4

RADIOMETRIC SURVEYS

The radioactivity of rocks is monitored using gamma-ray scintillometers and spectrometers. Although most radiometric instruments were developed with uranium search in mind, other uses were soon found. Among these were regional geological mapping and correlation, exploration for some industrial minerals and *in situ* determinations of phosphates. The same instruments may also be used to track the movement of artificial radioactive *tracers* deliberately introduced into groundwater, and to assess health risks from natural and artificial radiation sources. Radon gas detectors, which monitor alpha particles, have some exploration uses but are most important in public health applications.

4.1 Natural Radiation

Spontaneous radioactive decay produces alpha, beta and gamma radiation. Alpha and beta 'rays' are actually particles; gamma rays are high-energy electromagnetic waves which, so quantum theory tells us, can be treated as if composed of particles.

4.1.1 Alpha particles

An alpha particle consists of two protons held together by two neutrons to form a stable helium nucleus. Emission of alpha particles is the main process in radioactive decay, resulting in a decrease of four in atomic mass and two in atomic number. The particles have large kinetic energies but are rapidly slowed down by collisions with other atomic nuclei. At *thermal* energies they soon gain two orbital electrons and become indistinguishable from other helium atoms. The average distance travelled in solid rock before this occurs is measured in fractions of a millimetre.

4.1.2 Beta particles

Beta particles are electrons ejected from atomic nuclei. They differ from other electrons only in having higher kinetic energies and so cease to be identifiable after being slowed down by multiple collisions. Energy is lost most rapidly in collisions with other electrons. In solids or liquids the average range of a beta particle is measured in centimetres.

4.1.3 Gamma radiation

Gamma rays are electromagnetic waves with frequencies so high that they are best regarded as consisting of particles, known as *photons*, with energies

proportional to the frequencies. The energy range for gamma rays is generally considered to start at about 0.1 MeV (a frequency of about 0.25×10^{20} Hz).

Because they are electrically neutral, photons penetrate much greater thicknesses of rock than do either alpha or beta particles and are consequently the most geophysically useful form of radiation. Even so, approximately 90% of the gamma photons detected over bare rock will come from within 20–30 cm of the surface and even over soil only 10% will come from below about 50 cm. Water is almost equally effective, with one metre absorbing about 97% of the radiation travelling through it. On the other hand, 100 m of air will only absorb about half of a gamma-ray flux. Attenuation is frequency dependent and (for once) it is the higher frequency, higher energy radiation that has the greater penetrating power. Half of a 1 MeV flux is absorbed by about 90 m of air but it takes about 160 m of air to absorb half of a 3 MeV flux. In either case, these figures imply that atmospheric absorption can generally be ignored in ground surveys.

4.1.4 Radioactivity of rocks

Gamma rays provide information on the presence of unstable atomic nuclei. The average number of decays in a given time will be directly proportional to the number of atoms of the unstable element present. The rate of decrease in mass of a radioactive material therefore obeys an exponential law governed by a *half-life* (Section 1.1.6).

Elements with short half-lives can occur in nature because they are formed in decay series which originate with very long-lived isotopes, sometimes termed *primeval*, that are mainly concentrated in acid igneous rocks and in sediments deposited as evaporites or in reducing environments. The principal primeval isotopes are ^{40}K, ^{232}Th, ^{235}U and ^{238}U. Others, such as ^{48}Ca, ^{50}V and ^{58}Ni, are either rare or only very weakly radioactive.

4.1.5 Radioactive decay series

The main radioactive decay schemes are shown in Table 4.1. ^{40}K, which forms about 0.0118% of naturally occurring potassium, decays in a single stage, either by beta emission to form ^{40}Ca, or by electron capture (K-capture) to form ^{40}Ar. The argon nucleus is left in an excited state but settles down with the emission of a 1.46 MeV photon. The half-life of ^{40}K is 1470 m.y. for beta decay and 11 000 m.y. for K-capture.

The other important primeval radioisotopes decay into nuclei which are themselves unstable. As with ^{40}K, there may be more than one possible decay mode, and the decay chains are quite complex. All, however, end in stable isotopes of lead. The decay series for ^{238}U and ^{232}Th are shown in Table 4.1. ^{235}U makes up only 0.7114% of the naturally occurring element

Table 4.1 *Natural radioactive decay of ^{238}U, ^{232}Th and ^{40}K*

Parent	Mode	Daughter	Half-life	γ energy (MeV) and % yield[†]
^{238}U	α	^{234}Th	4.5×10^9 yr	0.09(15) 0.6(7) 0.3(7)
^{234}Th	α	^{234}Pa	24.1 day	1.01(2) 0.77(1) 0.04(3)
^{234}Pa	β	^{234}U	1.18 min	0.05(28)
^{234}U	α	^{230}Th	2.6×10^5 yr	
^{230}Th	α	^{226}Ra	8×10^4 yr	
^{226}Ra	α	^{222}Rn	1600 yr	0.19(4)
^{222}Rn	α	^{218}Po	3.82 day	
^{218}Po	α	^{214}Pb	3.05 min	
^{214}Pb	β	^{214}Bi	26.8 min	0.35(44) 0.24(11) 0.29(24) 0.05(2)
^{214}Bi	β	^{214}Po	17.9 min	2.43(2) 2.20(6) 1.76(19) 1.38(7)*
^{214}Po	α	^{210}Pb	1.6×10^{-4} sec	
^{210}Pb	β	^{210}Bi	19.4 yr	
^{210}Bi	β	^{210}Po	5.0 day	0.04(4)
^{210}Po	α	^{206}Pb	138.4 day	
^{232}Th	α	^{228}Ra	1.4×10^{10} yr	0.06(24)
^{228}Ra	β	^{228}Ac	6.7 yr	
^{228}Ac	β	^{228}Th	6.1 hr	1.64(13) 1.59(12) 0.99(25) 0.97(18)*
^{228}Th	α	^{224}Ra	1.9 yr	
^{224}Ra	α	^{220}Rn	3.64 day	
^{220}Rn	α	^{216}Po	54.5 sec	
^{216}Po	α	^{212}Pb	0.16 sec	
^{212}Pb	β	^{212}Bi	10.6 hr	0.30(5) 0.24(82) 0.18(1) 0.12(2)*
^{212}Bi	β (66%)	^{212}Po	40 min	1.18(1) 0.83(8) 0.73(10)
^{212}Po	α	^{208}Pb	0.3×10^{-6} sec	
^{212}Bi	α (34%)	^{208}Tl	97.3 min	
^{208}Tl	β	^{208}Pb	3.1 min	2.62(100) 0.86(14) 0.58(83) 0.51(25)*
^{40}K	β (89%)	^{40}Ca	1.45×10^9 yr	
	K (11%)	^{40}Ar	1.17×10^{10} yr	1.46(11)

Notes: 1. The number of photons of the energy specified produced in each 100 decays is indicated as % yield (in parentheses). More than one photon may be produced in a single decay event [†].

2. Decay branches that involve less than 10% of a parent element are not shown.

3. Photons of numerous other energies are emitted in events marked [*].

and, although its rather greater activity allows it to contribute nearly 5% of the overall uranium activity, it may for most practical purposes be ignored.

By no means all decay events are accompanied by significant gamma emission. The first stage in the decay of ^{232}Th involves only weak gamma activity and the strongest radiation in the chain comes from the decay of ^{208}Tl, near the end. This decay is accompanied by emission of a 2.615 MeV photon, the most energetic radiation to come from a terrestrial source.

In the ^{238}U chain, ^{214}Bi is notable for the numbers and energies of the gamma photons produced. Those at 1.76 MeV are taken as diagnostic of the presence of uranium but the gaseous radon isotope, ^{222}Rn, which precedes ^{214}Bi in the chain, has a half-life of nearly four days and so can disperse quite widely away from a primary uranium source. Gaseous dispersion has much less effect in thorium decay since the half-life of ^{220}Rn is less than a minute.

4.1.6 Radioactive equilibria

If a large amount of a primeval isotope is present, and if all the daughter products remain where they are formed, an equilibrium will eventually be established in which the same number of atoms of each element are created as decay in a given time. Only the concentrations of the two end members of the series change.

In equilibrium decay, each member of the chain loses mass at the same rate, equal in each case to the mass of the element present multiplied by the appropriate decay constant. Equilibrium masses are therefore inversely proportional to decay constants. If more or less of an element is present than is required for equilibrium, decay will be respectively faster or slower than the equilibrium rate until equilibrium is re-established.

Equilibrium can be disrupted if any gaseous or soluble intermediate products have half-lives long enough to allow them to disperse before they decay. The exhalation of radon by uranium ores notably disrupts equilibrium and the primary source of a 'uranium' (actually ^{214}Bi) anomaly may be hard to find. *Roll-front* uranium ores are notorious for the separation between the uranium concentrations and the zones of peak radioactivity.

4.1.7 Natural gamma-ray spectra

Natural gamma rays range from cosmic radiation with energies above 3 MeV down to X-rays. A typical measured spectrum is shown in Figure 4.1. The individual peaks correspond to specific decay events, the energy of each photon falling somewhere within a small range determined by the nuclear kinetic energies at the time of the decay and by errors in measurement.

The background curve upon which the peaks are superimposed is due to *scattered* terrestrial and *cosmic* (mainly solar) radiation. Gamma photons can be scattered in three ways. Very energetic (cosmic) photons passing close to atomic nuclei may form electron–positron pairs, and the positrons soon interact with other electrons to produce more gamma rays. At lower energies, a gamma ray may eject a bound electron from an atom (*Compton scattering*). Some of the energy is transferred to the electron and the remainder continues as a lower-energy photon. At still lower energies, a photon may eject an electron from an atom and itself be totally absorbed (*photoelectric effect*).

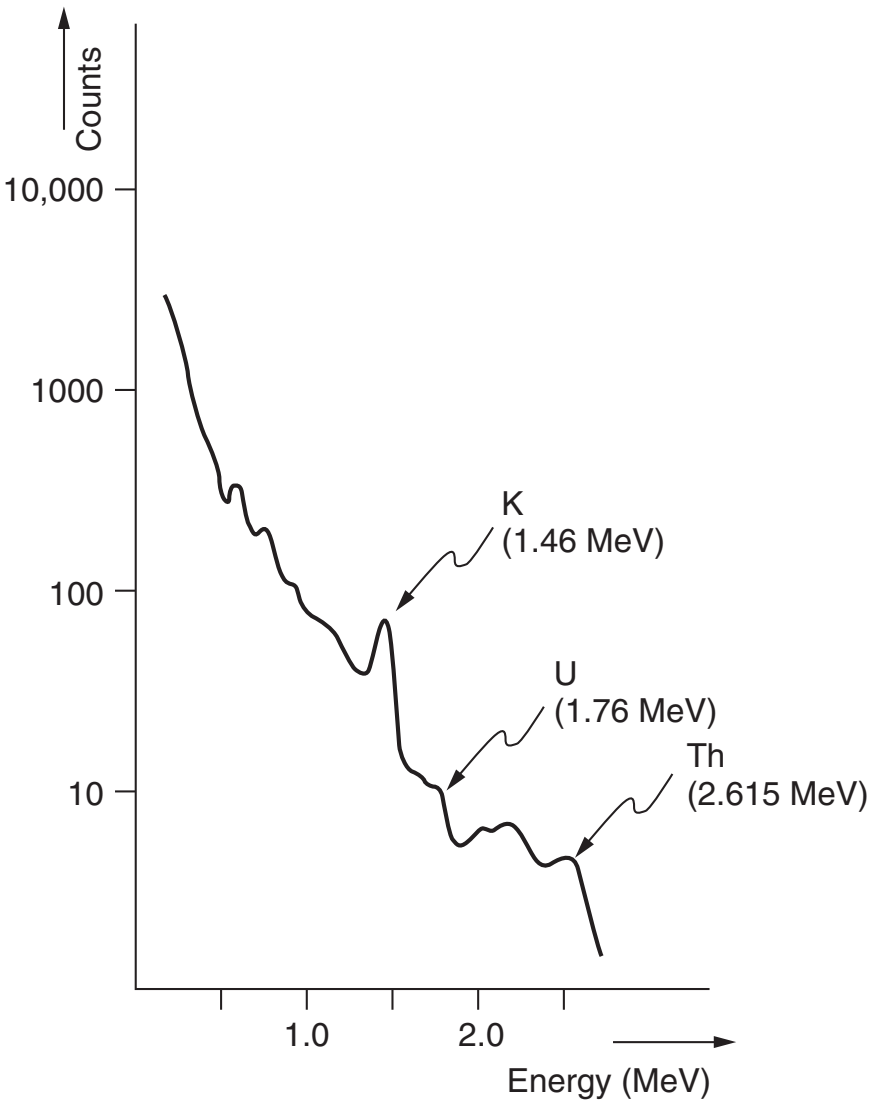

Figure 4.1 *A natural gamma-ray spectrum. Note that the vertical scale (numbers of counts) is logarithmic.*

4.2 Radiation Detectors

The earliest detectors relied on the ability of radiation to ionize low-pressure gas and initiate electrical discharges between electrodes maintained at high potential differences. These *Geiger–Müller* counters are now considered obsolete. They responded mainly to alpha particles and suffered long 'dead' periods after each count, during which no new events could be detected.

4.2.1 Scintillometers

Gamma rays produce flashes of light when they are photoelectrically absorbed in sodium iodide crystals. Small amounts of thallium are added to the crystals, which are said to be *thallium activated*. The light can be detected by photomultiplier tubes (PMTs) which convert the energy into electric current. The whole sequence occupies only a few microseconds and corrections for

'dead time', which in some instruments are made automatically, are required only at very high count rates.

A scintillometer consists of a crystal, one or more PMTs, a power supply (which must provide several hundred volts for the PMTs), and some counting circuitry. The results may be displayed digitally but quite commonly are shown by a needle on an analogue *rate meter*. Some instruments produce an audible click each time a gamma photon is detected, or have alarms which are triggered when the count rate exceeds a predetermined threshold, so that the dial need not be continually observed.

Radioactive decay is a statistical process. The *average* number of events observed in a given area in a given time will be constant, but there will be some variation about the mean. The continuous averaging of a rate meter is controlled by a time constant, and if this is too short, the needle will be in continual motion and readings will be difficult to take. If it is too long, the response will be slow and narrow anomalies may be overlooked. Where a digital display is used, a fixed count time is selected which must be long enough to produce a statistically valid result (Section 4.3.1).

The sensitivity of a scintillometer depends almost entirely on crystal size; larger crystals record more events. Count rates are thus not absolute but depend on the instrument and the crystal. Many instruments are designed to be compatible with several different crystals, which can be chosen on the basis of cost, time available for survey work and accuracy required.

Similar instruments with similar crystals should read roughly the same in the same places, but even this needs to be checked carefully since radioactive contaminants near, and within, the crystals can cause readings to differ. Different scintillometers may record different count rates because crystals are usually shielded so that they detect radiation from one direction only, and even instruments of the same type may have quite different apertures. If it is essential that comparable data be obtained, portable radioactive sources can be used for calibration and also to check the extent of shielding. Such comparisons are, strictly speaking, valid only at the specific (usually fairly low) gamma-ray energy of the source used.

4.2.2 Gamma-ray spectrometers

The energy of a gamma photon that produces a scintillation event can be estimated if a *pulse-height analyser* is incorporated in the PMT circuitry. Events with energies within certain predetermined energy *windows* or above preselected energy *thresholds* can then be counted separately, and the entire gamma-ray flux can be observed at a series of narrow adjoining windows to obtain a curve similar to that shown in Figure 4.1.

Strictly, the term *spectrometer* should be reserved for those instruments, with 256 or more channels, that can record a complete spectrum, but in

practice it is applied to any multichannel instrument with some degree of energy discrimination. Usually there are only four channels, one for total count and one each for the ^{208}Tl peak at 2.62 MeV (for thorium), ^{214}Bi at 1.76 MeV (for uranium) and ^{40}K at 1.46 MeV (for potassium). Typical windows for these peaks might extend from 2.42 to 2.82 MeV, from 1.66 to 1.86 MeV and from 1.36 to 1.56 MeV respectively. Concentrations of all three parent elements can thus be estimated, provided that the primeval radioelement is in equilibrium with its daughter products.

4.2.3 Stripping ratios

To estimate thorium, uranium and potassium abundances from spectrometer readings, corrections must be made for gamma rays scattered from other parts of the spectrum. The thorium peak must be corrected for cosmic radiation and for the 2.43 MeV radiation from ^{214}Bi in the uranium decay chain, which overlaps into the commonly used 'thorium' window. The uranium count must be corrected for thorium, and the potassium count for thorium and uranium. The correction process is known as *stripping*.

Stripping factors vary from detector to detector, primarily with variations in crystal size. They are listed in instrument handbooks and in some cases can be applied by built-in circuitry so that the corrected results can be displayed directly. Equilibrium is assumed when automatic corrections are made, and interpretations will be wrong if it does not exist. It is generally better to record actual count rates in the field and make corrections later.

The characteristics of the measuring circuits vary slowly over time (and also, more rapidly, with temperature) and the positioning of spectrometer 'windows' or thresholds needs to be checked regularly, using portable sources producing gamma rays of a single energy. An additional form of calibration is needed if spectrometer results are to be converted directly into radioelement concentrations. In the USA, Canada, Australia and some other countries, calibration sites have been established where instrument performance can be checked over concrete pads containing known concentrations of various radioelements. 'Null' pads allow background to be estimated. Portable pads are also available in some countries. If, however, several instruments are to be used in a single survey, it is wise, even if they have all been calibrated, to compare them in the actual survey area before attempting to reduce all results to common equivalent readings. Bases at which this has been done should be described for the benefit of later workers.

4.2.4 Alpha-particle monitors

The radon content of soil gas can be estimated by monitoring alpha activity, which may exist even in areas without obvious gamma-ray anomalies. Radon diffuses readily through rocks and soil and the presence of otherwise 'blind'

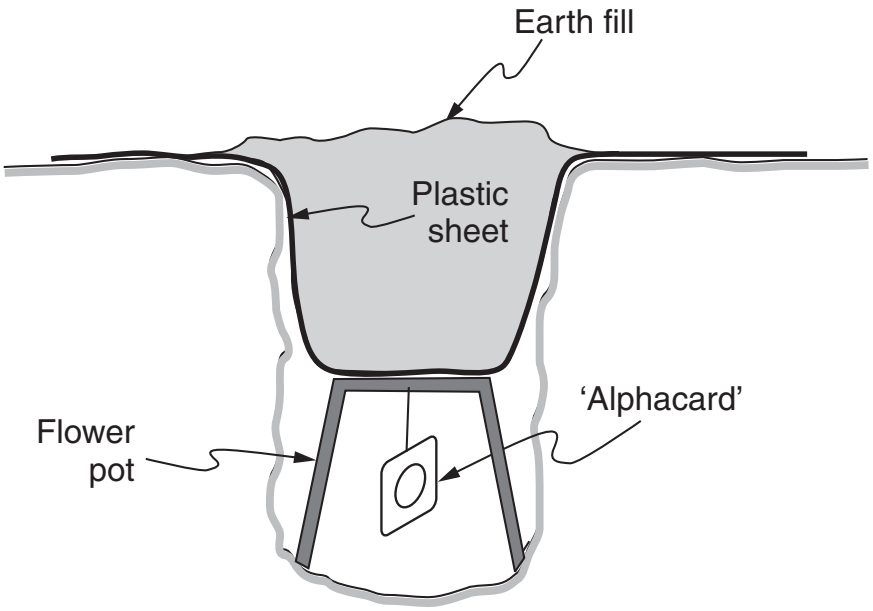

Figure 4.2 *Alphacard radiation detector in its hole.*

uranium mineralization can sometimes be indicated by this method, although locating it may still be difficult. Radon gas is also a potential health hazard in some areas, particularly in cellars, and may need to be monitored for that reason.

One form of monitor is a thin metallic membrane mounted on a frame about the size of a 35-mm slide, on which radon daughter products can collect. For field surveys, this *alphacard* is suspended in an inverted flower pot or similar container in a hole about 0.5 m deep. The hole is covered with a plastic sheet and earth is poured on top until the ground surface is again level (Figure 4.2). The sheet should be sufficiently large for its edges to project, so that it can be lifted out, together with the overlying soil, to allow the card to be removed. The hole is left covered for at least 12 hours. This is long enough for equilibrium to be established and longer periods of burial will not alter the reading. In public health applications, the card is simply left for 12 hours within the area being monitored. It is then removed and placed in a special reader which is sensitive to alpha radiation.

Other types of alpha-particle detector include photographic emulsions that can be etched by ionizing radiation, and sealed units in which the reading and data storage units are contained in a single housing. For exploration use, these should be inserted in holes similar to those dug for alphacards.

4.3 Radiometric Surveys

Ground radiometric surveys tend to be rather frustrating operations. Because of the shielding effect of even thin layers of rock or soil, it is very easy to overlook radioactive minerals in rocks that are only patchily exposed at the

surface. Reliance on stations placed at uniform distances along a traverse may be unwise and the field observer needs to be more than usually aware of the environment.

4.3.1 Reading times

Accurate radiometric data can be obtained only by occupying stations long enough for the statistical variations to average out. What this implies will depend on the count levels themselves and must be determined by actual experiment. The percent statistical error is equal to about $100/\sqrt{n}$, where n is the number of counts, and so is about 30% for 10 counts and only 1% for 10 000. A period of time which is fully adequate for total count readings may not be sufficient for readings on the K, U and Th channels.

There is little point in wasting time obtaining statistically accurate data if areas where count rates are low are in any case of no interest. It may be sufficient to cover the ground at a slow walk with a ratemeter. The rate of progress should be such that the narrowest source of interest would not be crossed completely in a time equal to the time constant selected.

Even when a spectrometer is used, it is usual to record only total count in the first instance, reserving the more time-consuming spectral readings for areas of total-count anomaly. There are, of course, dangers in this approach, as one radioelement might decrease in concentration in the same region as another increased.

4.3.2 Radiometric assays

If a bare rock surface is available, a gamma-ray spectrometer can be used to assay quantitatively for thorium, uranium and potassium. The rock should be dry, so that absorption by moisture, either on or below the surface, is not a factor. Observations must be taken over a sufficiently long period for statistical fluctuations to be smoothed out, which in practice means accumulating at least 1000 counts. Each count takes a few microseconds and at 10 000 cps the instrument would be 'dead' for several tens of milliseconds in each second. Corrections are therefore needed for 'dead' time when working with very radioactive material.

Radioelement concentrations are determined by inserting the observed count rates into equations, provided by the manufacturers, which are specific to the instrument and crystal being used, or by comparison with 'pad' calibrations.

4.3.3 Geometrical considerations

Source *geometry* is important in all radiometric surveys and especially in assay work. Radiation comes from a very thin surface layer and only a small anomaly will be detected if the lateral extent of the source is small compared

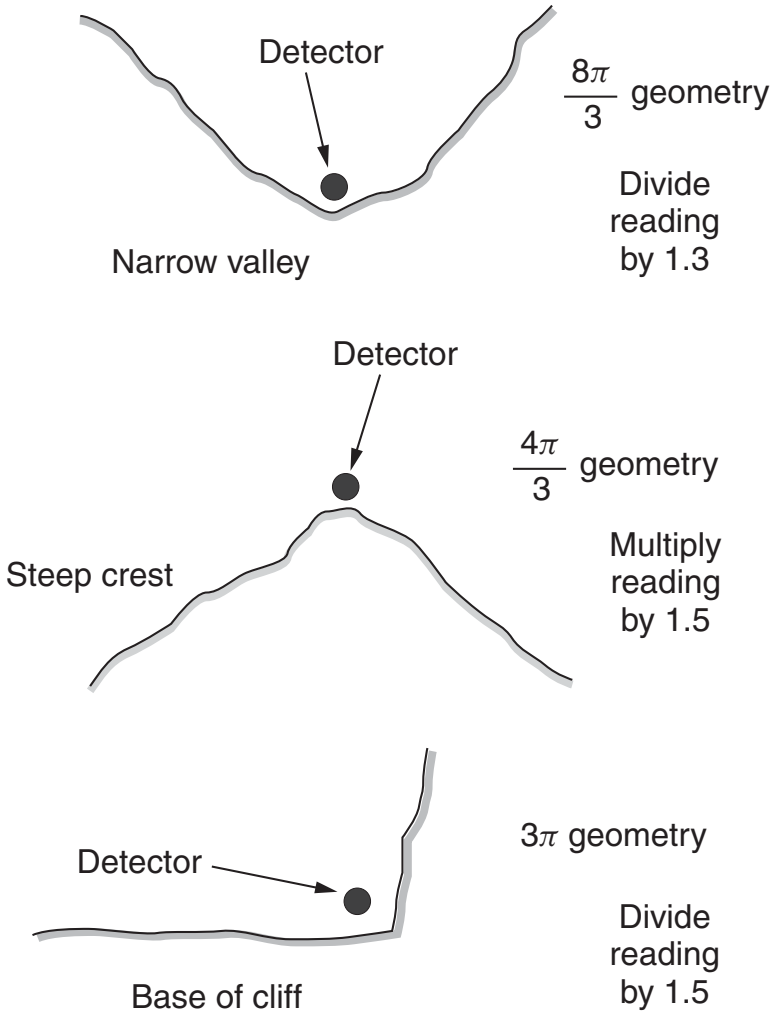

Figure 4.3 *Geometries and correction factors for radiometric surveys.*

with the distance to the detector. If, on the other hand, the source is extensive and at the surface, the height of the detector should not greatly affect the count rate. Generally, this condition (2π *geometry*) is achieved if the lateral extent of the source is 10 or more times the height of the detector above it.

2π geometry is often not possible in practice. Some other possible source geometries and factors for correction to standard 2π values are shown in Figure 4.3.

4.3.4 Corrections for background variations

Atmospheric radon, cosmic radiation and radioactive particles attached to the instrument itself produce background radiation unrelated to survey objectives. The background contribution is usually less than 10% of the total count and is often ignored in ground surveys. If corrections are necessary, either because very subtle variations are being observed or precise assay work is being done, their magnitude can be estimated by taking readings either in the middle of a

body of water at least 1 m deep and at least 10 m across or with the detector shielded from the ground by a lead sheet. Neither of these methods is likely to be very convenient, and sometimes 'background' is defined simply (and possibly unreliably) as the lowest reading obtained anywhere in the survey area. Variations in background, mainly due to atmospheric humidity changes (wet air absorbs radiation far more efficiently than dry) can be monitored using a fixed detector in this location.

The level of background radiation due to radioactive material in the detector crystal and housing should be constant over long periods and can be measured by placing the detector in a totally shielded environment, but in practice this is likely to be difficult to arrange. The correction is usually trivial and it is far more important to ensure that no dirt, which might be contaminated, is smeared on the detector housing.

The observer is an important possible source of spurious radiation, especially if the sensor is carried in a back-pack. In these circumstances the absorption of radiation by the observer's body has also to be taken into account, usually by direct experiment. Watches with radioactive luminous dials are now rare, but compasses need to be carefully checked. Obviously, a calibration source should not be carried.

A small amount of radioactive material is included in the vacuum chambers of some quartz gravity meters to ionize the residual gas and prevent build-ups of static electricity on the spring systems. Radiometric and gravity surveys are occasionally done together, and absurd conclusions have been reached.

4.3.5 Recording radiometric data

Because gamma radiation is strongly absorbed by both rock and soil, comprehensive notes should be taken during radiometric surveys. Departures from 2π geometry must be noted, together with details of soil cover. If bare rock cannot be seen, some attempt should be made to decide whether the overburden was transported into place or developed *in situ*, and to estimate its thickness. Weather conditions can also be important. In particular, since absorption is much greater in wet than in dry soil, recent rain and the presence of puddles of standing water should always be noted.

The ways in which readings are taken, including time constants or count periods, must be recorded. Field techniques should not be varied in the course of a survey and the location of the sensor (e.g. whether hand-held or in a back-pack) should be specified.