GEOSCIENCE

Dynamics of the Continental Lithosphere

Fission-track Thermochronology

Methodology and Applications to Geology

Coordinated by
Marc Jolivet

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Introduction

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The age, duration and speed of processes are essential parameters for most Earth science studies. For example, to describe the growth and subsequent dismantling of a mountain range, we need to date the emplacement of magmas, determine the age and speed of metamorphic processes, and measure the slip rates of faults and erosion.

The first attempts to determine the Earth's age date back to antiquity, with Aristotle (384–322 BCE) declaring that the Earth is eternal. This thesis lasted until the end of the Middle Ages, before giving way to attempts at calculation based on the Bible. The Irish archbishop J. Ussher (1581–1656) declared that the Earth was formed at Creation, at the beginning of the night before October 23 in the year 4004 of the Julian calendar. It was not until the beginning of the 20th century, following Henri Becquerel's discovery of radioactivity in 1896, that modern geochronology developed. Using radiogenic helium produced by the decay of radium, J.W. Strutt (Lord Rayleigh) was the first to provide an age greater than 1 billion years. However, his approach was largely biased by the fact that radiogenic helium is produced not only by the radioactive decay of radium, but also by that of many other elements such as thorium and uranium. In the 1950s, technical advances made during the Second World War, notably in mass spectrometry, enabled Patterson (1956) to show that meteorites and the Earth formed at the same time 4.55 billion years ago (± 70 million years) (Figure I.1).

Figure I.1. *Portraits of Aristotle, James Ussher (by P. Lely), John William Strutt (Lord Rayleigh) and Clair C. Patterson.*

From this period onwards, a whole series of geochronological methods were developed based on the "closure temperature" principle (see Chapter 1). Every geochronological system consists of a mineral and a radioactive element–radiogenic element pair. The closure temperature corresponds to the temperature below which

diffusion of the radioactive and radiogenic isotopes in question is no longer sufficient to allow exchanges with the outside of the mineral (Dodson 1973). Geochronological methods therefore exist to date a wide range of geological phenomena over a wide range of temperatures, providing information in the form of an age associated with a temperature (Figure I.2). The combined use of several geochronometers on a sample of the same rock enables us to follow the cooling history of this rock “in dotted lines”, highlighting periods of accelerated cooling, synonymous with tectonic movements (Figure I.3).

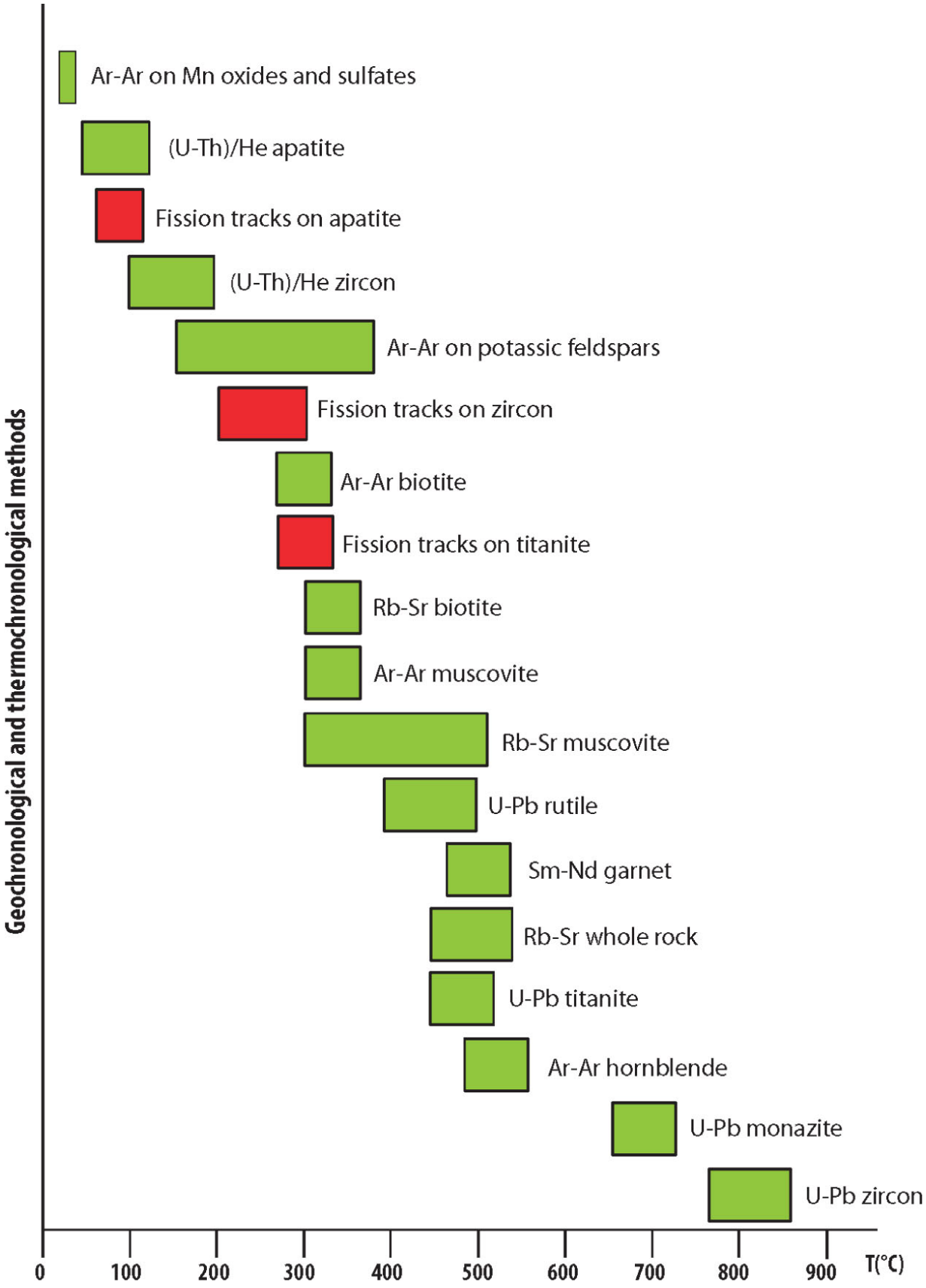
Geochronological and thermochronological methods
Ar-Ar on Mn oxides and sulfates
(U-Th)/He apatite
Fission tracks on apatite
(U-Th)/He zircon
Ar-Ar on potassic feldspars
Fission tracks on zircon
Ar-Ar biotite
Fission tracks on titanite
Rb-Sr biotite
Ar-Ar muscovite
Rb-Sr muscovite
U-Pb rutile
Sm-Nd garnet
Rb-Sr whole rock
U-Pb titanite
Ar-Ar hornblende
U-Pb monazite
U-Pb zircon
0
100
200
300
400
500
600
700
800
900
T(°C)

Figure I.2. *Main geochronometers and thermochronometers used and their temperature of application. Methods based on fission tracks are shown in red.*

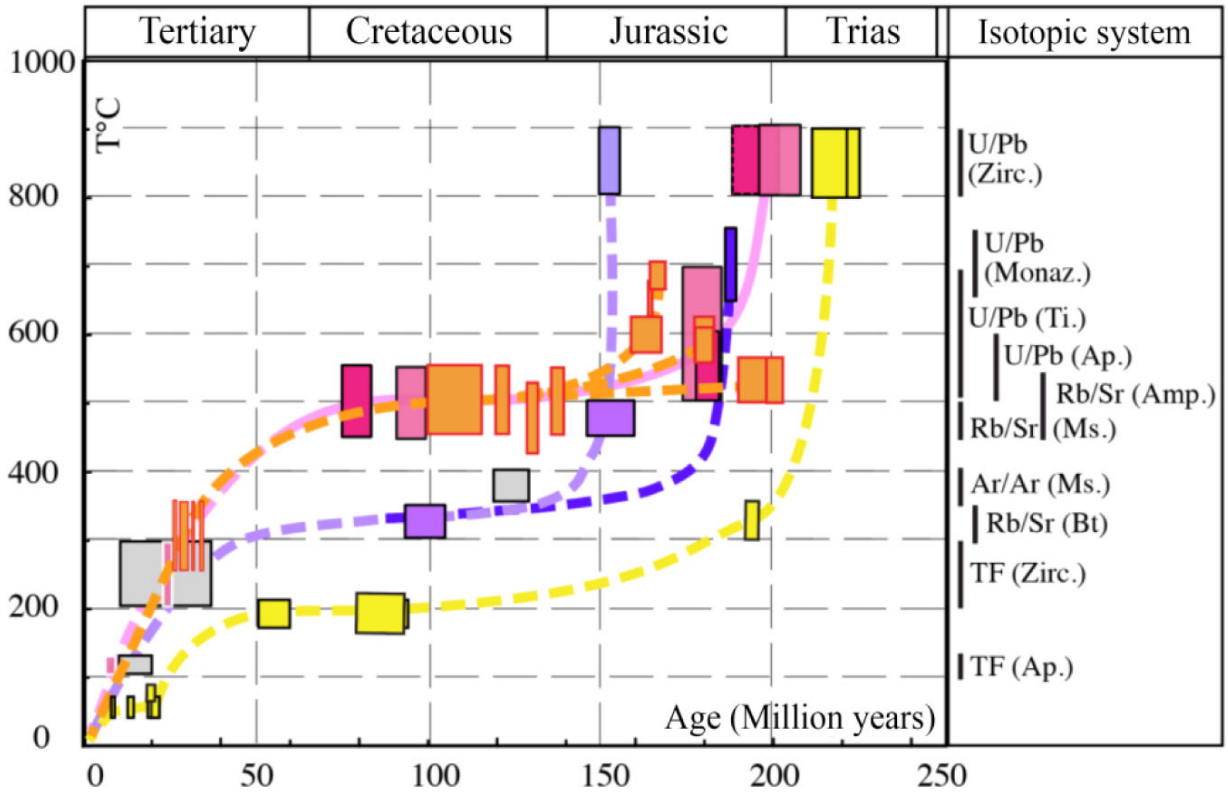

Figure I.3. *Example of a cooling curve drawn by assembling temperature-age points obtained from several geochronometers applied to the same sample. The thermal history obtained is discontinuous. Modified from Roger et al. (2011).*

In 1958, D.A. Young discovered that LiF crystals coated with a uranium film and irradiated with thermal neutrons showed a number of “holes” after chemical treatment. The number of these “holes” is in perfect agreement with the theoretical number of fission fragments of uranium atoms expected for the neutron dose applied (Young 1958). In fact, the spontaneous fission of an atom of ^{238}U or ^{232}Th generates two ionizing particles which, as they pass

through a solid medium, leave a “track”. In a crystallized solid, this “track” corresponds to the displacement of atoms in the crystal lattice. In an organic medium such as plastic, the track materializes as chains of broken molecules (Durani and Bull 1987). In the early 1960s, R.L. Fleischer, P.B. Price and R.M. Walker developed a method for detecting these “fission tracks”, adapting Young’s technique for revealing tracks by chemical etching to a wide variety of materials (minerals, glass, plastics) (Fleischer et al. 1965, 1975) (Figure I.4). As the number of fission tracks in a given mineral depends directly on the concentration of radioactive elements (mainly ^{238}U) and the time over which the mineral has accumulated tracks, it is possible to use this phenomenon as a geochronometer: measuring the concentration of ^{238}U and the density of fission tracks enables time to be calculated. Wagner (1968) demonstrated in 1968 that if minerals such as apatites or zircons are heated, the fission tracks they contain can be “erased” (the crystal lattice is reconstituted). The higher the temperature, the faster the tracks disappear. For each mineral, the temperature range in which the tracks disappear over a time scale compatible with geological time (a few million years to tens of millions of years) is called the partial annealing zone l (PAZ) of the tracks. In apatites, for example, it ranges from around 130°C to 60°C, and in zircons, it ranges from around 250°C to 180°C. Other parameters, such as pressure, have no appreciable effect on the rate at which tracks are erased (Fleischer et al. 1975). By measuring the distribution of track lengths in a mineral, it is then possible to statistically calculate a temperature-time path for each sample, making it possible to continuously monitor the thermal history of a sample in the PAZ temperature range (see Chapter 2).

Fission-track thermochronology has become a key tool in geological research, whether fundamental (tectonics,

geomorphology, sedimentology) or applied (hydrocarbon prospecting). In this book, we explore the latest methodological developments that are constantly improving the results obtained using this technique. The first chapter will first provide a general reminder of the principle behind the method, before detailing its application to detrital thermochronology. The second chapter deals with the statistical modeling of the thermal history of samples. The third chapter focuses on a brand-new technique for determining the ^{238}U concentration of a sample using in situ elemental analysis. The fourth chapter develops the (U-Th-(Sm))/He thermochronology method, based on the production of radiogenic He nuclei by the radioactive decay of uranium (^{235}U and ^{238}U), thorium (^{232}Th) and samarium (^{147}Sm). This method can be applied to the same minerals as the fission-track approach (essentially zircon and apatite) and covers very complementary temperature ranges from 50°C to 200°C (Ault et al. 2019; Gautheron and Zeitler 2020). Fission-track thermochronology and (U-Th-(Sm))/He are therefore often used together in geological studies. Finally, the last chapter proposes an application to geodynamics, explaining how fission-track thermochronology has been used to describe the thermal history of the Central Asian and Tibetan ranges in the context of the collision between the Indian and Asian continents.

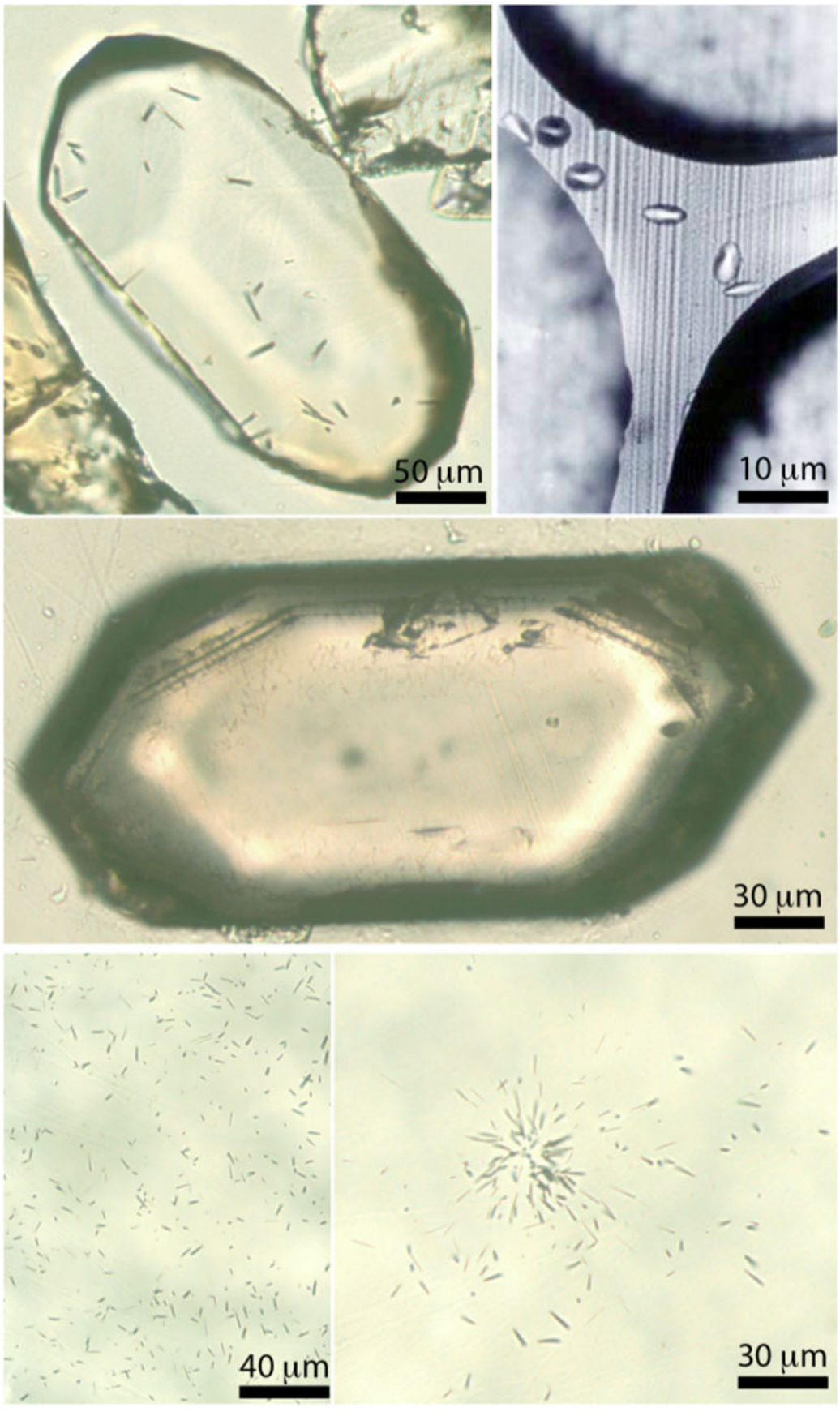
50 µm
10 µm
30 µm
40 µm
30 µm

Figure I.4. *Images of fission tracks in various minerals. From top to bottom and left to right: apatite, glass, zircon (note the very small size and large number of these tracks), white micas (irradiated in contact with apatites) and white micas (irradiated in contact with an apatite containing a zircon whose very high relative uranium content has caused the high density of "star" tracks)*

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1
Introduction to Detrital Apatite and Zircon Fission-track Thermochronology

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Italienische Reise

Noch wunderlicher erschien ich diesem Begleiter, als ich auf allen seichten Stellen, deren der Fluß gar viele trocken läßt, nach Steinchen suchte und die verschiedenen Arten derselben mit mir forttrug. Ich konnte ihm abermals nicht erklären, daß man sich von einer gebirgigen Gegend nicht schneller einen Begriff machen kann, als wenn man die Gesteinsarten untersucht, die in den Bächen herabgeschoben werden, und daß hier auch die Aufgabe sei, durch Trümmer sich eine Vorstellung von jenen ewig klassischen Höhen des Erdaltertums zu verschaffen. Auch war meine Ausbeute aus diesem Flusse reich genug, ich brachte beinahe vierzig Stücke zusammen, welche sich freilich in wenige Rubriken unterordnen ließen.

Johann Wolfgang von Goethe, Palermo, 4 April 1787

1.1. Introduction

The use of detrital apatite and zircon fission-track and (U-Th)/He dating or white mica ^{40}Ar-^{39}Ar dating of modern river and beach sediments or ancient sandstone is a common approach in sediment provenance, source rock exhumation and basin analysis studies. In this chapter, the focus is on detrital apatite and zircon fission-track dating. Both techniques are considered as low-temperature thermochronology dating techniques, with temperature sensitivities in the range of ~ 250–180°C for zircon and ~ 130–80°C for apatite in comparison to high-temperature dating techniques such as zircon or monazite U-Pb dating (Figure 1.1).

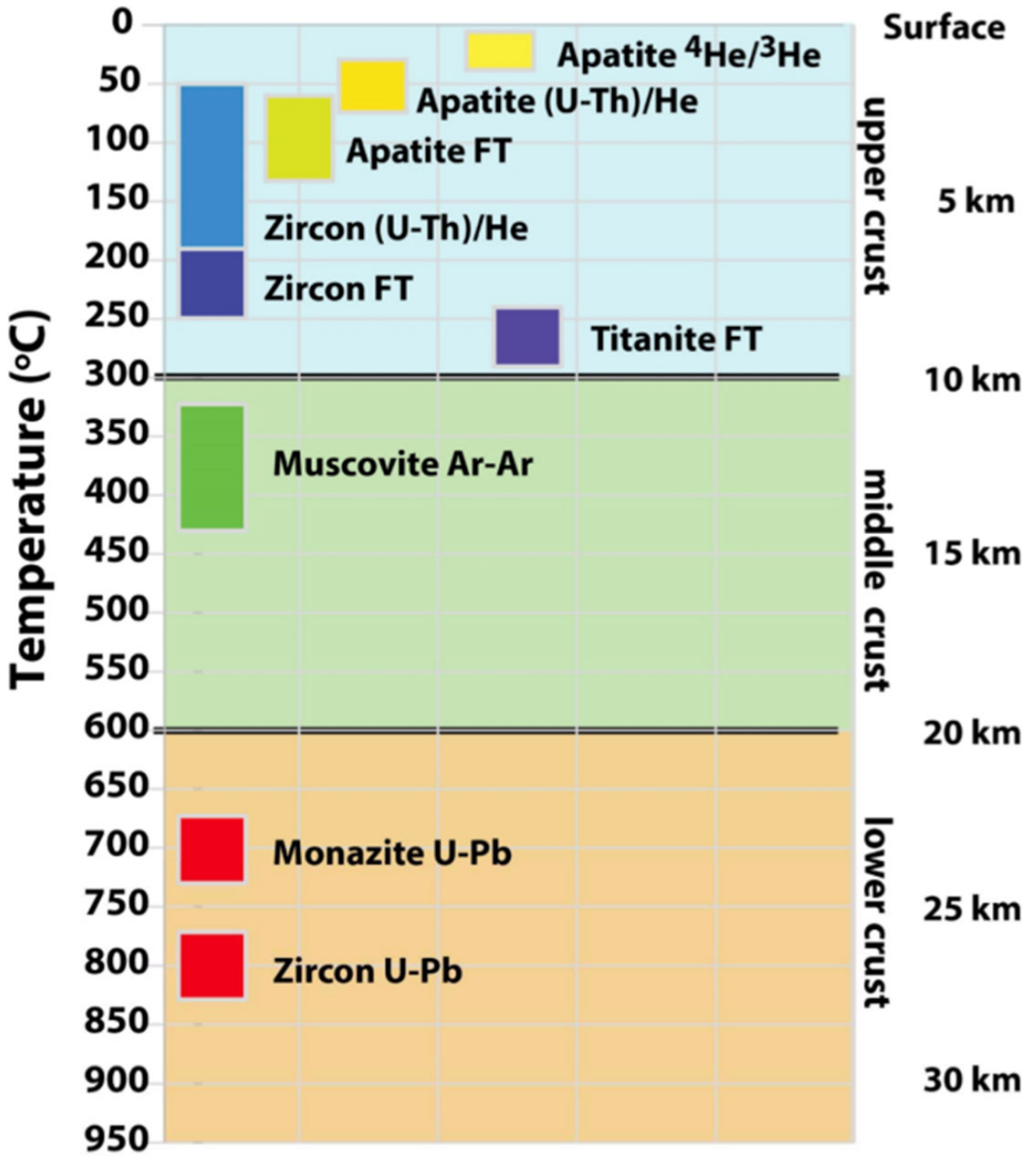

Figure 1.1. *Overview of the temperature sensitivity range of selected isotopic dating techniques.*

Apatite (density of 3.1–3.3 g/cm^3) and zircon (density of 4.5–4.6 g/cm^3) are heavy minerals in contrast to the density of quartz (2.65 g/cm^3). Despite the highly variable apatite and zircon fertility of many upper crustal plutonic, volcanic and metamorphic rocks, both apatite and zircon are relatively common accessory minerals in many sand-sized clastic sediments and sedimentary rocks (Malusà and Garzanti 2019). Although apatite is susceptible to dissolution in acid depositional environments (e.g. bogs) or soils, and abrasion during fluvial transport, zircon is considered as ultra-stable, as long as the grains have not accumulated too much α-radiation damage and are metamict (Malusà and Garzanti 2019; Malusà and Fitzgerald 2020). Both minerals are chemically stable under diagenetic conditions during burial in sedimentary basins or during basin inversion and exhumation.

Since the first detrital zircon fission-track analysis studies in the 1980s (e.g. Hurford et al. 1984; Cerveny et al. 1988), detrital apatite and zircon fission-track dating have developed into standard techniques that have been applied successfully to many different

E, F