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Overview of the Nirex Core Characterisation Programme

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RP Shaw and DE Bailey

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Core Characterisation, Sellafield, Dounreay, stratigraphy, structural geology, mineralogy, petrology, sedimentology, biostratigraphy, hydrogeology, geochemistry, engineering geology, geotechnics, and geophysics

Front cover

Cathodoluminesce image showing zonation within calcite crystals associated with vuggy porosity in a mineralalised fracture, PRZ2 borehole, Nirex Sellafield Investigations

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Keyworth, Nottingham NG12 5GG

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Parent Body
Natural Environment Research Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU

☎ 01793-411500 Fax 01793-411501
www.nerc.ac.uk

EXECUTIVE SUMMARY

The British Geological Survey was commissioned by United Kingdom Nirex Limited ('Nirex') to manage the Off-Site Core Characterisation Programme (OSCCP) as part of its investigations into the Sellafield and Dounreay areas as possible sites for a deep repository for solid low and intermediate level radioactive waste. The OSCCP provides rock property data for geological interpretation, safety assessment, and design studies associated with the repository development. A broad range of geoscientific tests and analyses were performed on samples of core, and on pore-waters extracted from core, from Nirex's deep drilling programme. In addition, the geological and geotechnical properties of the core were comprehensively logged. Interactive matching of core features and geophysical images allows the core to be orientated. The OSCCP draws on the expertise of geoscientists from many disciplines including stratigraphy, structural geology, mineralogy, petrology, sedimentology, biostratigraphy, hydrogeology, geochemistry, engineering geology, geotechnics, and geophysics. The broad scope of the programme was met by establishing liaison between a number of scientific consulting organisations. Work carried out under the OSCCP was controlled by Quality Assurance standards. A sample tracking database allows each sample to be identified along with its current location, sub-samples, and the tests to which it has been subjected.

The Nirex core characterisation programme for the Sellafield and Dounreay sites was designed for a hard, fractured rock site. The methodologies used in the Nirex Programme are not necessarily directly applicable or relevant to site investigation in a soft rock/clay site such as Horonobe.

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1. INTRODUCTION

The Off-Site Core Characterisation Programme (OSCCP) was established in 1991 and designed to provide geological, geotechnical, and hydrogeological data on core samples from the Nirex boreholes at Sellafiled and Dounreay. The data obtained were used for geological interpretation, safety assessment, and design studies associated with the investigation of the these two sites as possible sites for the development of a deep repository for solid low and intermediate level radioactive wastes. In 1992 Nirex decided to concentrate its efforts on the Sellafield site and work on core samples from the Dounreay site was restricted. This report concentrates on the work associated with the Sellafield investigations. The Nirex core characterisation programme for the Sellafield and Dounreay sites was designed for a hard, fractured rock site The methodologies used in the Nirex Programme are not necessarily directly applicable or relevant to site investigation in a soft rock/clay site such as Horonobe.

Prior to the excavation of an exploratory shaft, core was the sole source of representative samples (i.e. those not subjected to a prolonged history of surface processes) of the potential host rock and overlying formations. Some of the data requirements identified above can be met by a comprehensive study of the core, including logging, index testing, laboratory testing, and the application of a range of analytical techniques. These activities, which were intended to supplement and extend the scope of work already performed at the deep borehole sites, are referred to collectively in this document as the 'Off-Site Core Characterisation Programme'.

The scientific and technical requirements of the OSCCP were diverse, but may be considered to lie broadly within the following disciplines:

- Hydrogeology and geochemistry
- Structural geology
- Mineralogy, petrology, and sedimentology
- Stratigraphy
- Engineering geology and geotechnics
- Geophysics

A detailed understanding of the regional geological setting, including structural and stratigraphical aspects, was fundamental to the Sellafield and Dounreay investigations. This information was used in predictive modelling of the hydrogeology and geological structure of the site and thus influences any assessment of the long-term performance of the repository in isolating harmful radionuclides from the biosphere (Horseman et al. 1992). Since a borehole provides, essentially, a one dimensional 'sample' of the rock mass it penetrates, a basic geological requirement of the investigations was the ability to generalise the findings from this limited sample to three dimensions, at both the local and the regional scale. The geological sciences provide a number of well-established methodologies which were aimed at meeting this requirement. In simple terms the process had three components: (a) establishing borehole–borehole correlations, (b) establishing borehole–regional correlations, and (c) defining the regional geological structure. The contributing disciplines each have specific demands of the OSCCP in the following areas:

- Structural Geology

- Lithostratigraphy
- Biostratigraphy
- Magnetostratigraphy
- Chronostratigraphy
- Geophysics (Inter-borehole Geophysical Correlation)

In addition to activities performed under the Core Characterisation Programme contract, AEA Technology and its subcontractors undertake basic research on radioactive waste disposal within the framework of the Nirex Research and Development Programme. In the course of this research, some measurements of rock characteristics data were made on the drillcore. NGI (Norwegian Geotechnical Institute) undertake rock mass classification activities supported by the Core Characterisation Programme.

2. ON-SITE OPERATIONS

Prior to their shipment to the British Geological Survey at Keyworth, cores from Nirex's deep drilling programme were cleaned, photographed, and engineering geologically logged at the drill site (Plate 1). Detailed discontinuity logs were also prepared at this stage. Samples required for specialist testing were taken as soon as possible, allowing for on-site activities, after removal of the core from the borehole and preserved in foil, film, and wax. This helps to retain, as closely as possible, the *in situ* moisture content and pore fluid chemistry and protects mudstones and delicate clay structures (such as fibrous illite in pore spaces) from damage by desiccation.

As the programme evolved, the supplementary lithostratigraphical/sedimentological logging and core orientation activities, and the logging of fracture mineralisation and potentially flowing features described below, have been completed on-site prior to the shipment of the cores to Keyworth for sampling and testing activities. This had significantly refined the integration of data from the various logging and orientation activities and had, in effect, provided a much enhanced and expanded database through improvements in internal consistency between the individual data sets.

After completion of the on-site logging activities the cores were re-sealed in the plastic liners into which they were drilled to minimise disturbance and dispatched to the British Geological Survey at Keyworth. As soon after arrival at Keyworth as was possible the condition of the boxed cores was checked to ensure that no damage had been caused during shipment.

3. OFF-SITE OPERATIONS

Operations carried out under the OSCCP at Keyworth were summarised below and listed in Table 1. Space does not allow the detailed description of testing procedures which are described in outline only.

3.1 Supplementary lithostratigraphical and sedimentological logging

The main objectives of the supplementary lithostratigraphical logging were to define and describe the lithological and stratigraphical successions of the boreholes in as much detail as was necessary to establish a basic geological framework for three-dimensional interpretations and other studies, and to provide the background data for borehole–borehole and borehole–

regional correlations. For Dounreay borehole BH1 and Sellafield boreholes BH2, BH3, BH4, BH5, BH7A and BH7B the cores have been logged, from a lithological/sedimentological point of view, and detailed and summary reports submitted for each borehole by the British Geological Survey . For all subsequent boreholes (i.e. Sellafield boreholes BH10A, BH10B, BH10C, BH11A, BH12A, BH13A, BH13B, BH14A, RCF1, RCF2, RCF3, RCM2, PRZ2 and PRZ3) a log combining the on-site engineering geological and discontinuity logs carried out by Gibb Deep Geology Group with the lithological and sedimentological logging carried out off-site or on-site by the British Geological Survey had been prepared and submitted by Gibb Deep Geology Group. These combined logs also provide detailed, corrected orientation data for the majority of fractures logged in the core. This was a significant improvement to the overall data set arising from the integration of core orientation with core logging activities. For these boreholes summary logs have been produced by the British Geological Survey. A full list of reports detailing the logging is given in the Appendix.

The work was undertaken by a number of experienced geologists, each with a first-hand knowledge of the local geology and a specialist knowledge of the particular lithologies under examination. Where possible, the expertise of field staff engaged in mapping the Sellafield and Dounreay areas was utilised. In addition, British Geological Survey sedimentologists and palaeontologists contribute expertise during the logging of core from sedimentary horizons.

Summary composite geological and geophysical logs were prepared for each borehole using WELLOG, an in-house software package developed to process and present borehole data.

3.2 Core orientation

Core orientation was an extremely important operation since reliable orientation data were required for the meaningful analysis of certain core samples, especially those selected for fracture analysis and measurement of remanent magnetism. Orientation was a necessary preliminary operation in determining the true azimuths (dip directions) of fractures, bedding and other fabrics observed in the core, together with those of directional quantities such as remanent magnetic fields.

Boxed core-sticks were orientated using processed borehole wall images derived from the Schlumberger Formation MicroScanner (FMS), or Formation MicroImager (FMI), and Borehole Televiewer (BHTV), or Ultrasonic Borehole Imager (UBI), wireline geophysical logs (Fig 1). Orientation of the core relies upon matching geological features of known orientation, recognised in these images, with actual features in the core whose orientations have been measured with respect to an arbitrary reference line. The orientation of this line, for any core stick, may be calculated from the difference in the dip azimuths determined for features matched in the core and image. In practice the core was marked with two lines, one blue and one yellow or red, with the blue line on the left as the core was viewed looking up-hole (Plate 1). The orientation of all features measured on the core was expressed relative to the yellow (or red) line, which was taken as the reference line; the blue line provides an artificial ‘way-up’ criterion for any core sticks which need to be removed from their boxes.

Interactive fitting of the trace of planar features intersecting the borehole also enables fractures (including joints and veins), bedding and fabric orientations to be determined. These data were supplemented by additional goniometry measurements on the core. Dip directions determined by FMS/FMI analysis have been corrected to true north.

The FMS/FMI data were used as the primary image for the identification of features on the core due to the high resolution of this technique. In the case of the Permo-Triassic strata of

Sellafield BH2, a natural porosity of approximately 10–30% ensures excellent conditions for electrical conductivity. The BHTV/UBI data were also processed although these tools generally yield lower quality images of sedimentological features, being more efficient at identifying fractures and veins within a rock mass.

For Sellafield boreholes RCF1-3, RCM2, PRZ2-3, BH8A, BH9A and BH13A the Gibb Deep Geology Group discontinuity data set was able to be fully orientated (i.e. true orientations calculated for individual discontinuities logged in the core) as a result of enhancements in the programme leading to greater integration of core orientation activities with core logging, either on-site or off-site.

Structural data from interactive fitting of FMS/FMI and BHTV/UBI imagery and from core goniometry were analysed by the British Geological Survey to produce oriented discontinuity datasets which have been used in subsequent structural analysis.

Another product of the core orientation process was the generation of depth correction factors, derived from the matched discontinuity data, that allow the correction of drillers' depths to wireline depths using the FMS/FMI log as the reference datum. This assists in the reconciliation of a number of drilling-related depth errors, such as stick-up, core loss/gain and drill string measurement errors.

3.3 Core examination and sampling strategy

All sampling within this programme was undertaken on a 'by inspection' basis with the object of providing material for analysis and testing which was representative of the various lithologies and their variability, or which meets the specific scientific requirements of the discipline (e.g. fracture infillings, microfossils, etc.). Lithostratigraphical considerations were of prime importance in establishing the sampling points for bulk rock (matrix) characterisation.

During the early part of the programme routine sampling was carried out at regular intervals. These were generally at about 1 per 5m in Sellafield borehole BH2 reducing to 1 per 10 or 20 m in later boreholes up to borehole BH7B. More recent boreholes have been sampled on a less regular basis with specific objectives, principally detailed fracture mineralogical studies of flow zones. Bulk rock characterisation had been limited to confirming established stratigraphical correlations and providing data on lithological units not encountered in other boreholes. Since Sellafield borehole BH7B engineering geological testing had been confined to selected boreholes within the Potential Repository Zone.

During selection of hydrogeological and geotechnical samples intact cores will have been chosen for testing purposes as it was not possible to prepare machined samples from broken cores. Additionally very weak rocks may fail during the machining process. This will inevitably have led to a sampling bias in these areas away from weak (mainly mudstones) and fractured rocks.

The requirement for 'by inspection' sampling was met by the 'Core Examination Panel' (CEP) comprising staff with appropriate expertise in each of the scientific disciplines represented within the OSCCP. The CEP was held once supplementary lithostratigraphical- and sedimentological logging had been completed so that lithological logs were available for inspection. For logistical reasons the core orientation process was also completed before the CEP for a batch of core was held.

The CEP was responsible for collating the overall sampling requirements, reconciling any conflicting demands on material, and preparing the detailed sampling schedule which was used by the core-cutters. The CEP comprises British Geological Survey specialist geological staff and, as appropriate, specialists from other organisations with an interest in the OSCCP or a requirement for core samples for other programmes which was met through the CEP.

Each sample selected by the CEP was identified by a unique sample number. The first part of this number identifies the borehole from which the sample had been selected (e.g. Sellafield BH7A), the second part was a unique serial number for that borehole, and the final part was the 'P-code'. The P-code defines the tests to which the sample will be subjected and the associated sample preparation required. For example, a P01 sample was selected to be representative of the bulk rock and sub-samples will be tested for hydrogeological properties, geotechnical and geophysical properties, and mineralogy and geochemistry. Sample preparation involves the preparation of 25mm plugs for porosity and permeability testing, preparation of 38mm plugs for geotechnical and geophysical testing, and submission of the resulting 'cheese' for mineralogical and geochemical evaluation (Fig 2). Each sub-sample retains the number of its parent sample and was suffixed by a two letter code to indicate the specific sub-sample type, e.g. NSF7A/1775/P01-1/EA which was a 38mm plug destined for geotechnical testing.

An Oracle database holds details of all samples taken and allows depth intervals to be calculated and disseminated to the various testing laboratories.

Additional core photography can be undertaken if necessary. Sections of core representative of particular fabrics or sedimentological features were slabbed and photographed.

3.4 Core handling and sample preparation

The sample preparation and core handling requirement of the Core Characterisation Programme the British Geological Survey were serviced by the National Geological Records Centre at Keyworth. Storage and handling facilities available include storage of palleted boxed core samples prior to the Core Examination Panel; provision of core logging facilities; storage of preserved core samples in cold rooms; and presentation of the boxed cores for logging, orientation, and Core Examination Panel activities. Water/drilling fluid samples collected during the drilling and subsequent testing of boreholes were also stored in the cold rooms.

Sample preparation services were also provided by NGRC. Samples marked on the core at the CEP (Plate 1) were removed by cutting the samples from the core. Cuts were normally perpendicular to the core axis but may be oblique to it (e.g. parallel to fracture planes) if required. Each sample was matched to the sample form bearing its unique number, and other relevant details, and removed from the core boxes.

Secondary preparation of samples was dependent on the tests to be carried out. It includes:

- preparation and trimming of 25mm plugs for porosity and permeability testing
- preparation of 38mm plugs for geotechnical and geophysical testing. The plugs were trimmed to length and accurately surface ground
- preparation of 96mm samples for geotechnical testing by accurate surface grinding

- preparation of a range of precision machined samples for specialist testing (principally P- and S-wave measurements and testing of thermal properties)
- slabbing and surface finishing of selected core samples for detailed photography of specific features, structures, etc.
- routine slabbing of ‘cheeses’ destined for bulk mineralogical studies
- routine slabbing of fracture samples.

Tertiary sample preparation, such as preparation of thin sections, polished thin sections, staining, stubs, etc. for analysis was carried out by the testing laboratories.

3.5 Hydrogeological core analysis

Hydrogeological properties were mainly measured on 25mm diameter plugs at British Geological Survey Wallingford laboratory. Three mutually perpendicular plugs were taken at each sampling point. One plug from each sampling point was used to measure effective porosity. The vertical plug and one of the horizontal plugs were tested routinely for gas permeability. At every tenth sampling location, the second horizontal plug was tested to examine variability of gas permeability in the horizontal plane.

Effective porosity, a measure of those voids that are interconnected (i.e. which contribute to the flow of fluids), was determined by helium porosimetry and liquid re-saturation porosimetry.

Permeability was a measure of the capacity of a rock to transmit fluid and was routinely determined by gas permeametry. Its value depends on the size, shape, and arrangement of the interconnected pores, or voids, within the rock. It should be noted that measurements were carried out on plugs orientated parallel and perpendicular to the core axis. Assuming the principal components of the permeability tensor to be orientated parallel and perpendicular to the bedding, these measurements do not allow the permeability tensor to be fully defined when the bedding was other than perpendicular to the borehole axis.

The Brockram, the Permian basal breccia horizon, was not amenable to the preparation of 25 mm diameter plugs and the testing of such small samples would not be appropriate for such a coarse-grained rock. Therefore, for this unit, gas permeametry and liquid re-saturation porosimetry tests were carried out on samples with a diameter corresponding to the whole core (nominally 96mm).

Additional tests include mercury injection porosimetry (MICP) and measurements of pore volume compressibility. The MICP technique may be used to give an indication of both the dominant size and the range of sizes of pore throats in a sample. If the density of the sample was known, MICP tests can also be used to give an estimate of porosity. However, as the samples used in MICP tests were smaller than the plugs used in standard core laboratory porosimetry the results were not always comparable.

A comparative study had been completed between gas and liquid permeability of samples from the sandstones at Sellafield to derive the Klinkenberg correction in order that routine gas permeability measurements can be corrected to equivalent liquid (water) permeability values.

3.6 Mineralogical, petrological, and geochemical characterisation

The objectives of this component of the work are: (a) to provide a full lithological, mineralogical, and geochemical characterisation of the core; (b) to determine the controls on physical, hydrogeological, and hydrochemical properties of each lithotype; (c) to gather data which elucidate the geological history and evolution of the site and its regional context, with an emphasis on jointing, faulting, mineralisation, and alteration.

Bulk rock and fracture samples were taken for analysis by a wide range of techniques. The optical petrographical examination of thin and polished sections was carried out to provide an estimate of the modal mineralogical composition, including the trace occurrence of phases and a visual estimate of the total porosity. As far as may be determined optically, the paragenetic sequence of diagenetic minerals was described. High magnification and high resolution imaging of surfaces and three-dimensional relationships between mineral phases was provided by scanning electron microscopy (SEM). This information was used in studies of porosity and pore-surface characteristics and fracture surface mineralogy. This also gives valuable information on potential interactions with fluids. It was especially valuable in the analysis of delicate pore and fracture-lining fabrics which may be destroyed during thin section preparation. Phase identification during SEM analysis was aided by qualitative energy dispersive microanalysis (EDXA). Backscattered electron microscopy (BSEM) in conjunction with EDXA was also used to gain high quality petrographical and textural information at high magnifications, particularly with very fine-grained or cryptogranular phases, and had proved particularly useful in revealing subtle chemical zonation in phases such as carbonates. The chemistry of mineral phases was also studied using electron probe microanalysis. Cathodoluminescent microscopy (CL) was used to reveal cement ‘stratigraphy’ and fabrics not visible by other means, particularly K-feldspar, carbonate, and apatite fabrics.

Petrographical data from optical, BSEM, SEM, and CL were being used to elucidate alteration processes, rock–water interactions, and diagenetic and paragenetic histories. The data were also important in correlating the carbonate mineralogy of veins and altered wall rock in individual thin sections and between samples.

Evolved gas analysis, which had been developed by the British Geological Survey as a routine technique for the analysis of geological materials, was applied to core samples to quantify minerals which evolve volatiles during heating such as carbonates, sulphates, sulphides, and carbonaceous materials and organics. Heavy mineral analysis provides information used in provenance studies and the definition of stratigraphical characteristics and may aid in correlation at the regional scale. Bulk rock qualitative and quantitative X-ray diffractometry (XRD) was used in the evaluation of the major mineral components and for the identification and analysis of clay minerals. Major and trace element analysis of bulk rock samples was performed by X-ray fluorescence spectrometry (XRFS) with supplementary data for sulphur (e.g. in evaporites) being obtained by gravimetric methods and CSHN analyser.

Carbon, sulphur, and oxygen stable isotope determinations were used to constrain the temperature, composition, and source of fluids in the study of palaeofluid and mineralisation processes. These were further constrained by fluid inclusion analysis of fracture infill materials and diagenetic cements. The combined data may be used to correlate mineralising events within and between boreholes and to elucidate the fracture history and patterns of fluid movement and mineralisation on a regional scale. The sampling strategy allows samples selected for porosity and permeability determination to be fully characterised by mineralogical and petrographical techniques.

Detailed examination of fracture, fault, and shear zone infillings was carried out to yield information on the history of mineralisation and reactivation. Evidence from this examination can also be important in assessing matrix diffusion, in geochemical modelling, and in sorption studies (including studies of natural radionuclides such as uranium and thorium). Infillings also have direct effects on the hydraulic conductivity of joints and their geotechnical performance which can be inferred from such studies. Wall rock alterations may be indicative of fluid flow and such studies can assist in the identification of potential fluid pathways and give evidence of contemporary fluid movement and alterations. Fluid inclusion analysis of fracture minerals can provide data on palaeotemperatures and the composition of palaeofluids.

The sampling strategy allows samples selected for porosity and permeability determination to be fully characterised by mineralogical and petrographical techniques.

The applications of mineralogical and petrological studies of the bulk rock are numerous including the identification of lithologies and lithological variation, input into lithostratigraphy and regional correlation activities, the determination of mineralogical and petrographical controls on porosity and permeability, input into site geochemistry and mass transfer modelling, background analysis for fracture alteration studies, and in the calibration of geophysical tools such as the Geochemical Logging Tool. The following elements were routinely determined by X-ray fluorescence spectrometry: Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Rb, Sr, Y, Zr, Nb, Mo, Ag, Sn, Sb, Ba, La, Ce, Pb, Th, U, As, W, and Bi. Routine major oxides determined by this technique are: SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5, total, and LOI (loss on ignition).

Whole rock geochemical analyses were carried out in parallel with other petrological studies to meet a number of requirements including: the geochemical characterisation of basement lithologies for identification and regional correlation purposes; the provision of basic data in assessing the evolution of groundwater chemistries; the evaluation of U, Th, and K for the calibration of geophysical tools and in heat flow studies; and the determination of background concentrations of uranium for safety assessment, monitoring, and the assessment of radon potential.

3.7 Fractured rock mineralogical, petrological, and geochemical characterisation

The objectives of this component of the work were to gather data which elucidate the geological history and evolution of the site and its regional context, with an emphasis on jointing, faulting, mineralisation, and alteration. More recently these studies have been directed at a detailed characterisation of flow zones identified by production logging and the identification of potential flowing features.

Fracture samples were taken for analysis by a wide range of techniques. The optical petrographical examination of thin and polished sections was carried out to provide an estimate of the modal mineralogical composition, including the trace occurrence of phases and a visual estimate of the total porosity. As far as may be determined optically, the paragenetic sequence of fracture filling minerals was described. High magnification and high resolution imaging of surfaces and three-dimensional relationships between mineral phases was provided by scanning electron microscopy. It was especially valuable in the analysis of fracture-lining fabrics which may be destroyed during thin section preparation. Phase identification during scanning electron microscopic analysis was aided by qualitative energy dispersive microanalysis. Backscattered scanning electron microscopy in conjunction with energy dispersive microanalysis was also used to gain high-quality petrographical and textural information at high magnifications, particularly with very fine-grained and cryptogranular phases, and had proved particularly useful in revealing subtle chemical zonation in phases such as carbonates. The chemistry of mineral phases was also studied using electron probe microanalysis. Cathodoluminescent microscopy was used to reveal vein 'stratigraphy' and fabrics not visible by other means, particularly of carbonate veins.

Petrographical data from optical, backscattered scanning electron microscopy, scanning electron microscopy and cathodoluminescent microscopy were being used to elucidate paragenetic histories. The data were also important in correlating the carbonate mineralogy of veins and altered wall rock in individual thin sections and between samples.

Carbon, sulphur, oxygen and strontium stable isotope determinations were used to constrain the temperature, composition and source of fluids in the study of palaeofluid and mineralisation processes. These were further constrained by fluid inclusion analysis of fracture infill materials and diagenetic cements. The combined data may be used to correlate mineralising events within and between boreholes and to elucidate the fracture history and patterns of fluid movement and mineralisation on a regional scale.

Detailed examination of fracture, fault, and shear zone infilling can yield information on the history of mineralisation and reactivation. Evidence from this examination can also be important in assessing matrix diffusion and in geochemical modelling and sorption studies (including studies of natural radionuclides such as uranium and thorium). Infilling also have direct effects on the hydraulic conductivity of joints and their geotechnical performance which can be inferred from such studies. Wall-rock alterations may be indicative of fluid flow and such studies can assist in the identification of potential fluid pathways and give evidence of contemporary fluid movement and alterations. Fluid inclusion analysis of fracture minerals can provide data on palaeotemperatures and the composition of palaeofluids.

Investigations of fracture mineralisation from the early boreholes (Sellafield BH2, BH3, BH4, BH5 and BH7A, BH7B, BH10A and BH12A) focused on evaluating the overall mineral characteristics and mineral paragenesis, and on establishing the sequence of 'Mineralisation Episodes'. The investigations were aimed at elucidating the relationship of the fracture mineralisation to the faulting history, to the regional Lake District mineralisation, and to the diagenetic history and associated fluid movement in the Permo-Triassic cover rocks/ East Irish Sea Basin.

More recently (Sellafield boreholes BH8A, BH8B, BH11A, BH13A and BH14A) detailed mineralogical logging and petrological studies of the core have concentrated on fractures and fracture mineralisation associated with present-day groundwater flow zones (identified from hydrogeological testing) in the BVG and Permo-Triassic rocks. Specifically, these studies have focused on the mineralisation and associated characteristics of fractures and matrix intervals that were considered potentially to be capable of conducting groundwater flow at the present day (i.e. hydraulically conductive) within discrete zones of the borehole section in which groundwater flow into, or out of, the borehole had been identified from hydrogeological testing. These were referred to as 'potentially flowing features', or PFFs.

3.8 Geotechnical and geophysical testing

Routine measurements were made of bulk, dry, and grain density; uniaxial compressive strength; indirect tensile strength (Brazilian disc test); triaxial strength; and triaxial deformability (elastic moduli using strain gauges). All engineering geological tests described below were performed according to International Society of Rock Mechanics (ISRM) Suggested Methods (Brown 1981).

All strength and deformability tests were carried out on machined cylinders or discs whose axis was parallel to that of the borehole. Two different cylinder sizes were used, as most appropriate, for both uniaxial and triaxial strength tests and also for triaxial deformation tests. The dimension of these cylinders were 38mm diameter by 76mm long and 95mm diameter by 190mm long, the latter being full diameter (unplugged) core. Large (95mm diameter) specimens were used particularly where the grain or clast size of the lithology was large, for example with conglomeratic rocks.

Uniaxial and triaxial strength test specimens were surface-ground using a special jig which produces ends flat and parallel to better than 20 µm, even on 'non-straight' core. Specimens for the indirect tensile strength (Brazilian disc) test were discs of 95mm diameter and 48mm thickness.

All geotechnical test category specimens have their dimensions measured with callipers pre-test and all test specimens, with the exception of triaxial deformation, were pre-saturated with a synthetic pore fluid under vacuum. Triaxial, uniaxial, and indirect tensile strength test specimens were photographed post-test.

The dry density, grain density, saturated density, and effective porosity were determined using Archimedes' principle on 38mm diameter by 76mm long specimens. The procedure was suited to non-fissile, non-slaking, non-swelling rocks and involves the weighing of the specimen in air (pre- and post-oven drying at 105°C) and in water. Swelling, fissile, or slaking rocks were tested by measuring their dimensions and hence their volume, weight being determined in air only.

The Brazilian disc test uses the diametral compression to failure of a single 'disc' of full diameter core in a hydraulic compression machine with flat platens and a capacity of 2,000-kN. A diametral failure surface was created parallel to the compressive force direction, splitting the specimen, and giving an 'indirect' measure of the tensile strength in MPa, using a well-tried formula.

The Uniaxial Compressive Strength test uses the axial compression to failure of a single cylindrical specimen, with a length:diameter ratio of two, in either a 2,000kN or a 4,400kN compression machine, to determine the peak uniaxial compressive strength of the specimen. No lateral confining forces were applied. The specimen was loaded between ball-jointed platens which allow drainage.

In order to determine the Triaxial Strength of a sample five similar saturated cylindrical specimens were axially compressed to failure, each at different confining pressures, and a plot of shear strength versus confining pressure was produced. From this plot the failure criterion for the rock can be quantified using least squares curve-fitting techniques. For this test to be representative of the rock the five specimens have to be homogeneous, and hence were taken from a single stick of core where possible. One of the five tests equates to a uniaxial test as a zero confining stress was used. The specimens were loaded between ball-jointed platens which allow drainage to atmosphere. A confining pressure was applied by oil pressure acting across a jacket inside a Hoek cell-type pressure vessel. Axial force was measured by both electrical load cell and analogue pressure gauge and the confining pressure was measured by analogue pressure gauge.

Independent axial and confining forces were applied to a single cylindrical specimen, using the same loading arrangement as the triaxial strength test, in order to determine its Triaxial Deformability. In this case, however, axial and radial strains were measured by means of three two-way electrical resistance strain gauges bonded to the specimen surface at mid-height and separated by 120°. The specimen was axially loaded and unloaded cyclically to 50% of peak compressive strength with strains monitored during each stage. The Young's Modulus of elasticity and Poisson's Ratio (ratio of radial to axial strain) were calculated from the axial force and the strains. Each strain was taken as the average of the three independent gauge readings. Young's Modulus was calculated from the 'Average Young's Modulus' of the linear portion of the final complete loading cycle, and the 'initial unloading modulus' from the initial unloading portion of the final cycle. Specimens were tested at their 'as-received' moisture content with minimal surface drying to enable the strain gauges to be bonded successfully to the rock.

A range of geophysical measurements were also performed on core samples to assist in the calibration of wireline geophysical logs and to resolve specific issues. These include resistivity; compressional wave (P-wave) ultrasonic velocity under unconfined conditions; compressional and shear wave (P- and S-wave) ultrasonic velocity under confined conditions; magnetic susceptibility; and remanent magnetism to provide data for magnetostratigraphy.

Induced magnetic susceptibility, resistivity, and P-wave velocity tests use a single, machined, 38mm diameter by 76mm long, right-cylindrical specimen, common to the geotechnical test category, whilst remanent magnetism uses a 25mm diameter by 21mm long, right-cylindrical specimen prepared using a special non-ferrous coring bit. All four tests were non-destructive. The remanent magnetism and induced magnetic susceptibility tests were carried out without pre-saturation. The other tests employ pre-saturation with synthetic pore fluid. The compressional, or P-wave, acoustic wave velocity in an axial direction through the rock specimen was obtained by measuring the time delay for ultrasonic pulses to travel the length of the specimen using a CNS Instruments Ltd. Pundit Mk 4 instrument connected to an oscilloscope.

P- and S-wave velocity measurements were carried out on right-cylindrical specimens 50mm in diameter, and 20mm in length. Determination of the compressional and shear wave velocities and frequencies were taken on samples isotropically stressed in a high pressure triaxial cell to between 10 and 65MPa. Measurements were carried out at room temperature on dry or saturated rock specimens. Development of the equipment for determination of these properties had been carried out in collaboration with the Postgraduate Research Institute for Sedimentology at Reading University.

Matrix thermal properties, including thermal conductivity, specific heat, and linear thermal expansion were also determined as input parameters in thermal scoping calculations. These tests were conducted on precision machined discs, rods, and plugs in a specially commissioned laboratory.

3.9 Biostratigraphical studies

Biostratigraphical studies of the sedimentary rocks at the sites were aimed at the identification of markers for correlation purposes. Methods include palynology (examination of fossil spores and pollen), studies of foraminifera, and identification of macrofossils, where these were evident. Palynological studies of the Permo-Triassic strata proved to be disappointingly inconclusive, however, studies of macrofossils in the Permian dolomites, together with foraminifera in the Carboniferous Limestone, provided valuable stratigraphical information. The requirement for non-destructive core-logging procedures precludes extensive macrofossil study.

3.10 Core pore-fluid extraction

Pore-waters have been extracted from core samples from the Sherwood Sandstone Group by immiscible liquid displacement centrifugation. Samples were selected from core protected by foil, plastic film, and wax to preserve the moisture content. Moisture content was calculated as a percentage of the 'wet' weight of the sample. The crushed samples were centrifuged for 30 minutes at 13,000 rpm with an inert heavy liquid displacent and any pore-water displaced was collected from the upper layer. Each sample was prepared in triplicate and the pore-water obtained from the three replicates bulked to provide a single sample for analysis. The bulk extract was filtered through a 0.45µm filter and preserved as two sub-samples, one acidified and one unacidified. If sufficient pore-water had been extracted, a further unpreserved and undiluted 7ml aliquot was stored for stable O and H isotope determination.

Residual solutes were leached from drillcore samples by centrifuging a milled sample with a basic aqueous leach. This provides quantitative data for conservative tracers in the sample, but only semi-quantitative or qualitative data for other solutes, which have their concentrations modified by water rock interactions. These interactions may enhance or deplete the concentration of solutes in a highly variable manner. An estimate of the original pore-water concentration was calculated using the original sample moisture content.

Total alkalinity, expressed in terms of bicarbonate, and pH were determined on all samples as soon as possible after collection. Major cations (Ca, Mg, Na, and K) and trace cations (Ba, Sr, total Fe, Al, and Li) and Si were determined by inductively coupled plasma optical emission spectrometry (ICP-OES) on the acidified sub-sample. Major and trace anions (Cl, SO_4, NO_3, NO_2, and Br) were determined by ion chromatography. Total Organic Carbon (TOC) and Inorganic Carbon (IC) were also determined. Stable oxygen and hydrogen isotope ratios ($^{18}O/^{16}O$ and $^{2}H/^{1}H$) were determined on extracted pore-waters at the Stable Isotope Laboratory at British Geological Survey Wallingford.

For the less porous formations, pore-water extraction had not been possible and aqueous dissolution from prepared core samples was the only means of recovering residual solutes for analysis. The preserved core was removed from its protective wrapping and prepared as if for pore-water extraction. Each sample was then milled to less than 350µm and leached using a basic aqueous procedure. This technique had been applied to core samples from the Sherwood Sandstone Group, for comparison with extracted pore-water data, as well as to samples from the less porous Brockram and Borrowdale Volcanic Group. Analysis was carried out as described for the extracted pore-waters, although stable O and H isotopes were not determined.

The aqueous leachate procedure had limitations relative to the extraction of solutes in 'undisturbed *in situ*' pore-water. Although quantitative concentration estimates were obtained for non-reactive solutes (Cl and Br), water-rock interactions experienced during the experimental procedure result in the modification of other solutes in a highly variable manner (Entwisle et al. 1989). The data obtained by both pore-water extraction and aqueous leaching were modified by contamination and dilution effects arising from the infiltration of drilling fluid.

Principal component analysis had been used on raw leachate data to enable more accurate qualitative interpretation and, potentially, quantitative estimates of interstitial water components to be made.

3.11 Radon emanation

The presence of radon in a planned repository was a potential problem which may require remedial measures. There is not necessarily a direct correlation between the uranium (the ultimate parent of radon) content in a rock and the radon emissivity of that rock, as this depends on a number of other factors including the mineralogy of the radon generating phase, the texture of the rock, and the presence of fluid which can transport the radon in solution.

Measurement of the radon (^{222}Rn) emanation from samples of the Borrowdale Volcanic Group had been carried out on 20cm lengths of core adjoining sections collected for detailed mineralogical studies. The initial intention was to test samples from the Moine Series strata at Dounreay but, following the decision to concentrate investigations in the Sellafield area, samples of Triassic Sherwood Sandstone Formation and Permian Brockram breccia originally selected for heavy mineral analysis and around 10cm in length were also tested. The samples used were not intended to represent fully the emanation rates or effective diffusion rates of all the lithologies, but should provide useful comparative information.

The core samples were sawn longitudinally into four sections, three of which were used for

emanation studies from the solid rock, and one of which was crushed for emanation studies from the powdered rock and for chemical analysis. The radon generated from each solid core was measured in air, and two samples of differing size and a sample of powdered core were measured in water. The samples were left for at least 28 days to allow the radon levels to equilibrate with the parent ^{226}radium.

3.12 Sequencing of activities, samples database, archiving, and reporting

3.12.1 Sequencing

The factors determining the sequencing of activities within the OSCCP were as follows:

- Scientific and technical priorities
- Interdependency of activities
- The need to correlate properties
- Integrity of the core (the destructiveness of certain sampling or testing methods)
- Duration of individual activities

Scientific and technical priorities, from the geological and geotechnical perspectives, were reflected in both the content of the OSCCP and the sequencing of activities. An underlying principle was that the characterisation of discontinuities was of paramount importance to the safety assessment and the engineering of a repository in a hard-rock formation. As already noted, many of the listed activities were interdependent. In some cases this demands that operations on the core were undertaken in a prescribed sequence; it may also dictate that analyses on a single specimen were performed in a logical sequence.

Correlation of material properties was an important part of core characterisation (e.g. resistivity with porosity; permeability with mineralogical and petrographical features). To achieve such correlations, a number of tests or analyses must be performed on the same, or closely comparable, specimens. This places additional constraints on sequencing.

One very important factor in sequencing activities was the need to preserve the integrity of the core for the duration of particular activities that demand undisturbed material. Logging, core orientation and goniometry must be performed before intensive sampling. Fractures, infills and wall-rock alterations must also be sampled before other more destructive operations on the core. These considerations impose a logical sequence for off-site characterisation (Fig 3) as follows:

(i) Examination

(ii) Orientation

(iii) Logging and Goniometry

(iv) Sampling of Fractures, Infills, etc.

(v) Sampling of 'Intact' rock

3.12.2 Sample database

The whole programme was carried out under strict a Quality Assurance programme. This was designed to conform to the requirements of BS EN ISO 9001 (British Standards Institution 1994); the early stages of the programme were carried out in conformance with BS 5750 (British Standards Institution 1987). This had included the establishment of a sample tracking database which not only uniquely identifies each sample and sub-sample and its current location, but also the test(s) to which it was subjected by means of its sample code.

3.12.3 Sample archiving

After testing, residual samples, off-cuts, and all other core samples and sub-samples, unless totally destroyed by testing, were boxed were placed in long term storage in Nirex's core store with the rest of the core in west Cumbria. In 2000 the cores, samples and supporting records were given to the BGS to be included in the national geological archive Bulk rock and fracture petrography samples were retained by the British Geological Survey along with all associated thin-section, polished thin-section, and SEM stubs etc. as a permanent record. In 2000 the cores, samples and supporting records were given to the BGS to be included in the national geological archive and the cores moved to purpose built permanent storage at the BGS headquarters at Keyworth near Nottingham.

3.12.4 Reporting and location of test results

In order to expedite availability of data within the Nirex programme, test results were initially reported as a series of Interim Factual Reports. These reports reported limited data sets, for example the UCS test results from BVG samples in borehole 2, with minimal comment. Subsequently, all test results were formally reported in the form of a series of phased Compiled Factual Reports covering, for example, all porosity and permeability test results for a single borehole. In these reports the data were reported in context, with comment on test and analytical techniques and some basic interpretation of the data. Special Topic reports were prepared covering a number of topics and usually involve additional interpretation of test results, reviews of data etc that were outside the scope of the Compiled Factual Report.

A complete listing of published Core Characterisation Programme reports by subject area is provided as an Appendix. In total about 750 reports were issued by the OSCCP, of which about 120 were published as Compiled Factual or Special Topic Reports.

Digital copies of the data were held in a variety of formats by the British Geological Survey and were accessible *via* the Nirex Digital Geoscience Database. Some reports, such as the Core Orientation Compiled Reports, include digital copies of the data within the report.

The detailed interpretation of the results was continued, outside the Core Characterisation Programme, by the interpretation teams established by Nirex to carry out this task.

A total of over 17.3 km of core from the Sellafield and Dounreay sites had been inspected and logged under the Core Characterisation Programme and in excess of 24,000 samples and sub-samples have been specifically selected for testing and analysis; many of the samples have been subjected to several testing or analytical procedures. As the investigations have preceded and the knowledge of the geology of the site increased the sampling requirements of the programme have evolved with less emphasis placed on basic geological characterisation and greater emphasis on resolving specific problems and on obtaining data for design requirements.

4. LESSONS LEARNT

Most of the individual elements of the Core Characterisation Programme were based on well-established techniques developed over a number of years. However, the success of the programme had depended critically on the facility to rapidly disseminate the data being acquired in a controlled way, and on continual feedback and appraisal of the programme from scientists into the programme management.

The most important adjustment to the programme had been the evolution to a fully integrated system of core logging (lithostratigraphical, sedimentological, engineering geological, discontinuity, mineralogical logging etc.) combined with core orientation, involving closer collaboration and data exchange between specialists from both GDGG and BGS.

The sequence of ‘Mineralisation Episodes’ (MEs) derived from detailed petrographical examination of a relatively few selected core samples had provided a framework for the mineralogical logging of core in the more recently characterised boreholes. The value of the mineralogical logging had been significantly enhanced by the availability of laboratory-derived data. In a related activity, building on the understanding of the mineralisation history, mineralogical and hydrogeological data have been integrated, leading to the identification and logging of Potentially Flowing Features (PFFs).

For Sellafield borehole PRZ1 summary lithological/sedimentological, discontinuity, fault-rock, ME and PFF logging had recently been completed as a single, integrated exercise, drawing on the experience gained during the course of the Programme.

5. REFERENCES

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BROWN, E.T. (editor) 1981. *Rock characterization testing and monitoring: International Society of Rock Mechanics, Suggested Methods.* Oxford, Pergamon Press.

ENTWISLE, D.C., REEDER, S., BATH, A.H., & ROSS, C.A.M. 1989. Techniques for the Characterisation of Solutes in Drillcore from Mudrocks. Nirex Safety Series Report NSS/R173.

HORSEMAN, S.T., SHAW, R.P., ROGERS, S.F., & IRELAND, T.J. 1992. Drill core characterization within the UK Nirex Ltd site investigation programme. Pp 135–140 in HUDSON, J.A. (editor) *ISRM Symposium: Eurock '92. Rock characterization.* British Geotechnical Society, London.

Table 1: Activities Carried out under the Core Characterisation Programme

CORE LOGGING
Lithostratigraphic logging and preparation of the definitive log

CORE ORIENTATION
Core orientation
Stereographic projection, contouring and identification of joint sets
Depth Corrections

HYDROGEOLOGICAL CORE ANALYSIS
Gas Permeability
Permeability to brine or water
Porosimetry (Liquid Resaturation, Mercury Injection and Helium Gas Expansion)
Pore Volume Compressibility

BULK ROCK PETROGRAPHY AND GEOCHEMISTRY
Thin section optical petrography
Reflected light microscopy
Cathodoluminescence microscopy
Scanning electron microscopy; secondary electron scanning electron microscopy / energy dispersive x-ray microanalysis (SEM-EDXA)
Scanning electron microscopy; Backscattered scanning electron microscopy — Energy dispersive x-ray microanalysis (BSEM-EDXA)
Electron microprobe analysis (EMPA)
X-ray diffraction (XRD)
Thermal analysis (EGA)
Heavy mineral analysis
Whole rock chemical analysis
Rare Earth Element (REE) Analysis
Aggregate properties

FRACTURE PETROGRAPHY AND GEOCHEMISTRY
Thin section optical petrography
Reflected light microscopy
Cathodoluminescence microscopy
Scanning electron microscopy; secondary electron scanning electron microscopy / energy dispersive x-ray microanalysis (SEM-EDXA)
Scanning electron microscopy; Backscattered scanning electron microscopy — Energy dispersive x-ray microanalysis (BSEM- EDXA)
Electron microprobe analysis (EMPA)
Fluid inclusion studies Stable Isotopes (C, O, S and Sr) Fracture logging

GEOTECHNICAL AND GEOPHYSICAL TESTING
Saturated density
Dry density
Grain density
Saturated water content
Effective porosity
Slake Durability
Swelling Index
Uniaxial compressive strength
Indirect tensile strength --- Brazilian method
Strength under triaxial compression
Elastic constants under triaxial confinement
Thermal conductivity
Specific heat
Thermal expansion coefficient
P- and S- wave velocities
Magnetic susceptibility (core plugs)
Magnetic susceptibility logging (Kappa meter)
Remanent magnetism (field direction)
Resistivity

PALAEONTOLOGY
Biostratigraphy

CORE PORE FLUID EXTRACTION AND ANALYSIS
Fluid extraction
Chemical analysis
Principal component analysis

RADON EMANATION
Radon emanation studies

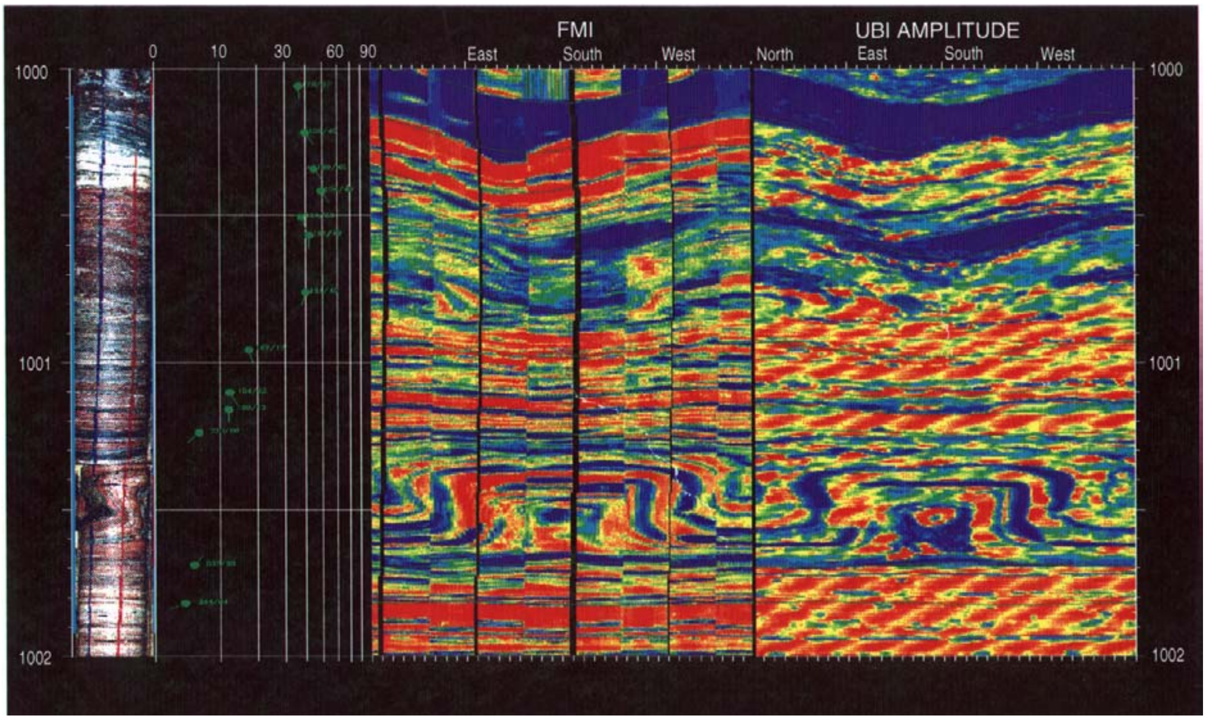

Figure 1: Two-metre section of laminated siltstone and anhydrite from the St Bees Evaporite. A convoluted fold visible in the rock core (left) is also prominent in the corresponding FMI and UBI images of the borehole wall. The two reference lines are visible on the core. The orientations of individual features were logged relative to the red line; the blue line provides an artificial 'way-up' criterion for samples removed from the core box. The correlation of key features in the core with the geophysical images allows the orientation of the reference line, and thus the orientations of all logged features, to be determined. Planar features appear on the images as sine waves; green 'tadpoles' indicate the dip and azimuth of sine waves interactively fitted to (and superimposed on) features in the images. In the colour scales used, red indicates high resistivity (FMI) and high acoustic amplitude (UBI).

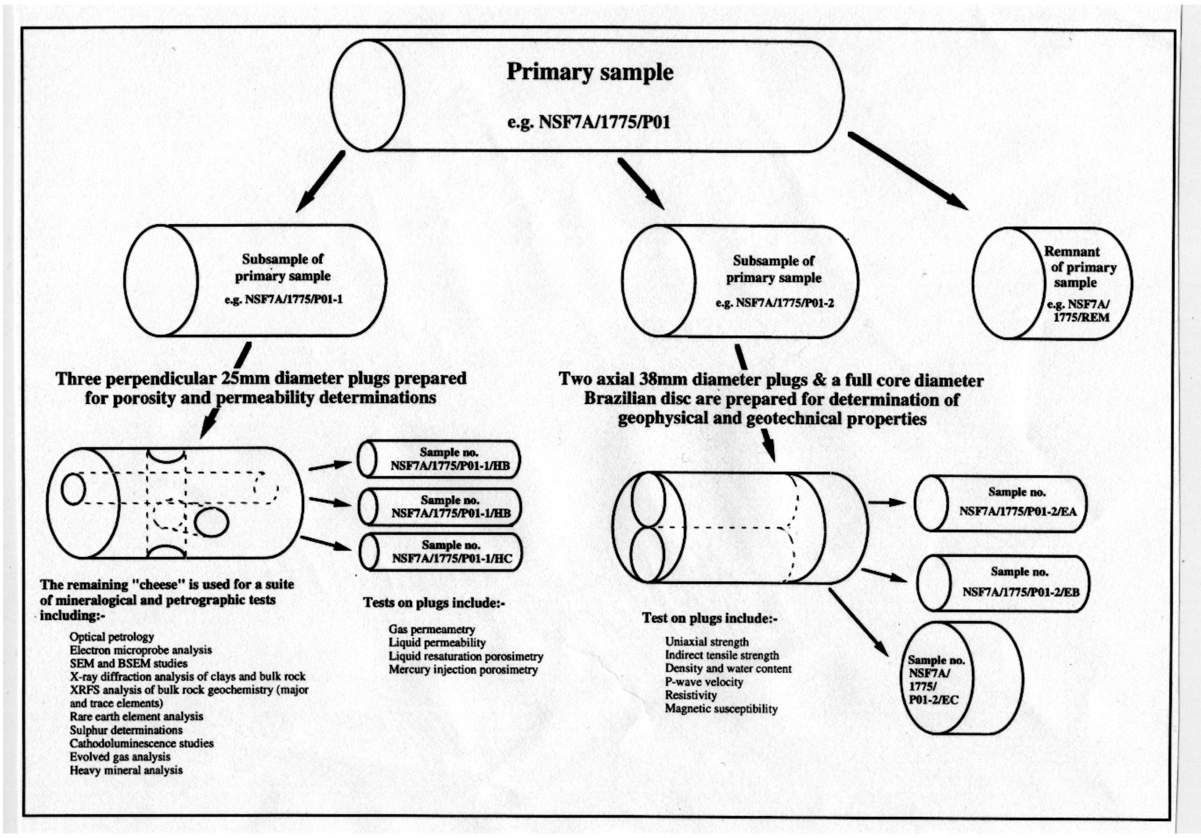

Figure 2. Subdivision of bulk rock core samples, illustrating sample code protocol and analytical and testing schedule.

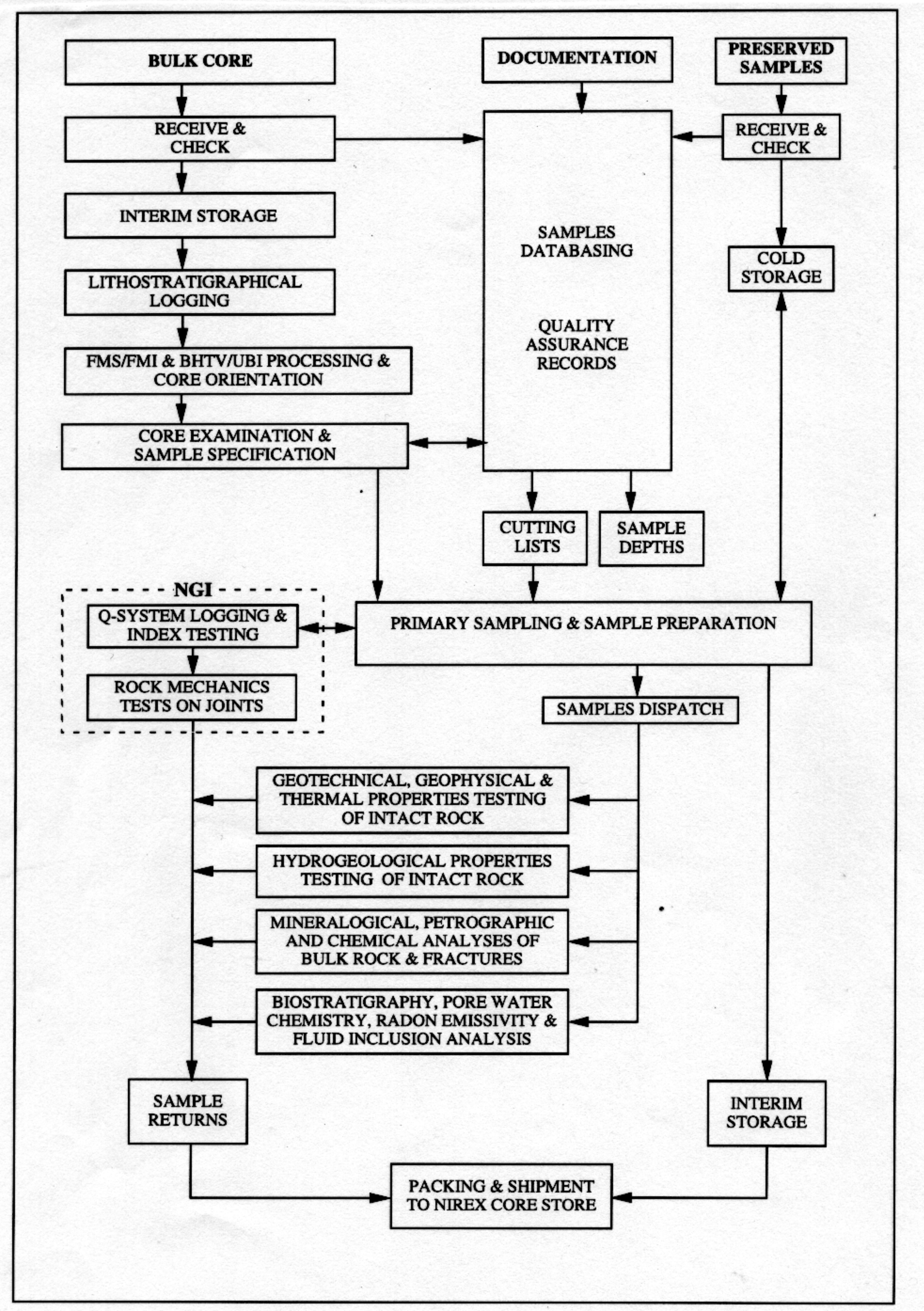

Figure 3: Flow diagram to illustrate the sequence of activities carried out under the OSCCP.

Plate 1: Boxed core from Borrowdale Volcanic Group rocks in Sellafield Borehole 2.
The top half of the core liner has been removed to reveal the core. The core reference lines (blue and yellow) used in the determination of core orientations may be seen, as well as sections of core marked for sampling. The base of each core run (nominally 6 metres in length) is marked 'A', borehole depth increases from left to right.

APPENDIX: SUMMARY LISTING OF CORE CHARACTERISATION PROGRAMME REPORTS APPROVED BY NIREX

Supplementary/Lithological Logging

Geology of Sellafield Number 2 Borehole. (1992) Nirex report No. 184
The Geology of Sellafield Borehole No. 3. (1992) Nirex report No. 195
The Geology of Sellafield Borehole No. 4. (1992) Nirex report No. 196
The Geology of Sellafield Borehole No. 5. (1992) Nirex report No. 205
The Geology of Sellafield Boreholes Nos. 7A and 7B. (1992) Nirex report No. 203
The Geology of Sellafield Boreholes 8A and 8B. (1994) Nirex report No. 638
The Geology of Sellafield Boreholes 10A, 10B and 10C. (1993) Nirex report No. 219
The Geology of Sellafield Borehole 11A. (1994) Nirex report No. 532
The Geology of Sellafield Borehole 12A. (1993) Nirex report No. 220
The Geology of Sellafield Boreholes 13A and 13B. (1994) Nirex report No. 632
The Geology of Sellafield Borehole Number 14A. (1994) Nirex report No. 548
The Geology of Sellafield Borehole No. RCF1. (1994) Nirex report No. 537
The Geology of Sellafield Borehole No. RCF-2. (1994) Nirex report No. 539
The Geology of Sellafield Boreholes RCF3 and part of RCM2. (1994) Nirex report No. 541
The Geology of Sellafield Borehole No. PRZ2. (1995) Nirex report No. 650
The Geology of Sellafield Borehole PRZ3. (1994) Nirex report No. 646
Lithological descriptions of slabbed core photographs of samples from the Permo-Triassic sedimentary rocks from the Sellafield boreholes. (1993) Nirex report No. 221
Geology of Dounreay No. 1 Borehole. (1991) Nirex report No. 185

Core Orientation

FMS/BHTV Derived data for Sellafield BH2-7. (1994) Nirex report No. 540
Generation of an orientated discontinuity data set for Sellafield Boreholes 8A/B. (1995) Nirex report No. 647
Generation of an Orientated Discontinuity Data Set for Borehole 9A. (1994) Nirex report No. 644
Interpretation of the FMI and UBI data from Sellafield Borehole 9B. (1995) Nirex report No. 738.
Orientation of the Core of Sellafield BH10A/B. (1994) Nirex report No. 547
Orientation of the Core of Sellafield BH11A. (1994) Nirex report No. 637
Orientation of the Core of Sellafield BH12A. (1994) Nirex report No. 628
Generation of an orientated discontinuity data set for Sellafield Boreholes 13A/B. (1995) Nirex report No. 649
Orientation of the Core of Sellafield BH14A. (1994) Nirex report No. 633
Generation of an Orientated Discontinuity Data Set for Borehole RCF1. (1994) Nirex report No. 543
Generation of an Orientated Discontinuity Data Set for Borehole RCF2. (1994) Nirex report No. 544
Generation of an Orientated Discontinuity Data Set for Borehole RCF3. (1994) Nirex report No. 545
Generation of an Orientated Discontinuity Data Set for Borehole RCM2. (1994) Nirex report No. 546
Interpretation of FMI data from Sellafield Boreholes RCM1, RCM2 and RCM3. (1994) Nirex report No. 631
Generation of an orientated discontinuity data set for Sellafield Boreholes PRZ2. (1995) Nirex report No. 648
Generation of an Orientated Discontinuity Data Set for Borehole PRZ3. (1994) Nirex report No. 642

Bulk Rock Petrology

The Petrology of the Borrowdale Volcanic Group within Sellafield Borehole No. 2. (1992) Nirex report No. 204
The petrographic, mineralogical and lithogeochemical characteristics of Permo-Triassic rocks from Sellafield BH2. (1993) Nirex report No. 734
The Petrology of the Borrowdale Volcanic Group within Sellafield BH 3. (1993) Nirex report No. 216
The petrographic, mineralogical and lithogeochemical characteristics of Permo-Triassic and Carboniferous rocks from Sellafield BH3. (1994) Nirex report No. 733.
The Petrology of the Borrowdale Volcanic Group within Sellafield Borehole No.4. (1994) Nirex report No. 224
The Petrology of the Borrowdale Volcanic Group within Sellafield Borehole No.5. (1994) Nirex report No. 225
The petrographic, mineralogical and lithochemical characteristics of Permo-Triassic rocks from Sellafield BH5. (1994) Nirex report No. 538
The Petrology of the Borrowdale Volcanic Group within Borehole 7A. (1993) Nirex report No. 217
The petrographic, mineralogical and lithochemical characteristics of Permo-Triassic and Carboniferous rocks from Sellafield boreholes 7A and 7B. (1994) Nirex report No. 536.
The Petrology and lithogeochemistry of the Borrowdale Volcanic Group within Sellafield Boreholes 8A and 8B. (1995) Nirex report No. 744

The petrographic, mineralogical and lithogeochemical characteristics of Permo-Triassic rocks from Sellafield BH 10B. (1995) Nirex report No. 754.
The Petrology of the Borrowdale Volcanic Group rocks within Sellafield Boreholes 10A and 12A. (1995) Nirex report No. 652
The petrographic, mineralogical and lithogeochemical characteristics of Permo-Triassic and Carboniferous rocks from Sellafield Borehole 10A. (1995) Nirex report No. 735.
The Petrology and lithogeochemistry of the Borrowdale Volcanic Group within Sellafield Boreholes 11A. (1995) Nirex report No. 741
The petrographic, mineralogical and lithogeochemical characteristics of Permo-Triassic rocks from Sellafield BH 11A. (1995) Nirex report No. 749.
The petrographic, mineralogical and lithogeochemical characteristics of Permo-Triassic and Carboniferous rocks from Sellafield Borehole 12A. (1995) Nirex report No. 736.
The Petrology and lithogeochemistry of the Borrowdale Volcanic Group within Sellafield Boreholes no 13A. (1995) Nirex report No. 747
The petrographic, mineralogical and lithogeochemical characteristics of Carboniferous and Permo-Triassic rocks from Sellafield BH 13A/B. (1995) Nirex report No. 748.
The petrographic, mineralogical and lithogeochemical characteristics of Carboniferous and Permo-Triassic rocks from Sellafield BH 14A. (1996) Nirex report No. 750.
The Petrology and lithogeochemistry of the Borrowdale Volcanic Group within Sellafield Boreholes 14A. (1995) Nirex report No. 742
The mineralogy, petrology and geochemistry of the Devonian and Moine Rocks of Dounreay borehole 1. (1994) Nirex report No. 639

Fracture Petrology

The petrology of fractures and fracture mineralisation in Sellafield BH2. (1994) Nirex report No. 542
The petrology of fracture and fracture mineralisation in Sellafield BH3. (1994) Nirex report No. 641
The Petrology of Fractures and Fracture Mineralisation in Sellafield BH4. (1994) Nirex report No. 643
The Petrology of Fractures and Fracture Mineralisation in Sellafield BH5. (1994) Nirex report No. 651
The Petrology of Fractures and Fracture Mineralisation in Sellafield BH7A and BH7B. (1995) Nirex report No. 743.
The Petrology of Fractures and Fracture Mineralisation in Sellafield BH10A. (1995) Nirex report No. 752.
The Petrology of Fractures and Fracture Mineralisation associated with Potential Flowing Features in Sellafield BH11A. (1996) Nirex report No. 756.
The Petrology of Fractures and Fracture Mineralisation in Sellafield BH12A. (1995) Nirex report No. 737.
The Petrology of Flow Zones and Potential Flowing Features in Sellafield BH13A. (1995) Nirex report No. 751.
The Petrology of Flow Zones and Potential Flowing Features in Sellafield BH14A. (1995) Nirex report No. 755.
The isotopic composition of Sr in vein and cement carbonate and sulphate minerals from Sellafield boreholes 2, 3, 4, 5, 7, 10 and 12. (1995) Nirex report No. 740.
Orientation of fractures in Core Characterisation Programme fracture petrology samples from the Sellafield Boreholes. (1995) Nirex report No. 739.

Porosity/Permeability

Sellafield 2, Permo-Trias Poro-Perm Compiled Factual Report. (1991) Nirex report No. 181
Sellafield 2, Compiled Factual Report. Permeability, Porosity and MICP Results for the Borrowdale Volcanic Group. (1992) Nirex report No. 182
Special Topic Report on Pore Volume Compressibility of Selected Permo-Trias Samples from Sellafield 2. (1992) Nirex report No. 199
Permeability, Porosity and MICP Results for Samples from Sellafield Borehole Number 3. (1992) Nirex report No. 193
Permeability, Porosity and MICP Results for the Borrowdale Volcanic Group Core Samples from Sellafield 4. (1992) Nirex report No. 194
Compiled Factual Report. Permeability,Porosity and MICP Results from the Permo-Triassic. of Sellafield Borehole 5. (1992) Nirex report No. 200
Compiled Factual Report. Permeability, Porosity and MICP Results from the Borrowdale Volcanic. Group of Sellafield Borehole 5. (1992) Nirex report No. 208
Permeability, Porosity and MICP Results for core samples from the Permo-Trias and Carboniferous of Sellafield Borehole 7. (1993) Nirex report No. 211
Permeability, Porosity and MICP Results for core samples from the Borrowdale Volcanic Group of Sellafield Borehole 7. (1993) Nirex report No. 212

Permeability and Porosity results for samples from the Permo-Trias, Carboniferous and Borrowdale Volcanic Group of Sellafield borehole 10. (1994) Nirex report No. 226
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