Routine Core Analysis Workflow

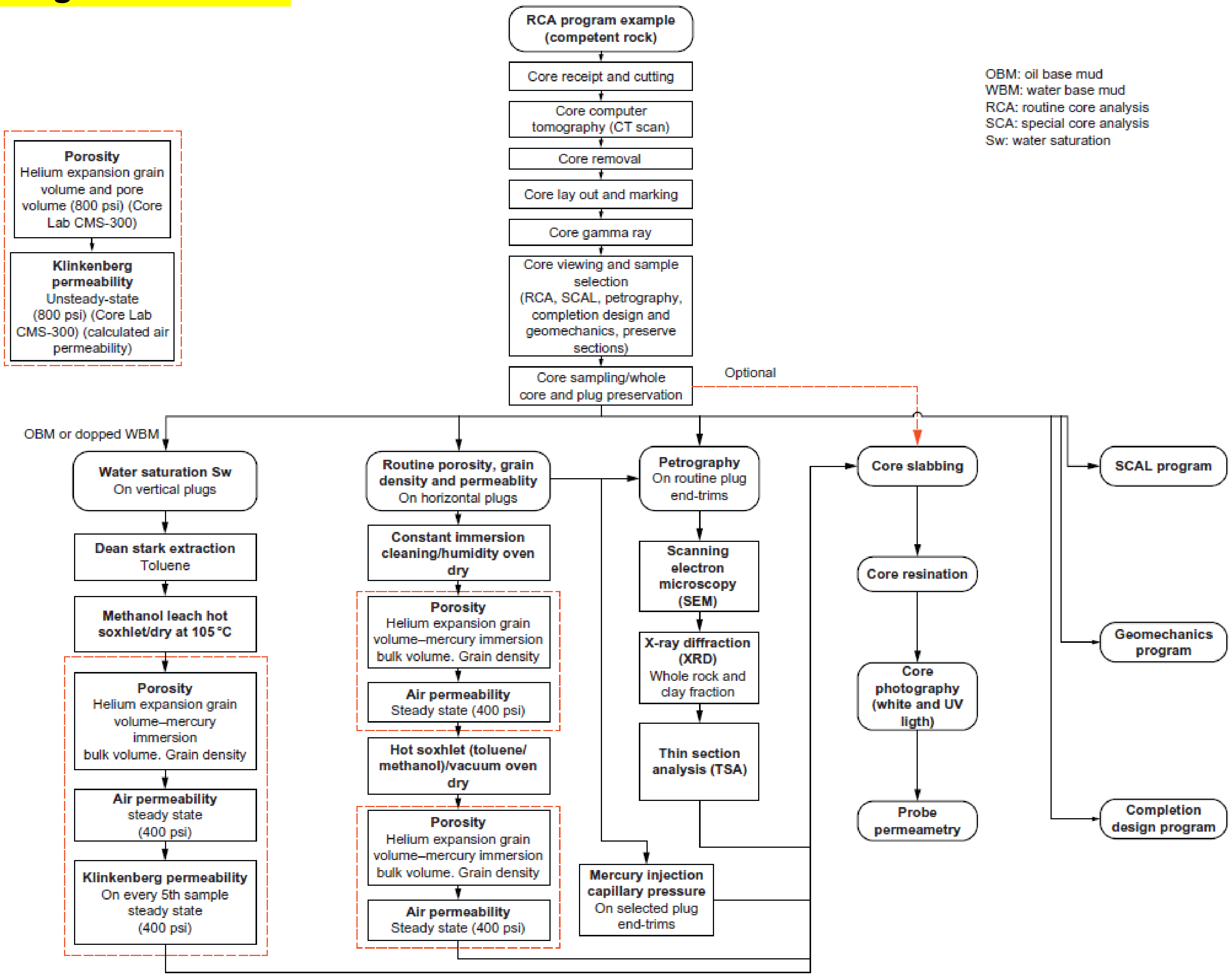
Below is an example of RCA program for both oil and gas reservoir core. This is only intended to provide a guide to the design decisions required and the potential programme workflows— and they are NOT supposed to be applicable to every reservoir and every rock type.v Each core analysis programme must be designed to meet the explicit data requirements, in the specific reservoir type, and specific lithology.

The design of a typical RCA programme is illustrated in the following examples from a competent rock on a gas or oil field

The following requirements have been identified for an RCA programme on a typical well:

- core–log depth matching;
- water saturation (core drilled with OBM or doped WBM)
- porosity and permeability (delicate clays present)
  if delicate clays are known present, a subset may be required to undergo staged cleaning, to investigate effective versus total porosity effects;
- mercury injection capillary pressure curves (MICP);
- petrography;
- core photography;
- probe permeametry.

Example of an RCA Program Workflow



Recommended RCA Tests

The anticipated tests and the data deliverables required for initial characterisation and to input for petrophysical and reservoir simulation models include the following tests:

Test	Purpose	Deliverable
Core CT scan	To document recovery, quality of recovered core, to locate any fracture zones, to evaluate any core damage, examine the degree of core heterogeneity, to observe bedding (if existing) for orientation and confirm suitability for further analyses. To aid in the selection of plugging sites (sample selection)	• Core photo CT scan images • Criteria for sample selection
Core gamma ray	To verify wellsite gamma ray, to correlate the depths of the well logs (core–log depth shifting) and to get an early idea of core recovery/quality	• Log of core depths versus core total and spectral gamma ray
Core viewing and sample selection	Inspect retrieved core to assess its quality and condition. Select sampling locations, sample dimensions, number of samples per test type, preserved sections, etc. using CT scans, well logs and core gamma ray as a guide The core analysis programme may need to be redesigned at this stage to take into account the actual core conditions This will need to be agreed among the different parties involved	• Core analysis programme is updated according to core characteristics • Tests are added or deleted accordingly • Lab personnel to recommend best sampling approach
Core sampling/ whole core and plug preservation	To take samples from the core following the core viewing/inspection/sample selection phase. Plugs to be preserved for SCAL and geomechanics tests	• Set of RCA plugs • Set of SCAL plugs (preserved) • Set of geomechanics plugs (preserved) • Whole-core preserved sections
Core slabbing (optional at this stage)	Allows for core preservation and preparation for core photography, probe permeametry and additional core logging. Recommended to slab the core once routine porosity and permeability data is available and it is decided that no further core plugging is required Slabbing may be required to reveal bedding for plug orientation, but slabbing before plugging limits the size of horizontal plugs	• Slab cuts depends on company/ regulatory authority requirements • One-third slab section (usually for regulatory authorities) • Two-third slab section (for future use)

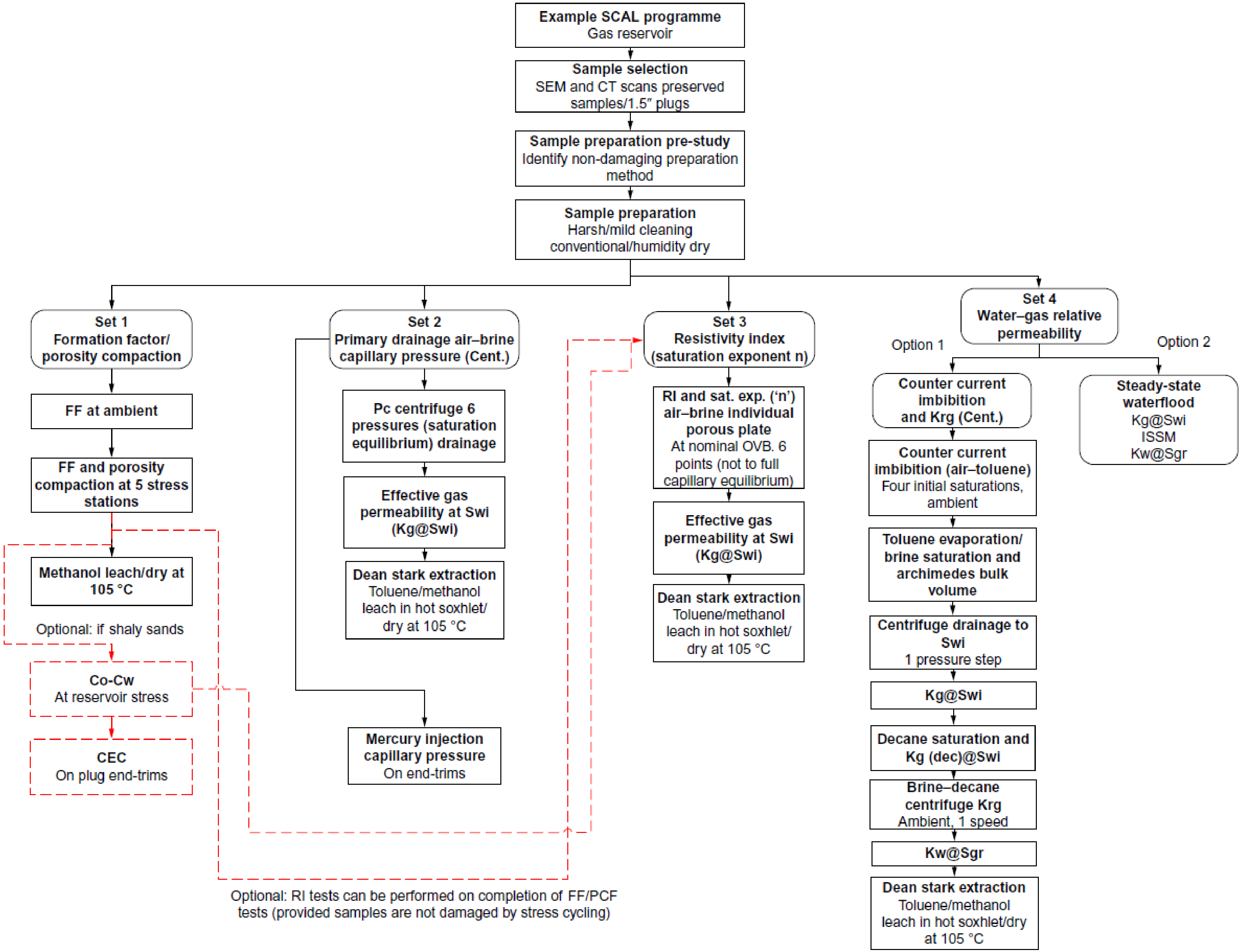
Test	Purpose	Deliverable
Water saturation (Sw) (Dean-Stark)	To obtain a direct measurement of extracted water volume (indirectly Sw), which can be used to develop quick-look saturation–height models (with MICP data) and to constrain saturation exponent estimates from resistivity index (RI) tests The technique is particularly suited to the case where the cores have been drilled with an oil-based mud and where the core water saturation has not been affected by mud filtrate flushing, or fluid flushing, on pressure expansion during core recovery. The core in the laboratory may be assumed to be at the same irreducible water saturation as in the reservoir. Plugs for this test are taken in the vertical direction, at the centre of the core were to minimise mud invasion Can be used with WBM provided mud doped with suitable tracers	• Water saturation (Sw) per plug (depth)
Routine porosity, grain density and permeability (horizontal plugs)	To measure base porosity and permeability of routine plugs Initially, the samples will be cleaned and dried following a mild procedure (constant immersion and humidity drying) as there are doubts about the influence of cleaning on delicate clays. Subsequently, a harsh cleaning and drying method will be followed; this is to allow for total porosity calibration with the logs. The methods and procedures for porosity and permeability measurement should be consistent with legacy data. For example, if lab propose unsteady-state Klinkenberg permeability measurements at 800 psi NCS and the legacy data were obtained using steady-state methods at 400 psi NCS, then the RCA programme should include both measurements on a representative subset of plugs to allow comparison between databases	• Porosity, permeability and grain density at ambient conditions for routine plugs cleaned following a mild preparation procedure • Porosity, permeability and grain density at ambient conditions for routine plugs cleaned following a harsh preparation procedure
MICP	At the RCA stage, MICP objective is to obtain relatively rapid drainage capillary pressure curves that can be used to develop a quick-look saturation–height model. Data can also be used during SCAL to design test pressure steps for drainage centrifuge capillary pressure. Data are also useful to design drilling muds for future drilling operations. Tests can be carried out on routine plug end-trims	• Pc versus Shg primary drainage capillary pressure curves • Entry pressures per sample

Petrography—scanning electron microscopy	SEM analysis provides visual information on clay and cement distribution, pore geometries and on the microstratigraphy of the mineralogical phases. Tests can be carried out on routine plug end-trims	• Full SEM description (including photomicrographs at varying magnification) per sample, documenting significant rock properties, pores, pore throats, clays, framework grains and cements • Pore controls on petrophysical parameters (including authigenic clays)
Petrography—X-ray diffraction	XRD analysis (whole rock and clay fraction (<2 μm)) provides semi-quantitative determination of sample mineralogy. Bulk and clay XRD analysis are performed to aid in reservoir description and evaluation of reservoir diagenesis. Identification of sensible clays and their proportion in the system can also provide useful information for sample preparation. Tests can be carried out on routine plug end-trims	• Whole rock and clay fraction composition of core samples (tabular format)
Petrography—thin-section analysis	TSA provides characteristics and distribution of detrital and authigenic minerals, including their grain shape, grain size, grain sorting and packing (textural features) and solution behaviour. The description and analysis permit the porosities/permeabilities to be traced on the basis of the properties of the detrital component and the plugging potential of authigenic minerals. Data may be semi-quantitatively substantiated by point counting. Tests can be carried out on routine plug end-trims	• Full TSA description (including photomicrographs) • Modal analysis (quantitative analysis of thin sections by point counting) • Mean grain size, sorting and point count determination of mineral abundances and porosity. Shale distribution, porosity varieties and abundances with a discussion of diagenesis, diagenetic sequence, porosity origins and development, controls on porosity and permeability

Test	Purpose	Deliverable
Core slabbing	Allows for core preservation and preparation for core photography, probe permeametry and additional core logging	• Slab cuts depends on company/partners/regulatory authority requirements • One-third slab section (usually for authorities) • Two-third slab section (for future use)
Core resination	To preserve core integrity after slabbing. A 'biscuit' cut may be set in labelled trays. This can be used for core photography, probe permeametry, sedimentology analysis and visual inspection (easy to handle/store)	• Resinated slab (biscuit) in trays
Core photography (white and UV light (oil or gas condensate reservoir))	High-quality–high-resolution digital images of the core surface (resinated slab) are taken under white light to record sedimentary detail and ultraviolet light to reveal fluorescing hydrocarbons and minerals. Very useful for future core analysis QC and interpretation, as samples can be located without the need of physically viewing the core. Also useful for SCAL sample selection and for any future reference to the core	• White and UV light slabbed-core images (digital and printed format)

Special Core Analysis Workflow

Below is the workflow of the SCA of a Gas Field


Example SCAL programme
Gas reservoir
Sample selection
SEM and CT scans preserved samples/1.5″ plugs
Sample preparation pre-study
Identify non-damaging preparation method
Sample preparation
Harsh/mild cleaning
conventional/humidity dry
Set 1
Formation factor/ porosity compaction
FF at ambient
FF and porosity compaction at 5 stress stations
Methanol leach/dry at 105 °C
Optional: if shaly sands
Co-Cw
At reservoir stress
CEC
On plug end-trims
Set 2
Primary drainage air–brine capillary pressure (Cent.)
Pc centrifuge 6 pressures (saturation equilibrium) drainage
Effective gas permeability at Swi (Kg@Swi)
Dean stark extraction
Toluene/methanol leach in hot soxhlet/ dry at 105 °C
Mercury injection capillary pressure
On end-trims
Set 3
Resistivity index (saturation exponent n)
RI and sat. exp. (‘n’) air–brine individual porous plate
At nominal OVB. 6 points (not to full capillary equilibrium)
Effective gas permeability at Swi (Kg@Swi)
Dean stark extraction
Toluene/methanol leach in hot soxhlet/ dry at 105 °C
Set 4
Water–gas relative permeability
Option 1
Option 2
Counter current imbibition and Krg (Cent.)
Counter current imbibition (air–toluene)
Four initial saturations, ambient
Toluene evaporation/ brine saturation and archimedes bulk volume
Centrifuge drainage to Swi
1 pressure step
Kg@Swi
Decane saturation and Kg (dec)@Swi
Brine–decane centrifuge Krg
Ambient, 1 speed
Kw@Sgr
Dean stark extraction
Toluene/methanol leach in hot soxhlet/dry at 105 °C
Steady-state waterflood
Kg@Swi
ISSM
Kw@Sgr
Optional: RI tests can be performed on completion of FF/PCF tests (provided samples are not damaged by stress cycling)

Test	Purpose	Deliverable
Core CT scan	To locate any fracture zones, evaluate any core/plug damage, examine the degree of core/plug heterogeneity, to observe bedding (if existing) and confirm suitability for further analyses. To aid in sample selection. CT scanning provides useful information on internal heterogeneity of the core (preserved section) and aids in assessing locations for cutting SCAL plug samples. If SCAL plugs have been preserved during the RCA programme, it is also recommended to carry out CT scan imaging on them	• Core photo CT scan images • Criteria for sample selection
Rock characterisation tests (SEM)	SEM analyses are essential in the design of the SCAL tests and in understanding and interpreting the results of the tests as well as assessing the requirement for a pre-study. This is normally carried out during the RCA programme	• Pore controls on petrophysical parameters (including authigenic clays)
Sample selection	The final SCAL test sample locations will be selected after review of the core CT scans and the log and RCA data from the well. The number of samples tested will depend on technical and budgetary objectives of the client	• Set of samples to be tested with designated measurements
Pre-screening study	Investigate optimum core preparation procedures. It is essential to preserve or prevent damage to any delicate detrital and authigenic components of the rock (e.g. clays); otherwise, the subsequent SCAL data will not represent the native formation properties. Illite, in particular, is a common pore occluding component in this formation A pre-cleaning study is scheduled, though this will depend on the results of the RCA programme. It is essential to identify the least damaging preparation method for the samples in order to maintain accuracy of the results. In the absence of delicate authigenic components, the optimum preparation method would be to Soxhlet clean the samples with methanol and conventional oven dry. If the difference is judged to be significant, all samples scheduled for main SCAL programme will be cleaned using a benign method (e.g. solvent flush cleaning and humidity drying)	• Optimum sample preparation procedure

Porosity/formation factor tests at overburden (including optional brine permeability at overburden)	These tests will define Archie's cementation exponent 'm' at representative reservoir conditions. Data acquired at ambient conditions are not representative and, worse, suffer from laboratory artefacts. Porosity is also determined during the test sequence, and these measurements provide porosity compaction factors The equivalent hydrostatic stress at initial reservoir pressure must be calculated, and the test stress stations must be defined. Brine permeability can also be measured at each stress station (optional)	• Archie cementation exponent 'm' at reservoir stress (input for log calibration to calculate Sw) • Porosity compaction factor for density log interpretation • Absolute ambient to brine overburden permeability transform (optional)
CEC (destructive)	To determine the CEC of the rock (Qv) as an input to the Waxman–Smits shaly sands equation for log calibration. This is the most widely used technique because it is cheap and rapid. It can be easily done for large number of samples. The method can be used as a first pass to have an idea of the CEC of the sample. If the value is low, an Archie Sw model should be used. Test can be performed on end-trims or any available sample material—there are no specific shape requirements. However, sample preparation process tends to overestimate CEC	• CEC of the rock (Qv)
Multiple salinity method (Co–Cw) (non-destructive) (optional in shaly sands)	To determine the CEC of the rock (Qv) as an input to the Waxman–Smits shaly sands equation for log calibration. Qv can be determined at representative overburden stress in plugs on intact samples. CEC data used to select Co–Cw test samples	• CEC of the rock (Qv) on intact samples
Air–brine drainage capillary pressure (centrifuge) tests with final end-point effective gas permeability at Swi at overburden	Drainage Pc curve using appropriate fluid system (air–brine) Absolute to effective and ambient to overburden permeability transforms (option). Centrifuge tests are required to create a true capillary pressure curve, since porous plate tests would never attain residual saturation without resorting to extremely lengthy and costly desaturation periods. Moreover, since mercury injection can underestimate the inferred irreducible water saturation at high capillary pressures, the capillary pressure curve generated	• Saturation–height model (in conjunction with MICP data) • Kg at Swir • Absolute ambient to effective overburden permeability transforms

	by the centrifuge test will complement and will be merged with the air–mercury curves to yield fluid-appropriate drainage capillary pressure curves for saturation–height modelling Given the expected hydrocarbon column height, the tests must be performed using an ultra-centrifuge to achieve the equivalent capillary pressure On completion of the centrifuge test, the end-point effective gas permeability, Kg at Swir, is determined as a function of overburden pressure. These data will supplement similar data from water–gas relative permeability tests and can be used • to determine an absolute ambient to overburden effective permeability transform and • to convert all routine core air permeabilities to reservoir condition data This is essential when comparing core permeability with well-test permeability and in creating reservoir condition permeability maps Dean–Stark extraction is performed to corroborate the final plug water saturation	
MICP	Air–mercury injection tests are capable of defining the full capillary drainage pressure curves used to develop a saturation–height model, as well as providing useful pore size distribution (PSD) data. Although not strictly capillary pressure tests, as an irreducible wetting phase saturation is never attained, the tests provide an adequate description of saturation–height relationships in most gas reservoirs. It can be used in conjunction with centrifuge capillary pressure data and used as an input to design pressure steps	• Pc versus Shg primary drainage capillary pressure curves • Saturation–height model (in conjunction with centrifuge Pc data)
RI tests	These tests will provide data on Archie saturation exponent 'n' at nominal stress conditions. 'n' is not normally sensitive to stress, but tests are performed at a nominal overburden stress to minimise grain loss on handling and to minimise laboratory artefacts prevalent at ambient conditions	• Archie saturation exponent 'n' (input for log calibration to calculate Sw)

	The maximum air–brine capillary pressure that is possible with the standard porous plate system is about 180 psi (which is equivalent to a gas column of around 270 ft.). This potential limitation coupled with the time required to achieve capillary saturation equilibrium in porous plate tests in low-permeability material means that the drainage process is unlikely to reach a truly equilibrated water saturation within a reasonable experimental time frame. However, the primary objective of these tests is to determine the RI–brine saturation relationship for each plug, not necessarily to determine an equilibrium air–brine capillary pressure relationship, since resistivity equilibrium is normally established much more rapidly than capillary pressure equilibrium Dean-Stark extraction is performed to corroborate the final plug water saturation As an option, RI tests can also be performed on completion of formation resistivity factor and porosity compaction tests, and provided samples have not been damaged by stress cycling If appropriate Dean–Stark data have been acquired in the RCA programme (core from intervals where water mobility is low; core drilled with OBM; core drilled with doped WBM and saturations corrected for invasion), then inverse modelling of core Sw versus log-derived Rt can be used to calculate 'n' under appropriate reservoir conditions. This may obviate the need for expensive and time consuming RI tests	
Residual gas CCI (countercurrent imbibition) tests	The tests provide a composite residual gas versus initial gas saturation relationship. The test mimics an imbibition process dominated by capillary forces and involves imbibition of liquid from various initial gas saturation values, covering the range in the productive reservoir zones. From the data generated in other reservoirs, CCI tests have proved to provide a simple yet reliable simulation of water imbibition processes but normally provide a maximum bound of Sgr due to gas trapping on plug immersion	• Sgr versus Sgi relationship

Water–gas imbibition relative permeability	To fully describe water movement in the reservoir as a function of gas production or reservoir depletion (e.g. aquifer influx, coning), imbibition water–gas curves are required. Imbibition water–gas tests are extremely difficult to do and are costly to perform. Dynamic tests using unsteady-state water-displacing gas methods can often yield a residual gas saturation that is too low due to the extremely favourable mobility ratio of the water flood and the imposition of viscous forces which overcome the capillary forces that trap gas at residual saturations. This is a particular problem in low-permeability samples where the viscous forces (even at low rates) are high. Steady-state tests, in contrast, often provide a Sgr that is too high All gas–liquid flood tests are prone to disequilibria, i.e., mass transfer between the gas and the liquid, leading to errors in end-point saturations. Differential pressure must be controlled as a function of the pore pressure (recommend $<2\%$) to reduce such effects The centrifuge technique proposed is a compromise with decane replacing the gas phase (both will be non-wetting in this formation). In centrifuge tests, the relative permeability obtained is that of the phase that is being displaced—not the displacing phase. Thus, water-displacing-decane is used to generate an imbibition cycle gas equivalent relative permeability. Decane is used as a replacement for gas due to compressibility and diffusion issues experienced when performing tests using gas. The IFT for water–decane systems at lab conditions is also close to that for gas–brine at reservoir conditions of $\sim$50 dynes cm^{-1}. The use of a capillary dominated flood also better replicates the potential field conditions (aquifer influx) than a dynamic test Dean–Stark extraction is performed to corroborate the final plug water saturation	• Kg@Swir • krg (water imbibition) • Kw@Sgr

Steady-state water–gas (imbibition) relative permeability	To determine intermediate krw and krg imbibition curves for comparison with centrifuge tests (krg only) Steady-state tests in which water and gas are injected simultaneously require non-invasive saturation monitoring to determine accurate saturations All gas–liquid flood tests are prone to disequilibria, i.e., mass transfer between the gas and the liquid, leading to errors in end-point saturations. Differential pressure must be controlled as a function of the pore pressure (recommend <2%) to reduce such effects Requires careful design of test rates to avoid flow instabilities. Sgr may be too high but data can be scaled using end-point scaling Injection and production test data required for coreflood simulation Imbibition Pc data also required to enable coreflood simulation	• Intermediate krw and krg imbibition curves