iSciMP
Physical Properties Working Group Report
(Revised)

Revised from a Report by
Douglas Schmitt, Christian Buecker, Mike Lovell, & Saneatsu Saito

5th December 2003
Revised June 2004

Contents

1. Introduction

The Physical Properties working group was begun at the June 2002 iSciMP (the interim Scientific Measurements Panel) meeting in College Station, Texas in order to address issues related to physical property measurements in the context of the IODP. The focus of the working group is to re-evaluate the current physical property measurements, both shipboard and on land, and to explore new directions that physical property measurements should take.

This is a revised report (June 2004).

2. Plan for Physical Property Measurements

a. Suggested Minimum Measurements Mandatory – All Platforms

As with other scientific measurements, it is difficult to know exactly what the differing scientific needs will be across the many different platforms. The need for value added scientific measurements will likely be increased for long term ‘complex drilling programs’ but only minimal physical properties may required for some of the ‘mission specific platforms’ and even this might be difficult under certain circumstances on small platforms. Further, the types of materials cored, i.e. whether soft sediments, lithified sediments, or crystalline rocks, will influence core logging and sampling strategies. However, there is a minimum set of measurements that needs to be carried out in the large majority of IODP projects. These are to enable cross correlation of core measurements with geophysical logs and surface/wellbore seismics, to assist matching lithology between wells, and to provide other disciplines with appropriate physical properties data (e.g. Formation Factor for pore water geochemists). The minimum set of measurements includes discrete measurements and those currently made on the MST/MSCL core logging systems:

- gamma ray attenuation bulk density(GRA)
- moisture and density measurements
- magnetic susceptibility (MS),
- P-wave logging (PWL) (on soft sediments), and
- natural gamma radiation (NGR).
- We strongly recommend adding *electrical resistivity* to this list; the technology for resistivity measurement, likely by a noncontact induction technique, that is now available as part of an MST.
- We also recommend adding color reflectance

The MST/MSCL is reasonably portable, and should be standardized on both the riser and non-riser vessels and be incorporated into mission specific platform (MSP) projects. Where an MSP cannot make these measurements on board, facilities should be established close by on shore to enable ephemeral measurements.

Additional discrete samples should be taken for QA/QC and calibration procedures of ephemeral properties against the MST. This is planned for the MSP Arctic Coring Expedition (ACEX).

Recommendation: The MST/MSCL should be standardized on both the riser and non-riser vessels and be incorporated into mission specific platform (MSP) projects. Discrete samples should be taken for QA/QC and calibration procedures of ephemeral properties against the MST.

b. Supplemental Physical Property Measurements – Phase I vessel

Initial consideration is given to Phase I drilling with the non-riser (riserless) vessel.

The requirements for the non-riser vessel are similar to the riser (see Appendix 3) in that the vessel will generally be stationed for a significant period in one region and will usually collect a significant amount of core during a single leg.

One aim here is to have sufficient data to relate downhole data to core through physical measurements, thus enabling integration of the downhole in situ observations with the shipboard and shore-based geological observations. Another is to provide sufficient physical property data to achieve the scientific objectives; unfortunately not all of the objectives are defined at the time of the leg, since the program provides a legacy of data for future investigations.

Continuous measurements (MST) provide detailed high resolution logs for integration with downhole data, and enable detailed planning of sub-sampling programmes on-board ship.

Discrete measurements (e.g. thermal conductivity, P-wave on hard rock) provide reference data for integration, as well as independent reference points for checking calibration of MST. Discrete measurements of index properties (grain density, porosity) are important and need to be done immediately, prior to transport-induced disturbance.

Additional property measurements that could be included in Phase II include: XRF scanner, CT tomography, particle size analyzer, geotechnical tests, and magnetic resonance.

Recommendation: The final ODP operations for physical properties measurements be taken as a minimum requirement for IODP Phase I operations, but with the addition of resistivity. Furthermore, we recommend that the following be urgently considered: colour reflectance upgrade, implementation of calibration standards, and upgrade of natural gamma ray.

c. Supplemental Physical Property Measurements – MSPs

MSPs provide complex and varied environments for physical property measurements. Some may have ample laboratory room; others may have none (e.g. beach-based, inter-tidal lorry on scaffolding planks above the water level!). But the science has to drive the programme and consequently we have to plan the best feasible route for obtaining sufficient variety and spatial sampling of data. An MST needs to be as close as possible to the drill site. Running this at the drill site and on-shore provides a quantitative measure of any core disturbance or fluid loss.

Shore-based labs, preferably close to the drill site (not Core Repositories some distance away) need to provide additional detailed ephemeral properties (porosity, thermal conductivity). These could be specific to the project or based at a nearby institution; if the latter then adequate calibration between standards is required.

Some properties such as grain density can be measured anywhere, anytime, unless there is the possibility of imminent diagenesis, perhaps where sensitive clays are present.

Consensus Statement: SciMP should examine petrophysical plans in detail for each MSP expedition. This examination is to ensure the proposed measurement strategy adequately meets the requirements of the science objectives and the legacy nature of IODP data.

d. Supplemental or Advanced Physical Property Measurements – Land

Geotechnical properties are unlikely to be achieved to a sufficiently high standard on a routine basis on any of the platforms, although standard consolidation tests could be performed onboard given customized, computer-controlled equipment, and could constrain the elastic rebound component of the dilation. These should be planned and described separately as appropriate, support the science objectives, and be carried out rigorously.

Permeability is a valuable characteristic but is difficult to measure in water-saturated cores (either they are too fine grained and thus have a low k which takes considerable time to measure, or they are permeable, coarse grained material which doesn't core as well). Permeability on dried lithified cores is easier, but requires careful removal of salts during the drying process (cleaning of cores and avoidance of any consequent damage to minerals).

Physical property imaging: increasingly we can obtain both surface images (2d) and internal images (2d slices or 3d tomography) using a variety of measurements. It would be good to encourage these developments as shore-based advanced techniques.

NMR T1 and T2 relaxation measurements on core are now possible using fairly small commercially available equipment. This provides useful information on pore-size distribution with links through algorithms to permeability (which, however, has to be calibrated against core measurements). This could be a routine measurement on the Chikyu, possibly on the non-riser too. It has proved particularly useful in downhole investigations of hydrates.

3. Recommendations

1. Physical properties measurements are important for the following prioritized reasons:

    a) Safety
    b) Drilling decisions
    c) Scientific Objectives:
        i. Ephemeral properties
        ii. Routine physical properties for core-log-seismic integration and hole-to-hole correlation
        iii. IODP Legacy for future studies

It is important that all of these are satisfactorily addressed in any drilling proposal.

2. For the Riser vessel and the Riserless vessel this will tend to be easily assessed through almost routine use of the vessel and its facilities. While most measurements will take place at sea, there may be occasions (such as severely dilated samples) where shore-based work forms an integral and important part of the ship-based strategy. For the MSP's this shore-based work will inevitably be of high importance on a more frequent basis.

3. Each drilling expedition will have different objectives, and these will be severely constrained by the facilities available. This situation impinges mainly on the MSP's and thus SciMP should carefully assess the Physical Properties measurements proposed in any drilling expedition.

4. While it is impossible to define the essential measurements for any scientific expedition without consideration of the Scientific Objectives we recommend the following as a minimum requirement:

i. The MST/MSCL is reasonably portable, and should be standardized on both the riser and non-riser vessels and be incorporated into mission specific platform (MSP) projects.

ii. Additional discrete samples should be taken for QA/QC and calibration procedures of ephemeral properties against the MST. This is planned for the MSP Arctic Coring Expedition (ACEX).

4. References

Blum, P., Physical Properties Handbook: A guide to the shipboard measurement of physical properties of deep-sea cores, available at http://www-odp.tamu.edu/publications/tnotes/tn26/INDEX.HTM, November, 1997.

Schön, H.J.: Physical Properties of Rocks; Fundamentals and Principals of Petrophysics. Handbook of geophysical exploration, Section I, Seismic Exploration: v.18, K. Helbig and S. Treitel (eds.), Elsevier Science, 1998.

Appendix 1: Overview of Physical Properties

Physical property measurements on retrieved core and drilled cuttings provide a great deal of additional information that assists in correlation between nearby holes and cores. Further, these data can be used to assist in the processing and interpretation of both geophysical well logs, and surface and wellbore seismic observations. The physical properties themselves can reveal a great deal about the formation, composition, and in situ conditions of the materials. Physical properties can also be used as proxy measures indicative of paleoclimate, fluid flow, permeability, and deformation to name only a few. In short, physical property measurements are a necessary part of nearly all modern integrated studies in the earth sciences and particularly any program in which the earth is sampled by drilling either on the oceans or continents.

There are many different physical properties, or perhaps more precisely characteristics of earth materials. This list is not inclusive but attempts to represent those properties that would be of most interest in studies. Many of the measurements are made in geophysical well logs and core based measurements provide useful ties to the downhole information. Many of these properties are routinely measured, as will be discussed in the next section, but others would be difficult to carry out under the time and resource constraints shipboard. Some also overlap with the interests of other working groups (such as chemistry for example). A listing of the physical properties often measured in earth materials includes:

- Porosity ϕ – the ratio of the void space to the total volume. (dimensionless).
- Permeability κ - the capacity for fluid of a given viscosity to be transported through a porous medium by a gradient in fluid pressure according to Darcy's Law (applies to laminar flow and is generally only be measured on cores, often using inert gas on dried samples). (units = $m^2 = 1.01 \text{ X } 10^{12}$ Darcy)
- Mineralogical and Fluid Composition and Texture – the mineralogic modes (mass or weight percentages) and the fluid composition including fluid salinity, absorbed gas, or hydrocarbons. Texture of the rock refers to the preferential alignment of minerals and pores that can lead to anisotropy. Modes and fluid compositions may be described by dimensionless volumetric ratios but texture is more difficult to properly define.
- Fluid Saturation – the ratio of the void space that is filled with fluid; In ocean drilling this usually consists principally of water (S_w), although gas (S_g) may also be present. In hydrocarbon situations oil (S_o) may also be present. Saturation is important where gas hydrates are present, especially given the unstable and hence dynamic nature. (dimensionless)
- Density ρ - ratio of the mass to volume (kg/m^3)
- Moisture content
- Magnetic Susceptibility k – A measure of the modification of the magnetic field by the secondary field induced by presence of the material in the original magnetic field. The magnetic field strength **B** is proportional to the magnetic intensity **H** via $\mathbf{B} = \mu_o(1 + k)\mathbf{H}$ where mo is the permittivity of free space: a fundamental physical constant equal to $4\pi \text{ X } 10^{-7}$ Tm/A. (dimensionless)

- Dielectric Constant k' – a measure of the electric permittivity of a material $\varepsilon = k\varepsilon_o$ where $\varepsilon_o = 8.85 \text{ X } 10^{-12}$ F/m is the permittivity of free space. The dielectric constant is a measure of the polarizability of the material and for most practical purposes depends on the free water content as $k \sim 80$ for water and typically well below 10 for most other earth materials. The dielectric constant is frequency dependent and influences the propagation speed v of electromagnetic radiation through the material via $v = c/\sqrt{k}$. (dimensionless)
- Elastic Wave Speeds – The compressional or P-wave V_P and shear or S-wave V_S velocities are measures of the elastic physical properties of the material. There are many different ways these relationships may be expressed but generally $V_P = \sqrt{(K + 4\mu/3)/\rho}$ where K and μ are the bulk and shear moduli, respectively and $V_s = \sqrt{\mu/\rho}$. These wave speeds (or the associated elastic moduli) and the variations of these with direction of propagation can reveal a great deal about texture, porosity, stress, and saturation state. Knowledge of such properties is critical to the interpretation of geophysical well logs and for calibration of seismic observations although serious complications arise in the comparison of laboratory to field dimensional scales and frequencies. (units – m/s or μs/ft).
- Deformation Properties – These depend a great deal on the material under study. In soft sediments aspects of consolidation and shear strength may be important. In consolidated rocks more complex criteria, such as those of Mogi or Mohr-Coulomb, describing shear failure under deviatoric stress states with frictional constraints may be required. Description of the drilling induced core fractures may in some cases yield indications of in situ stress states and faulting regimes.
- Natural Radioactivity – Due to the relative ease of measuring the natural radioactivity, or more precisely, the γ-ray radiation emitted primarily from the decays of unstable K, U, and Th isotopes, the measurement of the natural radioactivity of rocks is perhaps the most useful correlative tool. The natural radioactivity of sedimentary deposits is most often sensitive to the clay content and this can be indicative or depend on the depositional environment. (Units – usually in term of counts per time period but this may be calibrated against a standard that will account for the test configuration, in well logging this calibrated standard is referred to as API units with 200 API representative of a typical relatively radioactive deep water marine shale).
- Electrical Conductivity/Resistivity – Electrical conductivity of materials displays the largest range of variation over many magnitudes, for example the electrical conductivity increases by 7 orders of magnitude from pure distilled water to a saturated brine. Aside from some special materials such as graphite where electron mobility predominates, electrical conductivity in earth materials is primarily indicative of ionic transfer in liquids such as mineralized water or silicate melts. Other mechanisms relate to transfer of adsorbed ions along clay surfaces. Electrical conductivity will often be frequency dependent. Often, the electrical resistivity is used to infer related physical properties such as the tortuosity τ, a measure of the pore space path through the material, or the empirically based formation factor F that relates

resistivity to porosity in sands. Electrical conductivity is a standard measurement in geophysical logs and laboratory measurements can assist in the interpretation of such results. (units – resistivity in Ω•m, conductivity in S/m). The electrical formation factor is used by pore water chemists. Electrical conductivity is often related to porosity via the empirical Archies Law, which is valid for clean sandstones. In rocks containing a conductive matrix (e.g. clays or metallic minerals) the relationship to porosity is more complicated but still workable.

- Thermal Conductivity - λ - the thermal conductivity is a measure of the ability to transfer heat energy. A related property is the thermal diffusivity which is the ratio of the thermal conductivity to the average specific heat of the material. The primary importance of such measurements lies in providing data useful in determining the heat flow with knowledge of subsurface temperature gradients.
- Magnetic Resonance – Magnetic resonance studies of earth materials primarily focus on the behavior of Hydrogen (i.e. protons) under varying magnetic fields. There are two different time scales T_1 and T_2, the spin-lattice (or longitudinal) relaxation and the transverse relaxation times, respectively. In rocks these usually depend on the fluids contained in the pore space, their viscosity, and other characteristics of the pore space such as pore and pore-throat size distributions.
- Reflectance spectrophotometry and colorimetry – color is the human perception of reflected light over the visible spectrum (400 nm – 700 nm). This can be measured by ‘diffuse-reflected spectrophotometry’. These data can be used to provide time series of relative changes in the bulk composition that in some cases will allow for correlation hole to hole or core to core. This can further be used to examine the cyclicity of lithological changes. Spectral data can be used in some circumstances to provide a measure of the abundances of minerals.

Appendix 2: ODP Physical Property Measurements

A number of the physical property measurements are currently made on retrieved core in the laboratories on the JOIDES Resolution (Blum, 1997). The list of current physical property measurements possible include:

- Core Logging
    - Whole Core Multi-sensor track (WC-MST)
        - Density via Gamma Ray Attenuation Densitometry (WC-GRA)
        - Magnetic Susceptibility (WC-MS)
        - Natural Gamma Radiation (WC-NGR)
        - P-wave velocity logger (WC-PWL)
    - Slit Core Logger A
        - Diffuse Color Reflectance and Colorimetry
        - Magnetic Susceptibility (SC-MS)
        - Line-scan color imaging
    - Split Core Logger B (in place?)
        - Density via Gamma Ray Attenuation (SC-GRA)
        - P-wave velocity logger (SC-PWL0
        - Resistivity – not yet implemented.
- Discrete Measurements on whole or split core
    - Thermal Conductivity (TC)
    - P-wave velocity on split core (PWS1, PWS2, PWS3)
    - Shear strength on split core (AVS)
- Measurements on extracted core samples
    - Moisture and Density (MAD)
    - P-wave velocity on rock cubes or cylinders (PWS3)
    -

(see http://www-odp.tamu.edu/sciops/labs/physprops/types.html)

It is worth noting that four of these measurements are run in a standard fashion using the whole core Multi-Sensor Track (MST) station, these include gamma-ray densitometry (GRA), the magnetic susceptibility logging (MSL), the natural gamma-ray measurement (NGR), and the P-wave velocity logging (PWL).

Appendix 3: Additional properties for the Riser Vessel – Chikyu

The Chikyu has an added advantage of having a great deal of space. As such the physical property laboratories on the Chikyu are expected to include

- Whole core MSCL with:
    - GRA (Gamma Ray Densitometry)
    - Porosity evaluator (GRAPE, this refers to the estimation of porosity from the GRA densitometer measurements using an assumed grain density).
    - Magnetic Susceptibility
    - P-wave logger
    - Electrical Resistivity
- Natural Gamma Ray Spectrometer
- Digital Image MSCL – color line scanner
- Split Core MSCL
    - P-wave logger
    - Magnetic Susceptibility
    - Electrical Resistivity

- **Cuttings measurements**
- Density
- Susceptibility
- Gamma ray
- Thermal conductivity

- Color Spectrometer
- XRF Core Logger
- Laser Particle Analyzer
- X-ray system, soft x-ray camera
- Thermal conductivity system (contactless, new infrared system)
- Pycnometer (density and porosity)
- XRD – mineralogic composition
- Discrete P-wave, resistivity, and perhaps S-wave measurements too – for lithified core sampled in small pieces and for calibration check measurements against the MST and other labs?

The riser ship Chikyu gives the nice advantage of getting cuttings from the drilling process. These cuttings can in most cases also be used for a variety of physical and chemical measurements, and this opportunity should be used. Detailed proposals are required for the routine characterization of cuttings in terms of physical properties.