutes per box. The offer of images was very well received, but staff from a service company argued

Fig. 19. Registered Borehole Specimens B1 and B3 from Altcar Borehole, Lancashire. Brief descriptions state 'Keuper Marl' and 'Shaly Marl over Gypsum', respectively. Source: British Geological Survey, images nos P1025645 and P1025649.

Fig. 20. Washed and dried cuttings samples. Early ones in glass tubes, later ones in brown paper envelopes.

that as it generally took around 10 minutes to photograph a core, the whole move was likely to take over 10 years, rather than the 18 months suggested.

To make the core photographs of sufficiently high resolution to be really useful and an adequate incentive for the move, it was determined that a 1 m size-for-size image needed to be printed at 200 dpi, which equated to 25–30 MB images. The images needed to be downloaded within a few seconds, which excluded the use of cameras with scanning backs. The best choice at the time was a Phase One™ P45 camera, which cost approximately £25k.

Fig. 21. Drillcore held in 1 m cardboard boxes (1.8 mm thick, kraft covered both sides). Both cores have been halved before arrival at the British Geological Survey. Core on left is an aquifer; core on right is an oil reservoir. Plugs for porosity and permeability testing were taken before core was halved.

The images are made available as 10 MB files in JP2 or JPG2000 format. They are currently viewed online using the IIPMooViewer™ (IIPImage HTML5 Ajax High Resolution Image Viewer – Version 2.0), which downloads just the piece of the image you are currently viewing (i.e. there is no need to wait for the full 10 MB to download). In practical terms, JP2 files of this size and compression represent a virtually lossless compression (Fig. 24).

The Gilmerton team achieved an average of 1.25 minutes per box by using a conveyor system borrowed from the manufacturing industry, probably one of the first uses of such a system in digitization workflows (Fig. 25).

The core boxes were collected from the store, and each one was loaded into a special jig with rulers and standard grey and colour scales. The barcode on the box was scanned, and a small screen within the field of view was populated from the core database. It was recognized that many geologists preferred the traditional method of incorporating the basic metadata in the image, rather than just linking them later. The photographer then checked that the metadata on the screen agreed with any markings (particularly depth markings) on the boxes, and then scanned a barcode to take the photograph. A few seconds later, after the image had downloaded to the photographer's screen, they either accepted or rejected it by scanning appropriate barcodes. If they spotted metrication errors, they could correct the common ones by scanning other barcodes, or they could flag the box for subsequent attention by the conservation team. The boxes then

Fig. 22. The former Department of Trade and Industry (DTI) UK Continental Shelf core store at Gilmerton, Edinburgh. Source: British Geological Survey, image no. P504984.

moved down the conveyor for addition of packaging, and then the box barcode was linked to the pallet, before the pallet was held for transport to Keyworth. The entire methodology for the transfer is detailed by Howe (2011).

The three big challenges

During the period of 2018–21, three increasingly big challenges were compounded by the Covid pandemic.

Reduced commercial income

BGS charges for commercial access to the collections, but in line with NERC policy, purely to cover the additional costs. These include retrieving the material, laying it out, assisting with any subsampling, returning the material afterwards and ensuring compliance with the rules for returning raw and interpretative data, plus any preparations, offcuts and residues.

Between 2010 and 2015, annual commercial income peaked at almost £250k, and proved to senior

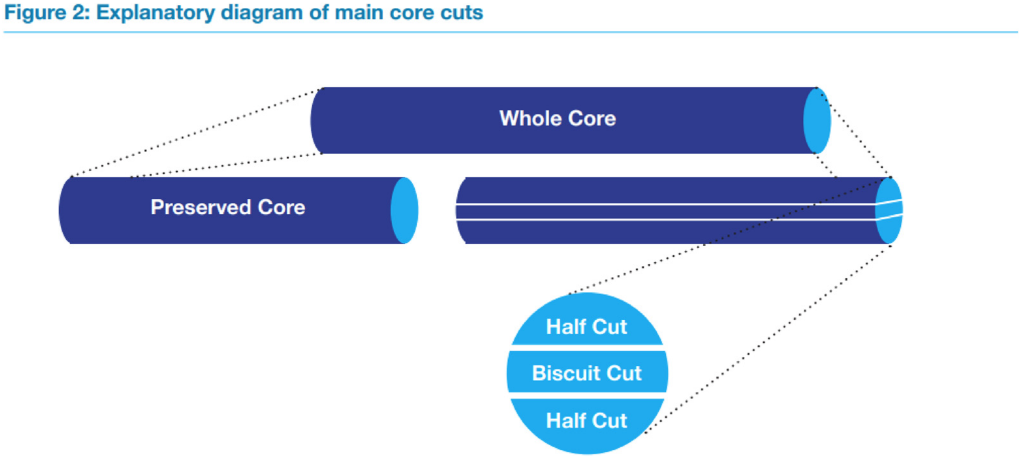


Fig. 23. Explanatory diagram of main core cuts. Figure 2, pp. 23 in Reporting and Disclosure of Information and Samples. Source: © OGA Oil and Gas Authority 2019. Reused under terms of Open Government License.

Fig. 24. Typical example of UK Continental Shelf high-resolution core image showing two boxes of core that would have been stored within a single outer box on the Gilmerton shelves. Also visible are the screen with the metadata download from the sample database, standard grey and colour scales, and an appropriate scale.

management the importance of the service provided. Most of this came from hydrocarbon and shale gas investigations. With the move to renewable energy and the moratorium on shale gas, annual income declined to £50k. With the restrictions caused by the Covid pandemic, income ceased.

Reduced central funding and investment

This period also saw a gradual reduction in real-terms central government funding. This made the business case for investing in extending the facility more difficult to argue, particularly in view of the reduced commercial income, the key indicator of commercial impact.

Increased operator disposal of legacy material

At the same time as resources were declining, operators were decommissioning fields, reviewing their legacy holdings in commercial storage and deciding to give OGA 6 months' notice of intended disposal.

Fig. 25. The conveyor system used for core photography, core audit and then core packing at the Gilmerton core store, before the boxes were palletized and shipped to Keyworth. Source: British Geological Survey, image no. P771988.

This material is then automatically offered to BGS to fill any gaps and augment heavily subsampled holdings. This has resulted in an increasing amount of material coming to BGS at a time when empty storage space is running low.

Solutions to current challenges

The potential solutions to the three challenges are based around 'smarter working'.

Smarter working: digitization

The Survey has been at the forefront of digital working for over 25 years, with online geographical information system (GIS) access since 2000, and a growing number of online databases between 2000 and 2010.

As part of the consolidation of core storage at Keyworth, the UKCS hydrocarbon cores were imaged at high resolution and made publicly available, as described above. A similar exercise has been done with the main collection of 160 000 petrological thin-sections, although these are more a discovery tool than a research tool. Fully rotatable and zoomable thin-section images can take several GB of storage. Both plane polar and cross-polar images can be viewed from the BGS online petrology database 'Britrocks' and also from the BGS online GIS, GeoIndex.

A similar exercise for British type fossils was funded by Jisc (formerly the Joint Information Systems Committee) as 'GB3D Type Fossils' (http://www.3d-fossils.ac.uk/) and carried out with a number of partner organizations. BGS rephotographed all of its type macrofossils and their labels, and where appropriate, took stereopairs, which were made available as red-cyan anaglyphs. Two thousand of the best specimens across the partners were also laser scanned to derive 3D digital models. Everything is made available for download for academic use and private study under a Creative Commons Attribution-NonCommercial-ShareAlike Licence. At the time (2013), this was the largest collection of downloadable 3D fossils.

The latest digitization facility is the 'Core Scanning Facility' described elsewhere in this volume (Damaschke *et al.* 2023). Some digitized cores are already available for downloading from the BGS website.

These online resources mean that users can better select sections of core, or rock or fossils they wish to see. Some enquiries can be solved without needing to visit (e.g. linking core depths to log depths, or selecting small pieces of core for subsampling for thin-sections). Other enquiries still require a visit (or possibly a loan), but the users can be far more selective in what they wish to view, allowing efficiency gains on both sides. The ease of viewing also means the user is less likely to miss critical samples; their work is more effective.

Smarter working: linking data back to the samples

There is a growing realization by academics of the importance of tracking their results back to the datasets and then to the underlying samples. It has long been a requirement that anyone loaning or working on BGS material submits copies of any resulting papers. This has been extended with the subsampling of boreholes to submit raw data and any interpretative reports or papers within a strict timeframe. Raw data are held confidential for 2 years and any interpretative reports for 5 years, unless there are commercial reasons for a longer period of confidentiality.

There are significant efficiency gains in linking any subsampling points to the resulting data, and barcodes are used to implement this. Anyone subsampling a borehole drops in a barcoded card (with an SSK (subsample Keyworth) series registration number on it – see Fig. 26) where the sample was taken. A copy barcoded sticker is then placed on the sample bag, and details of the SSK numbers, boreholes and depths are entered on a spreadsheet. This is then used to monitor the return of the data, which must include the SSK numbers. It should then be simple to scan the barcode in the core and retrieve the relevant deposited data. This removes the need for the unplanned duplication of analyses and promotes the more efficient and effective study of the core by facilitating access to all the relevant data. In due course, increased use of DOIs and other actionable PIDs (Persistent Identifiers) will greatly improve the linkage of samples to databases and then to publications, as well as in reverse.

Smarter working: aggregating databases

Discussions in the collections community are increasingly favouring the routine exporting of data from myriads of local databases to a few national or international aggregating databases. Coupled with this is the realization that basic metadata are not enough, but links such as to images, analyses, CT scans and field notebooks are of growing value. The concept of the extended digital specimen is growing in importance and support. Within the UK there is now UKRI funding for DISSCO-UK (Distributed System of Scientific Collections: Smith *et al.* 2022), and this is likely to be the way forward.

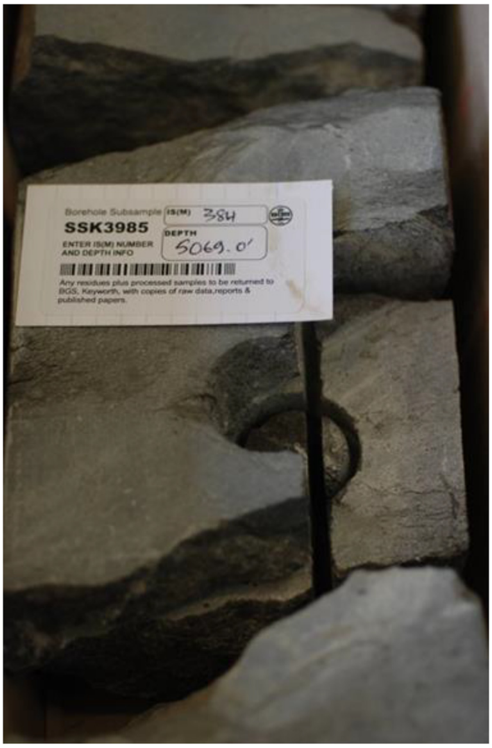


Fig. 26. Example of a barcoded subsampling ticket placed in the core to enable quick linking of the resulting data to its precise origin.

Smarter working: improved collaborative working

In addition to improving access for users, there are clearly potential efficiency gains from working more closely with 'suppliers', in particular the hydrocarbon operators. Much of the expense in curating new core is re-boxing and auditing. If core for archiving arrived in standard boxes it would simply need quality control, labelling and uploading to the database before placing on the shelf. This methodology avoids much of the labour, the cost of new boxes and the cost of disposing of the old, and it should not add significantly to the operator's costs. Similarly, there will probably be digital records of the top and bottom depths of core in each box, so exporting the metadata should avoid the need to re-key, and minimize consequent errors. These changes have been introduced under the Reporting and Disclosure of Information and Samples Guidance, and are already producing improvements.

BGS is now trialling an Application Program Interface (API) for its UKCS core images and core materials holding database, which is hoped will benefit operators who wish to link them to their systems. Using an API rather than simply mass downloading blocks of images helps BGS monitor usage and justify the deployment of maintenance resources.

Smarter working: improved targeting of resources

One function that consumes significant resources from both the NGR and the operator is the selection and curation of supplementary material from that earmarked for potential disposal.

Currently, the NGR operates the following selection priorities:

(1) core and samples currently missing from the PON9/EA16 requirements;
(2) additional set of washed and dried cuttings;
(3) a set of unwashed cuttings, if not already held;
(4) thin-sections, micropalaeo preparations, sidewall cores;
(5) additional core if required by usage matrix (see Table 2); and
(6) additional core if strong science case.

The most challenging criterion to evaluate is the science case. In most cases this involves identifying wells that have been used in key reference sections. The National Hydrocarbons Data Archive initiative involved an experienced hydrocarbon geologist assessing the science case for any core offered, but it proved too expensive. Attempts to use metrics such as publication citations have not proved helpful. Expert knowledge is the only solution, but it is unclear as to how this can be obtained without the expenditure of significant resources.

Table 2. Selection matrix used for determining when additional cuts of core are required to augment the existing archive

Subsampling	Quality of existing OGA core judged from images		
	Poor: narrow and badly broken	Intermediate	Good: wide cut in good condition
Never	No	No	No
Rare: 1–5	Yes	No	No
Frequent: 5+	Yes	Yes	No

Selection depends on the quality of the existing core and the frequency of viewing and subsampling. Where an archived core has never been subsampled, an additional cut would not be requested (no). Where an archived core had been frequently subsampled (on more than five occasions), an additional cut would be requested (yes) unless the existing cut represented a significant proportion of the original core and was in good condition (no).
OGA, Oil and Gas Authority.

Conclusions

The main conclusions of the review are as follows.

- There are opportunities to improve the core and sample archive, but they require smarter working due to central funding constraints.
- There is a need to re-evaluate alternative funding models.
- Better databases, data management and digital proxies facilitate more efficient working.
- There is no point in archiving core and samples without including and linking to basic metadata and any existing or subsequent analyses. Data, preparations (e.g. thin-sections, micropalaeontology slides) and related images need linking to their precise positions to remove the need for repeat analyses of a scarce resource, whilst also promoting better-informed research.
- Many areas of the UKCS are now so well characterized that they can be used to develop and test geological hypotheses for the long term.

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Author contributions **MPAH**: conceptualization (lead), data curation (lead), investigation (lead), project administration (lead), supervision (lead), writing – original draft (lead), writing – review & editing (lead).

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References

Bailey, E.B. 1952. *Geological Survey of Great Britain*. T. Munby, London, xii.

Damaschke, M., Fellgett, M.W., Howe, M.P.A. and Watson, C.J. 2023. Unlocking national treasures; the core scanning approach. *Geological Society, London, Special Publications*, **527**, https://doi.org/10.1144/SP527-2022-58

Dunham, K.C. 1973. *Report of the Director*. Pp. 3–4 in Annual Report for 1972. Institute of Geological Sciences, London.

Dunn, F.S., Kenchington, C.G., Parry, L.A., Clark, J.W., Kendall, R.S. and Wilby, P.W. 2022. A crown-group cnidarian from the Ediacaran of Charnwood Forest, UK. *Nature Ecology & Evolution*, **6**, 1095–1104, https://doi.org/10.1038/s41559-022-01807-x

Ford, T.D. 2006. *Charnia masoni* – 50th Birthday Party. *Mercian Geologist*, **16**, 280–284.

Hollyer, S.E. and Wheatley, C.W. 2000. *User guide to the British Geological Survey material collections*. British Geological Survey Report, **WO/00/002**, https://nora.nerc.ac.uk/id/eprint/502422/

Howe, M.P.A. 2011. *Gilmerton Core Sample Collection: Keyworth Transfer Methodology*. British Geological Survey Report, OR/11/049 (Unpublished), https://nora.nerc.ac.uk/id/eprint/531280/

Hunt, R. and Rudler, F.W. 1867. *A Descriptive Guide to the Museum of Practical Geology, with Notices of the Geological Survey of the United Kingdom, the Royal School of Mines and the Mining Record Office*. 3rd edn. H.M.S.O., London.

InfraPortal 2022. National Geological Repository, British Geological Survey. https://www.infraportal.org.uk/infrastructure/national-geological-repository-british-geological-survey [downloaded 28 March 2023].

Kenchington, C.G., Harris, S.J., Vixseboxse, P.B., Pickup, C. and Wilby, P.R. 2018. The Ediacaran fossils of Charnwood Forest: shining new light on a major biological revolution. *Proceedings of the Geologists' Association*, **129**, 264–277, https://doi.org/10.1016/j.pgeola.2018.02.006

Morton, G.H. 1896. Recent borings in the Red Marl, near Liverpool. *Geological Magazine*, **3**, 496–498, https://doi.org/10.1017/S0016756800131589

Oil & Gas Authority. 2019. *Reporting and Disclosure of Information and Samples Guidance*. North Sea Transition Authority.

Sharpe, T. 2020. *The Fossil Woman: A Life of Mary Anning*. Dovecote Press.

Simpson, F. 1982. *A users' guide to core-storage in the British Isles and Republic of Ireland*. Report, Institution of Geological Sciences, **No. 82/2**.

Smith, V.S., Hardy, H. *et al*. 2022. *Harnessing the Power of Natural Science Collections: a Blueprint for the UK*. Natural History Museum, 1–28, https://doi.org/10.5281/zenodo.6472239