Chapter 5: Porosity

5.1 Introduction and Definition

Total porosity is defined as the fraction of the bulk rock volume V that is not occupied by solid matter. If the volume of solids is denoted by V_s, and the pore volume as $V_p = V - V_s$, we can write the porosity as:

$$\boldsymbol{f} = \frac{V - V_s}{V} = \frac{V_p}{V} = \frac{\text{Pore Volume}}{\text{Total Bulk Volume}} \qquad (5.1)$$

The porosity can be expressed either as a fraction or as a percentage. Two out of the three terms are required to calculate porosity.

It should be noted that the porosity does not give any information concerning pore sizes, their distribution, and their degree of connectivity. Thus, rocks of the same porosity can have widely different physical properties. An example of this might be a carbonate rock and a sandstone. Each could have a porosity of 0.2, but carbonate pores are often very unconnected resulting in its permeability being much lower than that of the sandstone.

A range of differently defined porosities are recognised and used within the hydrocarbon industry. For rocks these are:

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(i)	Total porosity	Defined above.
(ii)	Connected porosity	The ratio of the connected pore volume to the total volume.
(iii)	Effective porosity	The same as the connected porosity.
(iv)	Primary porosity	The porosity of the rock resulting from its original depositional structure.
(v)	Secondary porosity	The porosity resulting from diagenesis.
(vi)	Microporosity	The porosity resident in small pores ($< 2\ \mu\text{m}$) commonly associated with detrital and authigenic clays.
(vii)	Intergranular porosity	The porosity due to pore volume between the rock grains.
(viii)	Intragranular porosity	The porosity due to voids within the rock grains.
(ix)	Dissolution porosity	The porosity resulting from dissolution of rock grains.
(x)	Fracture porosity	The porosity resulting from fractures in the rock at all scales.
(xi)	Intercrystal porosity	Microporosity existing along intercrystalline boundaries usually in carbonate rocks.
(xii)	Moldic porosity	A type of dissolution porosity in carbonate rocks resulting in molds of original grains or fossil remains.
(xiii)	Fenestral porosity	A holey ('bird's-eye') porosity in carbonate rocks usually associated with algal mats.
(xiv)	Vug porosity	Porosity associated with vugs, commonly in carbonate rocks.

It should be noted that if the bulk volume and dry weight, or the bulk volume, saturated weight and porosity of a rock sample is known, then the grain density can be calculated. This parameter is commonly calculated from the data to compare the results with the known grain

densities of minerals as a QA check. For example the density of quartz is 2.65 g cm^{-3}, and a clean sandstone should have a mean grain density close to this value.

5.2 Controls on Porosity

The initial (pre-diagenesis) porosity is affected by three major microstructural parameters. These are grain size, grain packing, particle shape, and the distribution of grain sizes. However, the initial porosity is rarely that found in real rocks, as these have subsequently been affected by secondary controls on porosity such as compaction and geochemical diagenetic processes. This section briefly reviews these controls.

5.2.1 Grain Size
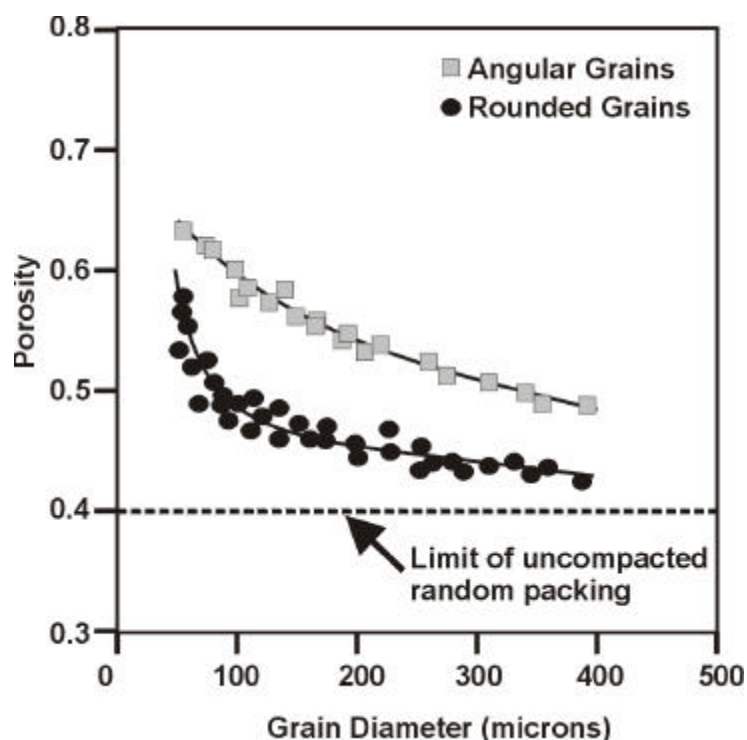
The equilibrium porosity of a porous material composed of a random packing of spherical grains is dependent upon the stability given to the rock by frictional and cohesive forces operating between individual grains. These forces are proportional to the exposed surface area of the grains. The specific surface area (exposed grain surface area per unit solid volume) is inversely proportional to grain size. This indicates that, when all other factors are equal, a given weight of coarse grains will be stabilised at a lower porosity than the same weight of finer grains. For a sedimentary rock composed of a given single grain size this general rule is borne out in Figure 5.1 (to the left). It can be seen that the increase in porosity only becomes significant at grain sizes lower than 100 μm, and for some recent sediments porosities up to 0.8 have been measured. As grain size increases past 100 μm, the frictional forces decrease and the porosity decreases until a limit is reached that represents random frictionless packing, which occurs at 0.399 porosity, and is independent of grain size. No further loss of porosity is possible for randomly packed spheres, unless the grains undergo irreversible deformation due to dissolution-recrystallisation, fracture, or plastic flow, and all such decreases in porosity are termed *compaction*.

5.2.2 Grain Packing

The theoretical porosities for various grain packing arrangements can be calculated. The theoretical *maximum* porosity for a cubic packed rock made of spherical grains of a uniform

size is 0.476, and is independent of grain size. The maximum porosity of other packing arrangements is shown in Table 5.1 and Figure 5.2.

Table 5.1 Maximum porosity for different packing arrangements

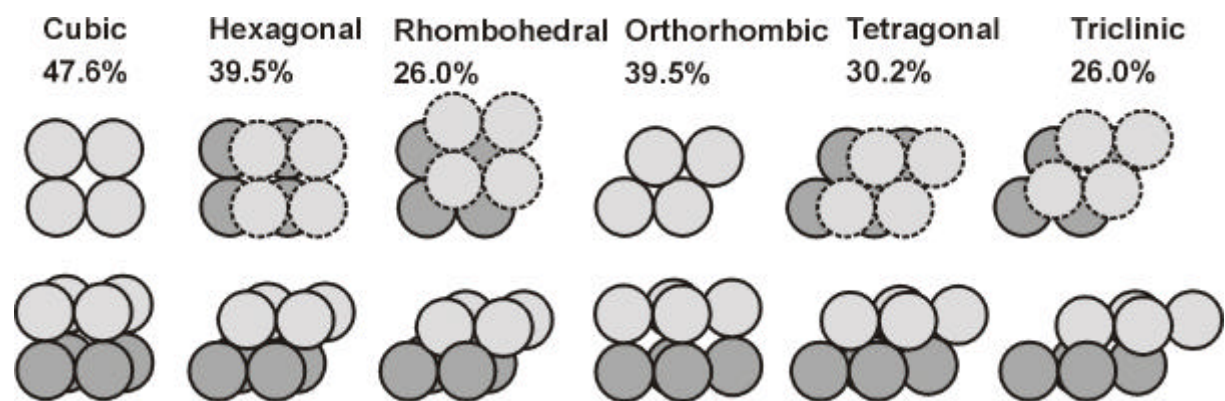| Packing	Maximum Porosity (fractional)
Random Cubic Orthorhombic Rhombohedral Tetragonal	≥0.399 (dependent on grain size) 0.476 0.395 0.260 0.302

Figure 5.2 The porosities of standard packing arrangements.

5.2.3   Grain Shape

This parameter is not widely understood. Several studies have been carried out on random packings of non-spherical grains, and in all cases the resulting porosities are larger than those for spheres. Table 5.2 shows data for various shapes, where the porosity is for the frictionless limit. Figure 5.1 shows data comparing rounded and angular grains, again showing that the porosity for more angular grains is larger than those that are sub-spherical.

Table 5.2 The effect of grain shape on porosity

Grain Shape	Maximum Porosity (fractional)
Sphere Cube Cylinder Disk	≥0.399 (dependent on grain size) 0.425 0.429 0.453

5.2.4   Grain Size Distribution

Real rocks contain a distribution of grain sizes, and often the grain size distribution is multi-modal. The best way of understanding the effect is to consider the variable admixture of grains of two sizes (Figure 5.3).
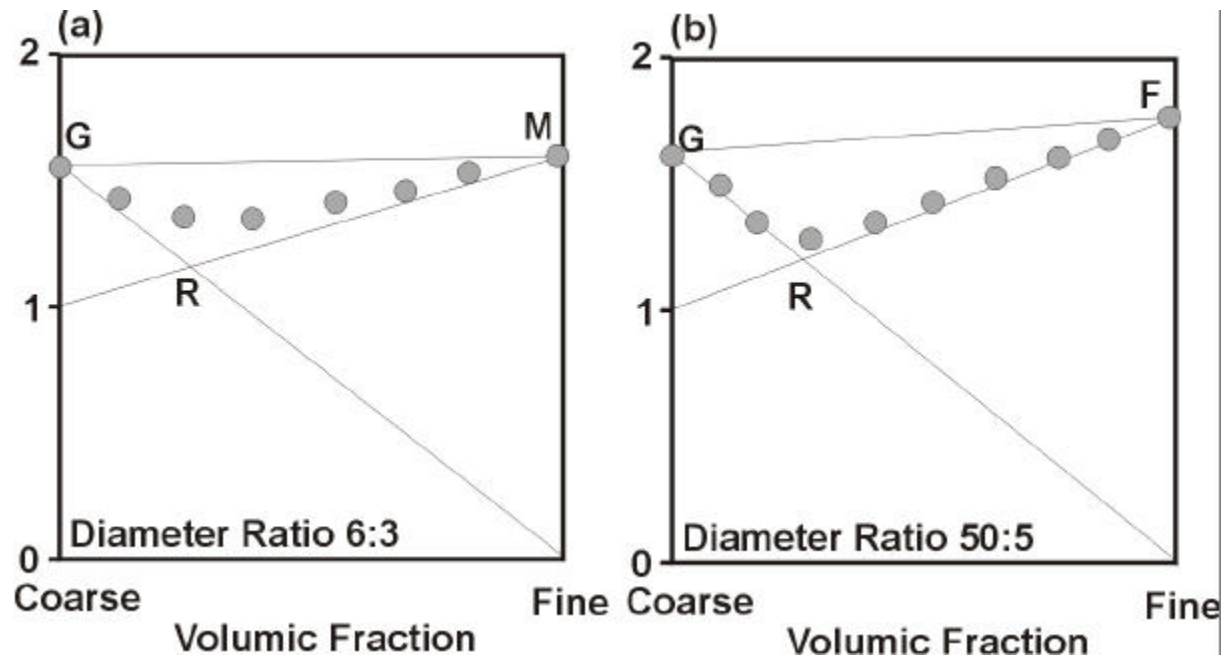

Figure 5.3 The behaviour of mixing grain sizes. Note that a mixture of two sizes has porosities less than either pure phase.

The porosity of the mixture of grain sizes is reduced below that for 100% of each size. There are two mechanisms at work here. First imagine a rock with two grain sizes, one of which has 1/100th the diameter of the other. The first mechanism applies when there are sufficient of the larger grains to make up the broad skeleton of the rock matrix. Here, the addition of the smaller particles reduces the porosity of the rock because they can fit into the interstices between the larger particles. The second mechanism is valid when the broad skeleton of the rock matrix is composed of the smaller grains. There small grains will have a pore space between them. Clearly, if some volume of these grains are removed and replaced with a single solid larger grain, the porosity will be reduced because both the small grains and their associated porosity have been replaced with solid material. The solid lines GR and RF or RM in Figure 5.3 represent the theoretical curves for both processes. Note that as the disparity between the grain sizes increases from 6:3 to 50:5 the actual porosity approaches the theoretical lines. Note also that the position of the minimum porosity is not sensitive to the grain diameter ratio. This minimum occurs at approximately 20 to 30% of the smaller particle diameter. In real rocks we have a continuous spectrum of grain sizes, and these can give rise to a complex scenario, where fractal concepts become useful.

5.2.5 Secondary Controls on Porosity

Porosity is also controlled by a huge range of secondary processes that result in compaction and dilatation. These can be categorised into (i) mechanical processes, such as stress

compaction, plastic deformation, brittle deformation, fracture evolution etc., and (ii) geochemical processes, such as dissolution, repreciptation, volume reductions concomitant upon mineralogical changes etc. The effect of stress mediated compaction on porosity will be discussed in section 5.4. The effect of chemical diagenesis is more complex, and is better assessed for any given rock by examination of SEM or optical photomicrographs.

5.3 Laboratory Determinations

There are many methods for measuring porosity, a few of which will be discussed below. Several standard techniques are used. In themselves these are basic physical measurements of weight, length, and pressures. The precision with which these can be made on plugs is affected by the nature (particularly surface texture) of the plugs.

5.3.1   Direct Measurement

Here the two volumes V and V_s are determined directly and used in Eq. (1). This method measures the *total porosity*, but is rarely used on rocks because V_s can only be measured if the rock is totally disaggregated, and cannot, therefore, be used in any further petrophysical studies. This measurement is the closest laboratory measurement to density log derived porosities.
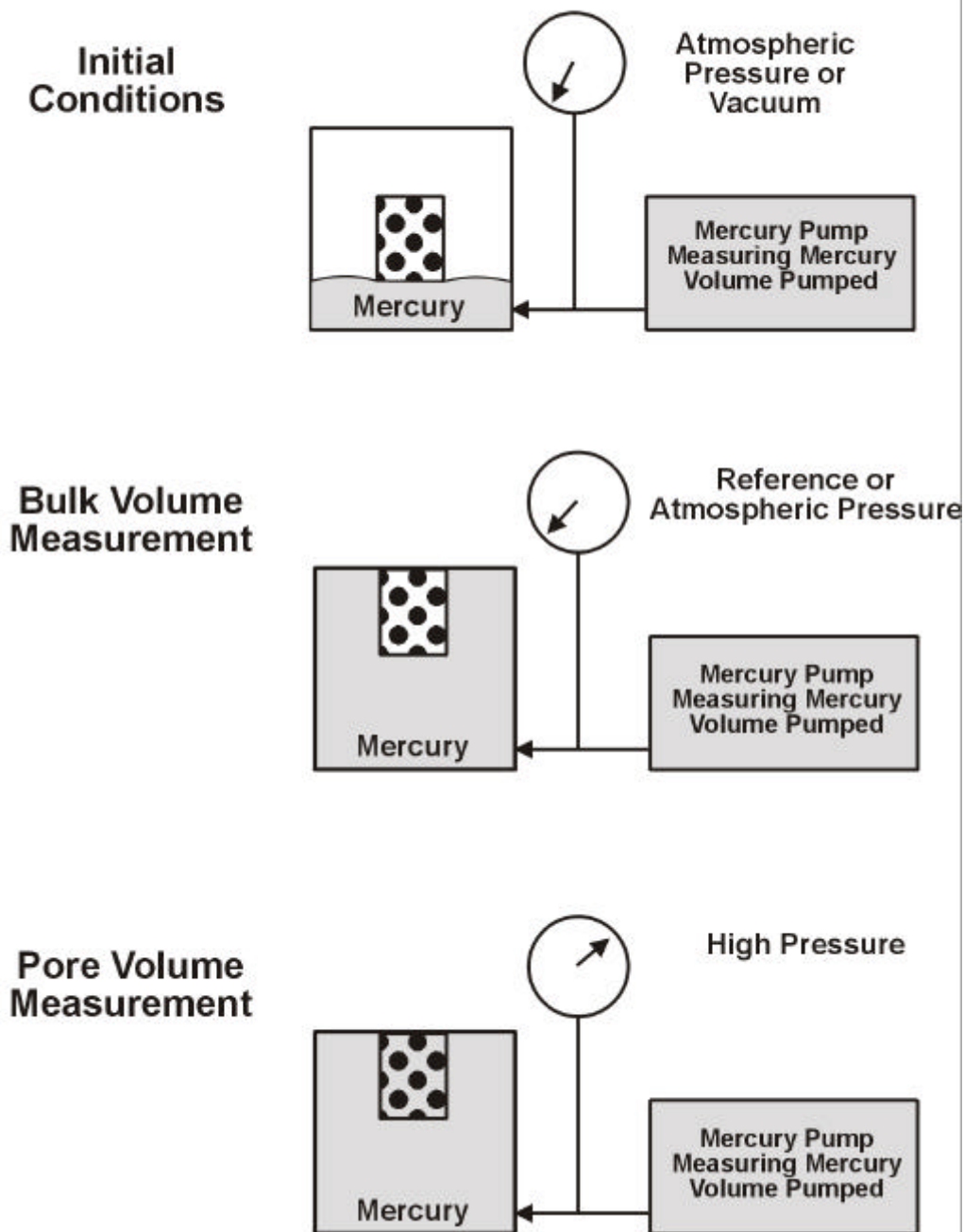
5.3.2   Imbibition Method

The rock sample is immersed in a wetting fluid until it is fully saturated. The sample is weighed before and after the imbibition, and if the density of the fluid r is known, then the difference in weight is $r\,V_p$, and the pore volume V_p can be calculated. The bulk volume V is measured using either vernier callipers and assuming that the sample is perfectly cylindrical, or by Archimedes Method (discussed later), or by fluid displacement using the saturated sample. V_p and V can then be used to calculate the *connected porosity*. This is an accurate method, that leaves the sample fully saturated and ready for further petrophysical tests. The time required for saturation depends upon the rock permeability.

5.3.3   Mercury Injection

The rock is evacuated, and then immersed in mercury. At laboratory pressures mercury will not enter the pores of most rocks. The displacement of the mercury can therefore be used to calculate the bulk volume of the rock. The pressure on the mercury is then raised in a stepwise fashion, forcing the mercury into the pores of the rock (Figure 5.4). If the pressure is sufficiently high, the mercury will invade all the pores. A measurement of the amount of mercury lost into the rock provides the pore volume directly. The porosity can then be calculated from the bulk volume and the pore volume. Clearly this method also measures the *connected porosity*. In practice there is always a small pore volume that is not accessed by the mercury even at the highest pressures. This is pore volume that is in the form of the minutest pores. So the mercury injection method will give a lower porosity than the two methods described above. This is a moderately accurate method that has the advantage that it can be done on small irregular samples of rock, and the disadvantage that the sample must be disposed of safely after the test.

Figure 5.4 Mercury Injection Apparatus

Initial Conditions

Atmospheric Pressure or Vacuum

Mercury

Mercury Pump Measuring Mercury Volume Pumped

Bulk Volume Measurement

Reference or Atmospheric Pressure

Mercury

Mercury Pump Measuring Mercury Volume Pumped

Pore Volume Measurement

High Pressure

Mercury

Mercury Pump Measuring Mercury Volume Pumped

The mercury method also has the advantage that the grain size and pore throat size distribution of the rock can be calculated from the mercury intrusion pressure and mercury intrusion volume data. This will be discussed at further length in the section on capillary pressure.

5.3.4   Gas Expansion

This method relies on the ideal gas law, or rather Boyle's law. The rock is sealed in a container of known volume V_1 at atmospheric pressure P_1 (Figure 5.5). This container is attached by a valve to another container of known volume, V_2, containing gas at a known pressure, P_2. When the valve that connects the two volumes is opened slowly so that the system remains isothermal, the gas pressure in the two volume equalises to P_3. The value of the equilibrium pressure can be used to calculate the volume of grains in the rock $V_{s.}$. Boyle's Law states that the pressure times the volume for a system is constant. Thus we ca write the PV for the system before the valve is opened (left hand side of Eq. (5.2)) and set it equal to the PV for the equilibrated system (right hand side of Eq. (5.2)):

$$P_1\left(V_1 - V_s\right) + P_2\, V_2 = P_3\left(V_1 + V_2 - V_s\right) \tag{5.2}$$

The grain volume can be calculated:

$$V_s = \frac{P_1\, V_1 + P_2\, V_2 - P_3\left(V_1 - V_2\right)}{\left(P_1 - P_2\right)} \tag{5.3}$$

Figure 5.5 Helium Porosimetry
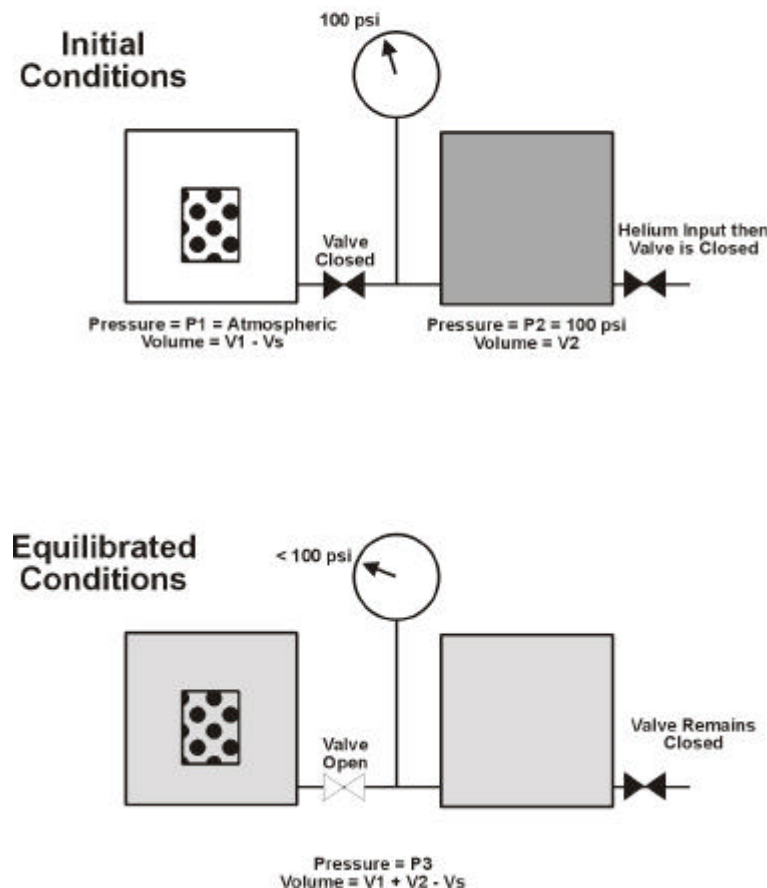
In practice P_1, P_2 and P_3 are measured, with V1 and V2 known in advance by calibrating the system with metal pellets of known volume.

The bulk volume of the rock is determined before the experiment by using either vernier callipers and assuming that the sample is perfectly cylindrical, or after the experiment and subsequent saturation by Archimedes Method (discussed later), or by fluid displacement using the saturated sample. The bulk volume and grain volume can then be used to calculate the *connected porosity* of the rock.

Any gas can be used, but the commonest is helium. The small size of the helium molecule means that it can penetrate even the smallest pores. Consequently this

Initial Conditions

100 psi

Valve Closed

Helium Input then Valve is Closed

Pressure = P1 = Atmospheric
Volume = V1 - Vs

Pressure = P2 = 100 psi
Volume = V2

Equilibrated Conditions

< 100 psi

Valve Open

Valve Remains Closed

Pressure = P3
Volume = V1 + V2 - Vs

method gives higher porosities than either the imbibition or mercury injection methods. The method itself is very accurate, insensitive to mineralogy, and leaves the sample available for further petrophysical tests. It is also a rapid technique and can be used on irregularly shaped samples. Inaccuracies can arise with samples with very low. Low permeability samples can require long equilibration times in the helium porosimeter to allow diffusion of helium into the narrow pore structures. Failure to allow adequate time will result in excessively high grain volumes and low porosities.

5.3.5   Density Methods

If the rock is monomineralic, and the density of the mineral it is composed of is known, then the pore volume and porosity can be calculated directly from the mineral density and the dry weight of the sample. This method gives the *total porosity* of the rock, but is of no practical use in petrophysics.

5.3.6   Petrographic Methods

This method is used to calculate the two dimensional porosity of a sample, either by point counting under an optical microscope or SEM, or image analysis of the images produced from these microscopes. Commonly a high contrast medium is injected into the pores to improve the contract between pores and solid grains. This method can provide the *total porosity*, but is wildly inaccurate in all rocks except those that have an extremely isotropic pore structure. However, it has the advantage that pore types and the microtextural properties of the rock can be determined during the process.

5.3.7   Other Techniques

Other techniques include porosity by (i) analysing all evolved fluids (gas+water+oil) and assuming that their volume is equal to that of the pore space, (ii) CT scanning, and (iii) NMR techniques.

5.3.8   Bulk Volume Measurement

Most of the methods reviewed above require the knowledge of the bulk volume of the rock sample. Three ways are commonly used. These are (i) by using callipers, (ii) using fluid displacement, and (iii) using Archimedes' method.

Vernier Callipers If the rock is a perfect right cylinder with smooth surfaces, then calliper measurements of length and diameter can give quite an accurate bulk volume. In this case several measurements (approx. 10) are made of the length and the diameter, and the arithmetic mean of each is used. Repeatability and accuracy then depend mainly upon surface texture of the sample. Repeat helium expansion determinations of porosity on samples with smooth surface textures where the calliper bulk volume is used should fall within ±0.3 porosity percent regardless of actual porosity. Inaccuracies can arise with samples with very high permeability. High permeability sandstone samples are frequently friable, have large grain and pore sizes, and do not produce smooth surfaced right cylinders when plugs are drilled and accurate bulk volume determination becomes difficult. Straightforward measurement with

vernier callipers is not possible and Archimedes method or other liquid displacement methods have to be used.

Fluid Displacement This method notes the displacement of fluid on a graduated scale when the rock sample is placed in a container containing the fluid. If the fluid automatically enters the pores errors will result. The method is commonly carried out with a non-wetting fluid such as mercury, or with other fluids with a sample that has already been saturated. Mercury displacement is carried out in a pyknometer fitted with a calibrated pump (Kobe method - Figure 5.4). The sample is immersed in mercury during this test and will give erroneous results where mercury enters samples with very large pores. There is also a tendency to give high bulk volumes if air is trapped where the sample touches the top of the chamber. The Kobe method is used as the first part of the mercury injection method (Section 5.3.3).

Archimedes Method The sample is weighed dry, fully saturated with formation brine whose density is accurately known. The saturated sample is then weighed suspended under a balance in air, and again while suspended in the fluid in which it is saturated. The various weight readings, and the density of the fluid allow the bulk volume of any irregular sample to be found accurately. The difference in the weight between the saturated sample suspended in air and that when suspended in the fluid is equal to $V_s \rho_f$, where ρ_f is the density of the fluid. There are few sources of significant error in this method, provided no fluid drains from the plug whilst it is weighed in air. The most difficult part is judging how much excess fluid to remove from the surface of the plug. Vuggy limestones present particular problems which may only be overcome by *whole core measurements*. The contents of vugs exposed on the plug surface may have been disturbed during drilling. Internal vugs may be partially filled with solids from the drilling fluid during the coring process. If exposed vugs are genuinely part of the pore volume, then bulk volume must be obtained by calipering since these will not be taken account of by liquid immersion techniques.

Figure 5.6 Overburden Porosity Cell

INSULATION

PRESSURE
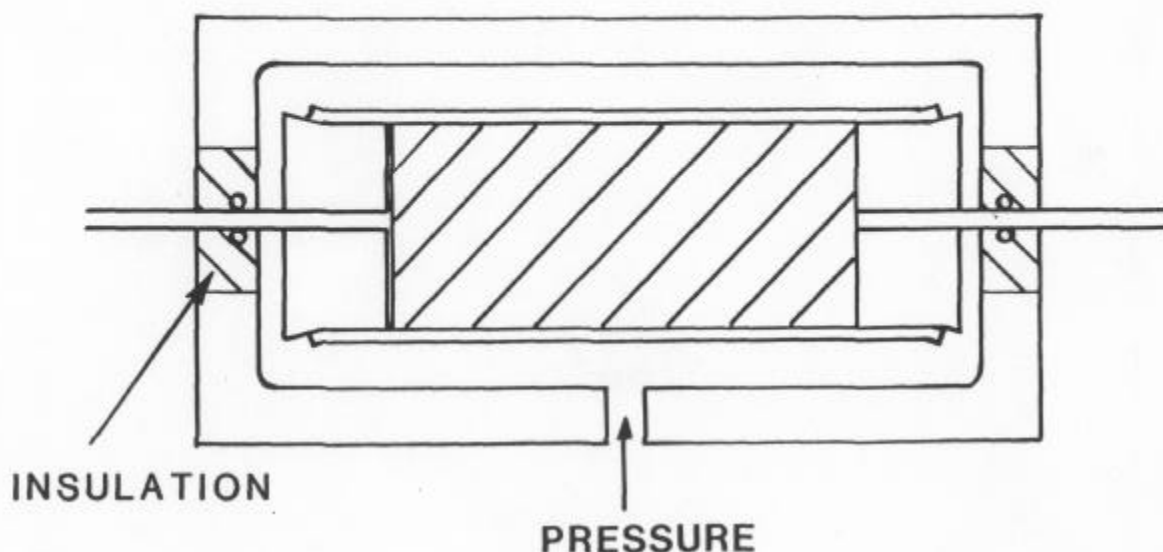
It should be noted that these are all laboratory methods. Well logging utilises several other different techniques, which all have larger errors associated with them. These are based on acoustic, electromagnetic, NMR, and radioactive processes.

5.4 Influence of Stress

SCAL porosity measurements have to be done at overburden pressure if they are to be correlated with downhole measurements. These measurements are made using the overburden cell (Figure 5.6) attached to a helium expansion porosimeter. Pore volume changes can also be observed whilst measuring formation factor at overburden pressures. It is not possible to repeat determinations without allowing time for stresses in the core to be relieved. It is conceivable that permanent damage could result when applying overburden to poorly cemented cores, thus if a plug has to be used for a number of tests, overburden measurements should form the later stages of the test sequence. As with routine poroperms, whole core measurements may be necessary if samples are vuggy, fractured or contain stylolytes. The precision of the data obtained is similar to that of routine poroperms. Care has to be taken that samples are given sufficient time to allow compaction to occur at each overburden pressure. The resulting porosity data is usually displayed as a fraction of that at ambient pressure as function of overburden pressure (Figure 5.7), or as pore volume compressibility (pore volume/pore volume/psi), as shown in Figure 5.8.

Figure 5.7 Effect of Overburden Pressure on Porosity

Figure 5.8 Effect of Overburden Pressure on Pore Volume Compressibility