INTRODUCTION

1.1. COURSE HISTORY AND OBJECTIVES

The origin of this course is based on the perception that each petroleum engineer should be able to recognise reservoir rock and its pore content from well logging information. For this reason at the start of the eighties ir. J.P. van Baaren started his introduction to Petrophysics; a lecture course and two weeks practice in interpretation. This course was based on a Shell training. Over the years the course debased from a fourth year petroleum course to a second year basic course with the objective of a general introduction in physical rock properties including some log interpretation . Subsequently prof. ir. M. Peeters started to revise the course to a general introduction, which also includes aspects relevant for groundwater surveys, coal and mineral exploration. Here the UK based company BPB Wireline Services provided training material for coal logging. The technical information provided by Welenco in their Water & Environmental Geophysical Well Log Volume, and the documentation from TNO-NITG, formed the basis for ground-water logging. For mineral logging papers of the 6th international symposium on borehole geophysics (Santa Fé - New Mexico October 1995) have been of value. In this 1999 version of the course the main objective is the integration of theory and practical work**. Lectures are mixed up with some mental exercises and laboratory experiments.** Each student will have the opportunity to realise several rock physical experiments. For this reason teamwork will be essential; the students are divided in groups with tasks and responsibilities for each of them.

Why is this course relevant?
Each of the students will meet in his geotechnical career situations in which the physical properties of natural or artificial rocks have to be defined or are to be used in project decisions. For example:
Running instruments in boreholes at the end of a wireline, called well logging, is applied in many industries. A log is the continuous record of a physical property of the subsurface as a function of depth. For wireline logging the registration equipment on the surface is connected by a steel armoured electrical cable to the instrument.

- The oil industry is the most important user of physical rock properties to identify hydrocarbon bearing layers, and to quantify the amount of producable oil or gas.
- Applications are also found in conventional mining operations. Examples are quantification of the ash & moisture content of coal, roof and floor strength of galleries and the mineral grade of ore deposits.
- The engineering geologist and hydro-geological engineer use rock physical measurements, or depth records obtained with soil penetrating probes, to measure soil friction, mechanical strength, gas content, water conductivity, etc.
- Physical measurements on rocks gradually are more and more in the detection of soil and aquifer pollution, normally with respect to chemicals and radioactive waste.

In a major part of this course the aspects of petrophysics or, more specific, the utilisation's in log evaluations are providing the exercises for applications of the theory. If one applies empirical relationships, it is essential to use as many checks as available from information and interpretations from other disciplines, to guarantee a meaningful rock physical evaluation. For example; the environment of deposition provided by geologists; stratigraphy extracted from seismic by geophysicists; fluid types provided by production technologists; and reservoir distribution data provided by reservoir engineers, should all be respected to escape from incorrect interpretations. This exchange of data and interpretations is a cyclic process and only the synergy of different disciplines can create an “image” of the subsurface, and “characterise” a water or (hydro-) carbon reservoir or mineral deposit with sufficient accuracy to make a reliable and economic development plan. For example; when a well is considered the first thing to know will be the types of rock that have been perforated and whether some strata contain economic zones. This first information on the lithology and fluid content of the penetrated layers available

LOCATION:	reservoir / coal / mineral - layers
DETECTION:	fluid content water / oil / gas / pollutant coal / ore body
EVALUATION: (for all applications)	lithology mechanical properties gross / net thickness
ROCK PROPERTIES	
hydrocarbon & water reservoirs	porosity / permeability capillary properties salinity / hardness of the water original hydrocarbon saturation movable hydrocarbon sat. residual hydrocarbon sat. % oil/gas/water reservoir pressure
coal	moisture content ash content fixed carbon content
minerals / soil mechanics	ore content and grade fluid/gas content

Table 1. 1: Objectives of a petrophysical interpretation.

is contributed by the drill cuttings and traces of oil and/or gas in the mud. The objectives for a more extensive rock physical evaluation are in table 1.1.
In addition to the direct well information measured rock physical data also are used for the estimation of the desired rock properties. The first group of data give direct "physical" information by means of rock and reservoir fluid samples, and will be discussed in the first part of this course.

DIRECT INFORMATION	***ROCK FRAGMENTS & FLUIDS*** - drill cuttings, mud shows - sidewall samples, cores or core slices - production tests, formation wireline samplers drill-stem tests	
INDIRECT INFORMATION:	***WIRELINE LOGS***	
	PHYSICAL PHENOMENON	**MEASURED PARAMETER**
	acoustic - waves	sonic velocities acoustic impedance
	gamma / gamma scattering	electron density photoelectric cross section
	thermal neutron density	hydrogen density
	thermal neutron decay	thermal neutron cross section
	neutron activation	elemental concentrations
	natural gamma radiation	Curie / Bequerel / API / REM
	spontaneous potential	membrane potential
	electromagnetic waves 35 Hz -20 kHz	electric resistivity / conductivity
	100 Mhz-2 GHz	dielectric permitivity
	nuclear magnetic proton resonance	free hydrogen index spin lattice relaxation time

Table 1. 2: Petrophysical evaluation data sources.

The second group of data consist of logging measurements. The theory behind these applications and some methods of interpretation will cover the major part of this course. Further the interpretation of log and core data for hydrocarbons, coal, minerals , groundwater and environmental applications come up in theory and in the mentioned laboratory experiments.

1.2. HISTORICAL DEVELOPMENT

Petrophysics as its name indicates, has to do with the physics of rock. Mining and the search for rock products, such as metals date from the earliest times. The flintstone caves in Limburg and the exploitation of bog iron deposits in Drente are early examples. Scientific recording of rock properties commenced with the publication in 1556 of the famed disquisition **De re metallica** by Georgius Agricola (1556). For many decades it was the leading work on exploitation of mineral bearing rock. In the following centuries Gilbert discovered and described the earth as a enormous and irregular magnet. In addition Newton's theory of gravitation also contributed to the first notions regarding the physics of rocks. The publication of Thalen's book; **“ On the Examination of Iron Ore Deposits by Magnetic Methods.”** in 1879, and the construction of his magnetometer for the determination of depth, dip, strike of magnetic dikes, appear to be the first utilisation based on physical rock properties. From the 19^{th} century on the continuous increase in the need for minerals, water and (hydro-) carbons raised a need to develop rock physical techniques of increasing sensitivity for the detection and inventory of invisible deposits and structures. Their detection depends upon those characteristics which differentiate them from the surrounding media. Methods for the detection of variation in electrical conductivity and in natural currents in the earth, the rates of decay of artificial potential differences introduced into the ground, local changes in gravity, magnetism and radioactivity, provide information to the geo-engineer about the nature of sub-surface structures to determine the most advantageous spot for locating the source or determining the quality of the source. The development of new electronic devices for field equipment and the widespread application of the digital computer in the interpretation of data improved the development of technical equipment; especially in Geophysics and Petrophysics. Many of the methods now used were developed for military purposes during the two World Wars. For example; when petrophysics is concerned, the application of rock physics into well measurements (both hydro-carbons and water) and data interpretation, show in the last eight decades the following evolution.

∗ 1910, introduction of rotary drilling.
∗ 1927, introduction of electric well logging by the Schlumberger brothers.
∗ late 1930’s, introduction of natural gamma-ray logging and the dipmeter.
∗ 1940's, development neutron-gamma logging.
∗ 1941 first electric survey run in a Dutch water well (J.H. Beltman)
∗ 1950's, introduction neutron-neutron logging.
∗ 1950's, development of sonic logging.
∗ late 1950's, introduction of induction, lateral and formation density logging.
∗ 1960’s introduction of wellsite tape recording and digitisation of logs
∗ 1965 introduction of pulsed neutron logging tools
∗ late 1960’s introduction of first nuclear magnetism, and dielectric tools
∗ 1970’s introduction of micro-resistivity and acoustic (BHTV) imaging tools,
∗ 1980’s introduction of array-induction and azimuthal resistivity imaging tools
∗ late 1980’s development of nuclear magnetic resonance tools with permanent magnets.

Besides applications in war, one should not forget that many applications already were in use for the exploration and exploitation of coal fields and minerals, originally from petrology, mineralogy, geochemistry, geomechanics and geophysics. Further space technology can be regarded as the new provider of knowledge for interpretation.

1.3. ROCK PHYSICAL DATA PLACED AGAINST PROFIT

As the roman business people already stated “pecunia non olet”, is certainly of valid in any geo-engineering project. Managers and investors want to dig in rock, want to build on rock and want to produce from rock with the main target: long term or short term profit! Initially all activities regarding research or analysis are too expensive. The costs “wasted” on rock physical information, or in our cases:

- petrophysical data logs,
- the evaluation of the logs,
- the acquisition of cores and outcrop samples, and
- the analysis of core and rock samples,

often depend on the total cost of the exploration or appraisal phase.

The significance of the gathered data, i.e.:

- contingency on repeated sampling,
- the risks involved in obtaining the data, i.e. well damage/loss, and
- the time needed for,

are also important to be considered when exploitation has to be interrupted or slowed down.

As an example; for wells the evaluation cost are in general between 6 and 12 % of the total expenditure. For shallow ground water wells and mineral/coal exploration wells the risks and total cost are usually relatively small (<< $ 100.000,-). As a result the evaluation cost will be in the order of a few thousand dollars. For an offshore oil exploration well, drilled with a floating rig in deep water, the total well cost can be 20 million dollars. Optimising the direct, derived and deduced knowledge gathered from this “unique” exertion will be necessary. Evaluation of the cost for such a venture can be amount to several millions of dollars.

1.4. A FOREWORD TO THE EXERCISES

1.4.1. PRACTICAL COURSE RELEVANCE FOR THE STUDY

Since this practical work is a part of the second year programme, the subjects are related to a wide field of interests. Petrophysics is an applied discipline, with connections and roots in many fields of exploration. Both geophysics and ore/coal exploitation are valuable sources for many petrophysical interpretation techniques. Examples of well log interpretations for various disciplines are:

- **Petroleum Engineering**

From logs the following information:
- Reservoir thickness, gross/net.
- Reservoir properties, such as; porosities, permeability, rock strength, wettability, etc.
- Fluid content and properties; water, %, salinity, gas, oil.
- Environment of deposition.
- Source rock potential.

- **Geophysics**

From logs the following information:
- Impedance as a product of Density and Sonic.
  Proper editing is needed, such as checks on calliper (washout sections useless to apply) environmental corrections such as; borehole size, mud type, invasion. In a gas bearing formation, the sonic shows erroneous velocities.
- With other logs the sonic-density can be made artificial.

- **Engineering Geology**

Objectives of well logging surveys:
- Geological; thickness, depth to engineering rock bed, establishing weathering profiles, location of buried channels etc.
- Resource assessment; location of aquifers, determination water quality, exploration of sand, gravel and clay deposits.
- Engineering parameters; dynamic elastic module, rock quality.

- **Mining; exploration and exploitation.**

Objectives of well logging surveys:
- Detection of ore bodies or other productive seams.
- Non recovered sections of cores can be correlated with logs

- **Coal logging**

Lithology interpretations from:
- Sonic, density and neutron readings.
- 100% matrix responses of the minerals; coal consists of: carbon (Vcarb, Dcarb, dTcarb), ash (Vash, Dash, dTash) and moisture (porosity) (Vmois, Dfl, dTfl).

$$dT = dTfl.Vmois + dTash.Vash + dTcarb.Vcarb$$
$$D_{bu} = Dfl.Vmois + Dash.Vash + Dcarb.Vcarb$$
$$1 = Vmois + Vash + Vcarb$$

Three equations, three unknowns: Vash, Vcarb, Vmois

- **Gold or ore Exploration**

Gold associated with pyrite (high conductivities)

- **Other**

Many other purposes can be mentioned, especially regarding drinking water resources, environmental aspects such as groundwater contamination, the use of brine, nitrogen injection, sub-surface (nuclear) waste storage, underground coal gasification, etc.

1.4.2. INFORMATION ON THE EXERCISES

This course is primarily an introduction to the basic elements of rocks and related physics and secondly an introduction to some useful aspects of borehole log interpretation. The emphasis lies on the application of theoretical work, supported by log interpretations.

During the first meeting relevant rock and fluid characteristics are introduced. Thereafter the world of pores is discussed, i.e. the relation between textures, porosity, permeability, capillary pressures, etc.. Subsequent sessions show more complex interpretation techniques, and by that the most important logs are used; calliper, gamma ray, spontaneous potential, induction, neutron, density, sonics. The number of interpretation techniques is kept to a minimum. The most important relations are dealing with:

- The resistivity of rock, pore fluid, mud (-filtrate), Archie, and by that porosity and Sw.
- Bulk density and porosity and by that shale volume determination.
- Lithology determination
- Calculation of gross/net volumes of specified strata and/or formation fluids/gases.

- **The exercise are presented within the lectures. So, attendance will be essential.**

After each session, the participants are urged to study the related course notes, as provided.

- **The practical work also consist of some laboratory work at the Dietz-laboratory.** This work includes the measurements on one solid core and two porous cores:
  - Measured are bulk volume and bulk weight and the related matrix volume and matrix density.
  - Calculation of the porosity on the two porous samples, with a dry method and the wet/dry method.
  - Calculation of the gas-permeability of the two porous samples.
  - Estimation of the measurement errors and calculation of the accuracies of the measurements.

This work is done in groups of five students in the Dietz laboratory and a technical report is hand in by each group. The report will be credited for 1/3 of the final mark.

Appointments for the practical work are made with B. Meyer and R. Ephraim