Chapter 2

Basic notions of radiometric geochronology

2.1 Isotopes and radioactivity

Thanks to discoveries by Niels Bohr, Ernest Rutherford, Arnold Sommerfeld, Joseph Thomson and James Chadwick, we know that rocks and minerals are made of atoms, atoms are made of a nucleus and an electron cloud, and the nucleus is made of nucleons of which there are two kinds: protons and neutrons. The total number of nucleons in the atomic nucleus is called the mass number (A). The number of protons (which equals the number of electrons in a neutral atom) is called the atomic number (Z). The chemical properties of a nuclide solely depend on the atomic number, which therefore forms the basis of the Periodic Table of Elements. The number of neutrons in the atomic nucleus may take on a range of values for any given element, corresponding to different isotopes of said element. For example, 816O is an isotope of oxygen with 16 nucleons of which 8 are protons (and N = A-Z = 16-8 = 8 are neutrons). Adding one extra neutron to the nucleus produces a second oxygen isotope, 817O, with identical chemical properties as 816O, but slightly different physical properties (e.g. boiling temperature). Adding another neutron produces 818O which, with 8 protons and 10 neutrons, is more than 10% heavier than 816O. Due to this mass difference, the 818O/ 816O ratio undergoes mass fractionation by several natural processes, forming the basis of 818O/ 816O palaeothermometry (see the second half of this course). When we try to add yet another neutron to the atomic nucleus of oxygen, the nucleus becomes unstable and undergoes radioactive decay. Therefore, no 819O exists in nature.

2.2 Radioactivity

As mentioned before, the Periodic Table of Elements (aka ‘Mendeleev’s Table’) arranges the elements according to the atomic number and the configuration of the electron cloud. The equally important Chart of Nuclides uses both the number of protons and neutrons as row and column indices. At low masses, the stable nuclides are found close to the 1 ÷ 1 line (N ≈ Z), with the radionuclides found at higher and lower ratios. At higher atomic numbers, the stable nuclides are found at higher mass numbers, reflecting the fact that more neutrons are required to keep the protons together. For example, 82208Pb, which is the heaviest stable nuclide, has 44 more neutrons than protons. The unstable nuclides (or radionuclides), such as 82209Pb or 819O may survive for time periods of femtoseconds to billions of years depending on the degree of instability, which generally scales with the ‘distance’ from the curve of stable nuclides. Radionuclides eventually disintegrate to a stable form by means of a number of different mechanisms:

α-decay

The atomic nucleus (e.g., 92238U, 92235U, 90232Th, 62147Sm) loses an α particle, i.e. the equivalent of a 24He nucleus. When these nuclei acquire electrons, they turn into Helium atoms, forming the basis of the U-Th-He chronometer, which is further discussed in Section 7.1. The recoil energy of the decay is divided between the α particle and the parent nucleus, which eventually relaxes into its ground state by emitting γ-radiation, i.e. photons with a wavelength of 10-12m or less. In addition to the aforementioned U-Th-He method, α-decay is central to the 147Sm-143Nd (Section 4.2), 235U-207Pb, 238U-206Pb and 232Th-208Pb methods (Section 5).

β-decay

Comprises negatron (β-) and positron (β+) emission, in which either an electron or a positron is emitted from the nucleus, causing a transition of (N,Z) → (N-1,Z+1) for β- decay and (N,Z) → (N+1,Z-1) for β+ decay. For example, the oxygen isotope 819O discussed in Section 2.1 decays to 919F by β- emission. In contrast with α particles, which are characterized by discrete energy levels, β particles are characterised by a continuous energy spectrum. The difference between the maximum kinetic energy and the actual kinetic energy of any given emitted electron or positron is carried by a neutrino (for β+ decay) or an anti-neutrino (for β- decay). Just like α decay, β decay is also accompanied by γ-radiation, arising from two sources: (a) relaxation into the ground state of the excited parent nucleus and (b) spontaneous annihilation of the unstable positron in β+ decay. β- decay is important for the 40K-40Ca, 87Rb-87Sr (Section 4.2) and 14C-14N (Section 4.1) clocks. It also occurs as part of the 235U-207Pb, 238U-206Pb and 232Th-208Pb decay series (Sections 5 and 9). β+ decay is found in the 40K-40Ar system (Section 6).

electron capture

This is a special form of decay in which an 'extra-nuclear' electron (generally from the K-shell) is captured by the nucleus. This causes a transformation of (N,Z) → (N+1,Z-1), similar to positron emission, with which it often co-exists. The vacant electron position in the K-shell is filled with an electron from a higher shell, releasing X-rays (~ 10-10m wavelength), which is the diagnostic signal of electron capture. This mechanism occurs in the 40K-40Ar decay scheme (Section 6).

nuclear fission

Extremely large nuclei may disintegrate into two daughter nuclei of unequal size, releasing large amounts of energy (~ 200 MeV). The two daughter nuclei move in opposite directions from the parent location, damaging the crystal lattice of the host mineral in their wake. The two daughter nuclides are generally radioactive themselves, giving rise to β-radiation before coming to rest as stable isotopes. 92238U is the only naturally occurring nuclide that undergoes this type of radioactive decay in measurable quantities, and even then it only occurs once for every ~2×106 α-decay events. Nevertheless, the fission mechanism forms the basis of an important geochronological method, in which the damage zones or 'fission tracks' are counted (Section 7.2). Nuclear fission can also be artificially induced, by neutron irradiation of 235U, e.g.:

235 236 90 143

92U + n → 92U → 36Kr + 56Ba + 3n+ energy

(2.1)

Note that every neutron on the left hand side of this formula generates three neutrons on the right hand side. The latter may react with further 235U nuclei and generate a chain reaction. This forms the basis of nuclear reactors, the atom bomb and the 'external detector' method (Section 7.2).