and gravel are also important raw materials which require sedimentological expertise.

The petroleum industry employs a very high percentage of the world's professional geologists. This industry has a particular need for research, and also has the financial capacity to invest in it. Because oil and gas are found largely in sedimentary rocks, exploration for and recovery of hydrocarbons is based to a large extent on sedimentology. Much of what we now know about the world's sedimentary basins and their regional geology is derived from seismic profiles which have been shot in connection with oil exploration and drilling for oil and gas. The oil industry has also helped to stimulate pure sedimentological research, and significant contributions to research in this area are published by the research laboratories of the oil companies. Research based on economic interests is also useful from a purely scientific point of view, because it often focuses on particular questions which may be quite fundamental.

Petroleum geology requires close teamwork between reservoir engineers and geologists, to establish in great detail the geometry and distribution of porosity and permeability in reservoir rocks. We also need very much to know more about the physical and chemical properties of reservoir rocks, for reasons which are discussed at the end of the book. Geophysical methods provide most of the information used in petroleum exploration and production and many petroleum geologists rarely examine real rocks in cores and cuttings. It is however important to know something about the textural and mineralogical composition of the sedimentary sequences. The geophysical data rarely provide unique solutions when inverting seismic and log data to rock properties.

2.1 Description of Sedimentary Rocks

2.1.1 Textures

The *textures* of clastic sediments include external characteristics of sediment grains, such as size, shape and orientation. These properties can be described relatively objectively and say a great deal about the origin and conditions of sediment transport and deposition.

By grain size we normally mean grain diameter, but the two are only strictly synonymous in the case of completely spherical particles. Most grains are not spherical, however, and it is difficult to identify a representative diameter, particularly in the case of elongated or flat grains. For this reason we have adopted the concept "nominal" diameter (d_n), defined as the diameter of a spherical body which has the same volume as the grain. In practice we are seldom in a position to measure the volume of individual grains, and we therefore use indirect methods to measure the distribution of grain size within a sample.

Sand and gravel can most simply be analysed by means of *mechanical sieving*. A bank of sieves consists of sieves with mesh sizes which decrease downwards. A sample is put in the uppermost sieve and the bank of sieves is shaken (Fig. 2.1). Grains which are larger than the mesh size will remain, while smaller grains will fall through and perhaps remain lying on the next sieve. By weighing the fraction of the sample which remains on each sieve, we can construct a grain-size distribution curve. The lower practical limit for sieve analyses is 0.04–0.03 mm; finer particles exhibit much more cohesion, which makes it difficult for them to become separated and pass through the finer sieves.

Fine silt and clay fractions can be analysed in a number of ways. Most classic methods are based on measurements of settling velocity in liquids, and are based on Stokes' Law:

$$v = cgR^2 \Delta\rho / \mu$$

Here c is a constant (2/9) and μ is the viscosity of the water. R is the radius (cm) of the grain and $\Delta\rho$ is the density difference between the grain and the fluid (water).

When the settling velocity of grains (falling through water, for example) is constant, the resistance to the movement (friction), which acts upwards, must be equal to the force of gravity, which acts downwards (Fig. 2.2).

$$6\pi R v \mu \text{ (friction)} = 4/3\pi g R^3 \Delta\rho \text{ (gravity)}$$

$$v = c\, gR^2 \Delta\rho / \mu$$

$$\text{Log}\, v = 2 \log R + c \text{ (a constant)}$$

The settling velocity is sensitive to temperature variations, which affect the viscosity of the water (μ).

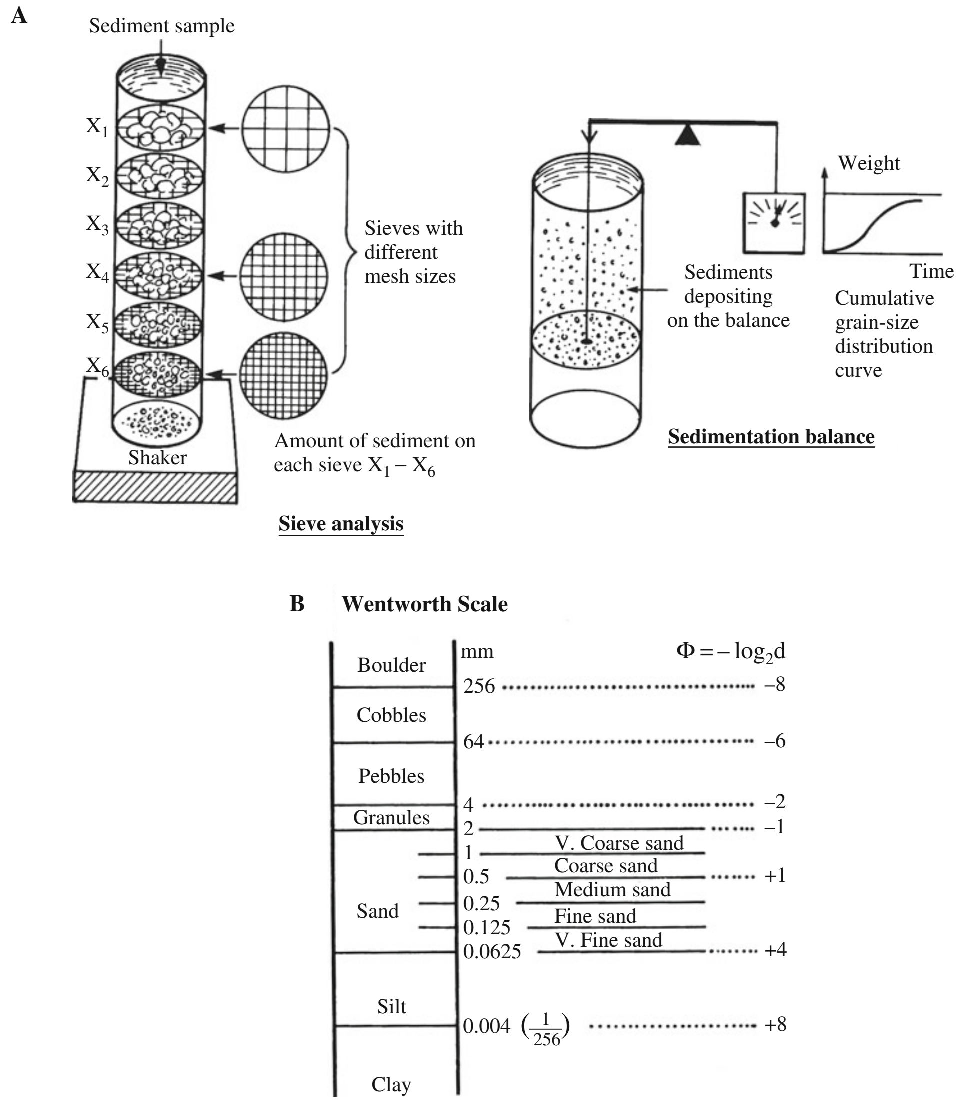

Fig. 2.1 (**a**) Sketch showing the principles involved in sieve analysis and use of a sedimentation balance. Sieve analysis is usually used for grain sizes down to 0.03–0.02 mm, but with wet-sieving even finer sediment grains can be sieved. The sedimentation balance gives us a direct expression of settling velocity, i.e. weight increase as a function of time. This is therefore a cumulative grain-size distribution. (**b**) Grain-size classification of clastic sediments. The grain size (*d*) is often described in terms of φ values ($\varphi = -\log_2 d$)

We can measure the settling velocities of sediment grains indirectly by measuring the density of the water with suspended sediment sample with a hydrometer, which registers the fluid density. We disperse the sample in a cylinder with a mixer so that at a start time T_o we have an even distribution of all grain sizes, and therefore of density, throughout the cylinder. The individual sediment grains then sink to the bottom at a rate which is a function of their size. The change in the fluid density as progressively fewer grains remain in suspension is therefore a function of the grain-size distribution. This applies for small particles, where the flow of the liquid around the grain is laminar and the concentration of grains is low.

When the grains are larger than about 0.1–0.5 mm, the settling velocity increases, and turbulence develops

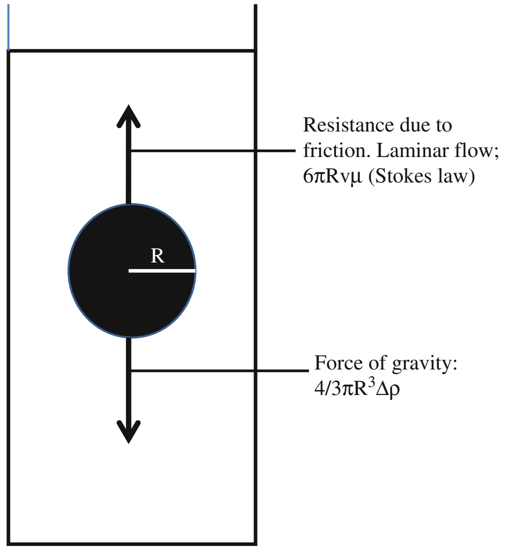

Fig. 2.2 The velocity of a falling grain in water is controlled by the gravity forces directed *downwards* and the resistance to the flow around the grain which is directed *upwards* ($6\pi R v \mu$). The force of gravity is a function of the volume of the grains ($4/3\pi g R^3$) and the density difference ($\triangle\rho$) between the grain and the fluid ($\rho_g - \rho_f$)

around the grains. The frictional resistance therefore increases, and in the case of larger grains (>1 mm) the settling velocity increases approximately in proportion to the square root of the radius. It is not practicable to measure each grain, but the settling velocity can be measured indirectly. A hydrometer floating in a suspension of sediments and water measures the density of the suspension through time. The rate of density reduction in the suspension is a function of the grains' size. By taking successive readings of the density we may plot a curve which expresses density reduction as a function of time. Since density reduction is a function of settling velocity, this curve can be calibrated to give a grain-size distribution curve.

When we analyse fine-grained sediments with a large clay fraction, or separate out clay fractions, it may be useful to use a centrifuge. We then increase the acceleration term **g** in Stokes' Law. There are also "sedimentation balances". Sediments suspended in a cylinder fall through the water column and accumulate on a balance pan at the bottom of the cylinder. This balance records and writes out the increase in weight, which is the precipitation from suspension, as a function of time. This gives a direct cumulative curve.

Other methods are based on the refraction or dispersion of a laser beam passed through suspensions producing a characteristic "scatter" which is calibrated against samples of known grain size. These machines use very small samples and have a high degree of repeatability. Equipment has also been developed which uses X-rays instead of light to produce the characteristic scatter patterns.

It is important to note that *no* method measures the nominal diameter. In methods which measure settling velocity, grain shape is a significant factor. A large, thin mica flake has a settling velocity which corresponds to that of a considerably smaller spherical grain. The diameter of a spherical grain with the same volume and settling velocity is called the *effective diameter* (d_e). With the scatter method, flaky grains are assigned a different, probably greater, diameter than that indicated by the settling velocity method.

2.2 Grain-Size Distribution in Solid Rocks

Lightly-cemented sandstones can be disintegrated by means of ultrasound in the laboratory and then analysed as loose sediment in the normal manner. Carbonate-cemented rocks may be disintegrated using acids. However, we must bear in mind that new clay minerals may have formed through post-depositional alteration (diagenetic processes), and that some of the original minerals may have been broken down mechanically or dissolved chemically. Consequently it is not certain that we are dealing with the original grain distribution. Diagenesis must be taken into account.

Well-cemented rocks must be analysed in thin section by means of a petrographic microscope. It is difficult to analyse the finer fractions (fine silt and clay) in this manner and we must always remember the "section effect", i.e. that in most cases we will not be seeing the greatest diameter of the grains. With spherical grains, the relation between the real diameter, d_r, and the observed diameter, d_o, can be expressed statistically: $d_r = 4d_o/\pi$.

2.3 Presentation of Grain-Size Distribution Data

Grain-size distribution is one of the many types of natural data which must be presented on a logarithmic scale for convenience. Wentworth's scale is based on logarithms to the base 2, and this is now the one most widely found in geological literature.

For the sake of convenience, these data are commonly plotted against a linear scale. The phi (φ) scale, where $\varphi = -\log_2 d$, allows convenient interpolation of graphic data. The reason this negative logarithm is used is that normally most of the sediment grain diameters (d) are less than 1 mm, so these will have a positive phi value (Fig. 2.3). It is convenient to plot grain-size distribution data as a function of phi values, especially on cumulative curves. In normal descriptions of grain size, however, it is more helpful to state grain size in mm, so the reader does not have to calculate back from phi values.

The simplest, and visually most informative, way of presenting grain-size distribution data is by means of histograms (Fig. 2.3). These show the percentage, by weight, of the grains falling within each chosen subdivision of the size range. It is then easy to see how well sorted the sediments are, and whether the distribution of grain sizes is symmetrical, or perhaps bi- or polymodal, i.e. with two, or more, maxima.

A *cumulative* distribution curve shows what percentage of a sample is larger or smaller than a particular grain size. The steeper the curve, the better the sorting. Note that engineers use the inverse term "grading", whereby well graded = poorly sorted.

If we use probability paper, distributions which are lognormal (following a logarithmic distribution) will plot as straight lines and the slopes of these will reveal the degree of sorting. Even if the whole distribution is not lognormal, it often appears that the curve can be regarded as a composite of 2–3 lognormal grain-size populations. These populations generally overlap, so that some sections of the curve represent a combination of parts of two populations, each of which may be lognormal. Each population may represent a different mode of grain transport, for example saltation, rolling (bedload) or suspension (Fig. 2.4).

It is important that we collect representative samples for grain-size distribution analysis, i.e. each sample only has material from one bed. This ensures that it represents deposition by a single sedimentary process. If we take a sample at the boundary between two beds, we will often get false bimodal distributions which can easily be mistaken for naturally produced bimodal sediments, leading to interpretation errors.

2.4 Grain-Size Distribution Parameters

Phi (φ) = $-\log_2 d$ (after Folk and Ward 1957) where d is the grain diameter in millimetres (as previously defined). The percentage of grains larger than a certain grain size (φ) is called the *percentile*. φ30 means that 30% of the grain population by weight is larger than the grain size. For $\varphi = 4$ the grain size is 0.0625 mm so that 30% of the sample is sand or larger grains.

2.5 Significance of Grain-Size Parameters

The *mean* diameter is an arithmetically calculated average grain size. The *median* diameter is defined by the grain size where 50% by weight of the sample grains are smaller, and 50% are larger. Only in the case of completely symmetrical distribution curves will the mean diameter (M) and the median diameter (M*d*) coincide. The mean will otherwise shift further than the median in the direction of the "tail" of the distribution. If the sample has a wide spread (tail) towards the fine grain sizes (larger phi values) and a relatively sharp delimitation at the large grain-size end, we say that the sample has positive skewness. This will be typical of fluvial sediments. There will be a fairly definite upper limit to the grain sizes that rivers can transport as bedload, while there will be no sorting of the fine fractions which are transported in suspension. Major variations in flow velocity, for instance during floods, will give poorer sorting.

Aeolian (wind) deposits are very well sorted (Fig. 2.5). They also have positive skewness because there is an upper size limit to the grains which can be transported. Although the finest particles may be removed selectively, there will still be a "tail" of fine