Tectonochronology

Tectonochronology:

Methods, Theories, and Cases

By

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PREFACE

Isotope chronology has developed over the last >100 years and has advanced in response to the requirements of geological and environmental research, and according to both theoretical and technical breakthroughs. Various methods have been established, allowing accurate and precise dating of geological materials, processes, and events. Chronology is based on isotopic decay, which is a natural process governed by the rules of radioactivity. In the context of geology, diffusion refers to the process by which elements and their isotopes migrate through minerals and rocks. This process can affect the distribution of parent and daughter isotopes, which can in turn affect the results of chronological dating methods that rely on measurements of the ratios of parent to daughter isotopes. These are the fundamental characteristics of chronology in geology (or "geochronology").

Physicists and geochronologists have developed various dating methods and instruments that have been used in geological, environmental, and archeological research. These methods and instruments continue to be refined, and new methods are being developed. However, the interpretation of chronological data is complex and presents its own issues. Data are produced in laboratories using various isotope chronology methods and analytical procedures, and ages of dated materials have been routinely used to represent the ages of events and processes such as volcanism, magmatism, sedimentation, and metamorphism. With the development and refinement of methods such as U–Pb, $^{40}Ar/^{39}Ar$, Rb–Sr, and Sm–Nd isotope analysis during the 1960s, fission track analysis during the 1970s and 1980s, and (U–Th)/He analysis during the last two decades, age dating has become more precise and accurate through improvements in measurement instruments and procedures, and can now be directly or closely linked to geologic events. Isotopic dating can provide information on magmatic periods, metamorphic events, mountain uplift, and orogenic processes.

The development of instruments and measurement protocols has given geologists a wide range of tools with which to identify events and resolve multiple stages of events and compare the chronology and geological evolution of different areas. In particular, U–Th–Pb and $^{40}Ar/^{39}Ar$ dating methods have evolved with the introduction and adoption of techniques such as TIMS, LA–ICP–MS, SHRIMP, and SIMS. These techniques will continue to evolve, and new techniques and instruments will inevitably be developed in the future. Technical improvements have allowed the dating of mineral grains to improve from analyses of more than 10 grains, to several grains, and to individual grains with several analytical spots. The diameter of the laser or ion used to measure analytical spots has also been reduced from >50 to <10 μm. These advances in precision and the use of instrumental components such as multiple collectors have made a crucial contribution to reconstructions of tectonic and orogenic processes and interpretations of regional or local geologic/tectonic evolution.

As techniques and instruments have improved, so too has the interpretation of age data and their geologic meaning and significance. Prior to the 1970s, isotopic ages were used as geological ages for events/processes such as magmatism and metamorphism, particularly with reference to the concept of closure temperature. With the understanding that ages at least partly reflect temperature and/or kinetics, all isotopic ages were initially considered cooling ages, a viewpoint that has persisted for >50 years. This approach is known as thermochronology and continues to be widely adopted and applied by geologists and geochronologists. To better understand the meaning and interpretation of ages, petrochronology has been developed and used to study the 2D and 3D diffusion and distribution of elements and their isotopes in geologic materials, including magma, rocks, and minerals. This transition from thermochronology to petrochronology has strongly influenced the development of chronology and has spurred the development of other instruments and methods, such as laser mapping techniques and analyses of single crystals, which have been used to identify within-grain compositional and age variations.

Despite advances in instrumentation, many challenges remain in the field of chronology, such as dating of volcanic eruptions, tectonic events, sedimentation, metamorphism, and environmental changes. These ages cannot be interpreted using thermochronology alone. To meet the demands of DEEPtime, geological comparisons, and exploration for oil, gas, and mineral deposits, and to understand magmatic processes, tectonic events, faulting, and climate change, highly precise ages are needed. To achieve this level of precision, the formation and stages of growth of minerals and crystals must be considered when they are dated using methods such as ID–TIMS. For example, when investigating magmatism using zircons, it is important to determine whether the dated zircon grain is a product of syn-magmatic crystallization, an inclusion, a relict, or a crustal xenolith (i.e., via contamination). To date tectonic events, syn-kinematic minerals or crystals are required. Isotopic diffusion and accumulation are not controlled solely by temperature; deformation, metamorphism, sedimentation, and environmental conditions must also be considered.

This book introduces tectonochronology as an approach to address significant issues in the field of chronology. Newly formed syn-kinematic minerals, fluid–mineral interaction, and the kinetic controls on isotopic dating of magmatism, sedimentation, deformation, and metamorphism are discussed. The book also covers the effect of strain on isotopic diffusion and the influence of fluids, including water, on newly formed minerals and isotopic diffusion. The formation and reactivation of crystals are also discussed. In regard to the formation of minerals, stress/strain and water/fluid are considered first, followed by temperature and pressure. Newly formed minerals in tectonic events are discussed in terms of new hypotheses and natural processes rather than traditional solid-state mineral–

mineral reactions in metamorphism and magmatism or other fields of study in earth science. The main focus is on kinetic factors such as stress–strain and fluids (particularly water) that influence isotopic diffusion, rather than just temperature. These concepts can be applied to the timing and interpretation of deformation, metamorphism, sedimentation, and environmental changes.

As well as technical, instrumental, and methodological advances in geochronology, dating targets have expanded from mineral associations to minerals, crystals, and the mineral formation process. This process includes stress, fluids, temperature, and pressure, not just pressure and temperature. The initiation and continuation of crystal growth and the processes involved in fracturing crystals (and in healing the fractures) are also considered.

Isotopic diffusion can now be measured with respect to the influence of stress and strain, allowing isotopic diffusion to be used to directly date deformation. Fluid water can also influence diffusion, allowing sedimentation and metamorphic events to be dated. Syn-kinematic minerals or crystals, combined with the consideration of stress, water, and isotopic diffusion, can be used for direct dating. This book includes cases from Chinese geology that refer to dating of folding, brittle faulting, ductile shear, and environmental change. These methods can be applied to other earth science topics and geological studies worldwide.

In summary, this book on tectonochronology contributes theory and methods to several important scientific topics: (1) the formation of new syn-kinematic minerals and crystals; (2) the influence of stress/strain and fluid on isotopic diffusion of fluid flow on mineral interaction and formation; (3) the formation of new minerals or associations based on elements, water, stress, and deposition, representing no solid-state mineral–mineral reactions; (4) the direct dating of deformation ages; and (5) the range of dating targets of minerals and crystals, emphasizing the formation and evolution of minerals influenced by stress, fluids, and temperature. Tectonochronology is more encompassing and widely applicable compared with thermochronology and can be used in studies of deformation, magmatism, metamorphism, sedimentation, and environmental changes.

In tectonochronology, new findings and highlights include the following:

1) Formation of new syn-kinematic minerals. These minerals are not formed by solid-state mineral–mineral reactions, as is the case in metamorphism and magmatism. During deformation, newly formed syn-kinematic minerals are formed via stress/strain fracturing and shear of rocks and minerals, allowing elements to be transported by fluid to a stress/strain-generated space. These elements form minerals via precipitation from fluid together with the interaction of fluid with host rocks and minerals. During sedimentation, newly formed minerals are formed by fluid–mineral interaction. Metamorphism in subduction and collision belts, particularly high-pressure metamorphism, is accompanied by the formation of new minerals or associations as a result of deformation.
2) Development of systematic methods of dating deformation and their use. For deformation involving folds, brittle faulting, and ductile shear, new methods have been developed for field investigation, sample collection, laboratory mineral analysis and separation, dating procedures, and interpretation of age data. These methods allow geologists to directly and accurately date regional and local deformation and compare different tectonic events. Similar concepts can also be applied to sedimentation, metamorphism, mineral deposition, magmatism, and environmental chronology, including the role of fluid, stress, and temperature kinetics in isotopic diffusion and accumulation.
3) Criteria for dateable minerals/crystals and methods for direct and precise dating. Direct and precise dating of deformation, sedimentation, metamorphism, magmatism, and mineral deposition is essential for advancing earth science and understanding the evolution of Earth.

Various minerals have been suggested for dating different types of deformation and sedimentation, along with criteria for analytical methods and geological interpretation. These criteria vary for different subjects in earth science and for different isotopic dating methods.

4) Relationship between mineral–crystal formation/evolution and isotope chronology. The formation and evolution of minerals/crystals and their textures are directly related to geological events and processes and to isotopic diffusion; therefore, these minerals and crystals are targets for direct and precise dating. Changes in crystal elements and textures are fundamental to isotope chronology. Therefore, the growth of new minerals and crystals, their fracturing, healing, composition, and texture, and the changes in these properties recorded in the minerals/crystals are emphasized. Stress, fluid, temperature, and chemical composition and variations in these factors are all involved in the formation of minerals and crystals.
5) Influences of strain and fluid on isotopic diffusion. Thermochronology uses closure temperature to constrain cooling ages and provide a probable time interval for geological events such as deformation, metamorphism, and mountain uplift. The assumption is that temperature is the primary control on isotopic diffusion; however, strain—regardless of its rate and duration—as well as shear and fractures, can also result in isotopic diffusion. When fractures heal and stress is absent, a new stage of isotope decay and accumulation begins, allowing brittle deformation to be dated. Similarly, fluid can also influence isotopic diffusion. When fluid flow ceases, the isotopic system closes but does not reopen, allowing for direct and precise dating of fluid-involved geological events such as magmatism, sedimentation, metamorphism, and mineral deposition (mineralization).
6) Improved understanding of stress, fluid, and temperature. Traditionally, geology research has emphasized the roles of temperature and pressure in processes such as magmatism, metamorphism, and sedimentation. In

recent years, the role of fluid has been considered in metamorphism and sedimentation, with investigations involving examination of fluid–mineral and fluid–rock interactions. These approaches have been used mainly in studies of oil–gas exploration, sedimentation, and environmental change. The influence of stress and fluid has been widely used in materials science, and discussions of the roles of stress and fluid, either individually or combined with temperature, are being increasingly included in studies of deformation and metamorphism.

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CHAPTER 1

INTRODUCTION

1.1 Development of isotope chronology

1.1.1 Basic knowledge and advances in isotope chronology

Chronology is based on two processes: isotopic decay, accumulation and diffusion. The first is a natural process. The second occurs in two different settings: in the laboratory and in geological processes. In-laboratory measurement of diffusion requires precise and high-quality multiple collectors, which have been developed over time and used in numerous studies. Diffusion in the laboratory can be precisely resolved and represents much less than 0.01% of the total diffusion. Hence, natural and environmental changes can be interpreted using data from isotopic decay and diffusion accumulation (Becker, 1908; Bateman, 1910; Barrell, 1917; Fleischer and Price, 1964; Ahrens, 1965; Fechtig and Kalbitzer, 1966; Dodson, 1973; Farley, 2000, 2007; Begemann et al., 2001; Reisberg and Meisel, 2002; Kohn, 2017).

Decay. Isotope chronology refers to the process of irradiation isotope dating, which involves the measurement of isotopic elements in the natural environment. These elements naturally change from one isotope to another, forming a stable element that can be dated. This process is known as decay, and in cases where parent and daughter isotopes reach equilibrium (Figure 1-1), the element (and therefore the material hosting the element) can be dated. The decay ratio can be physically calculated and allows division into

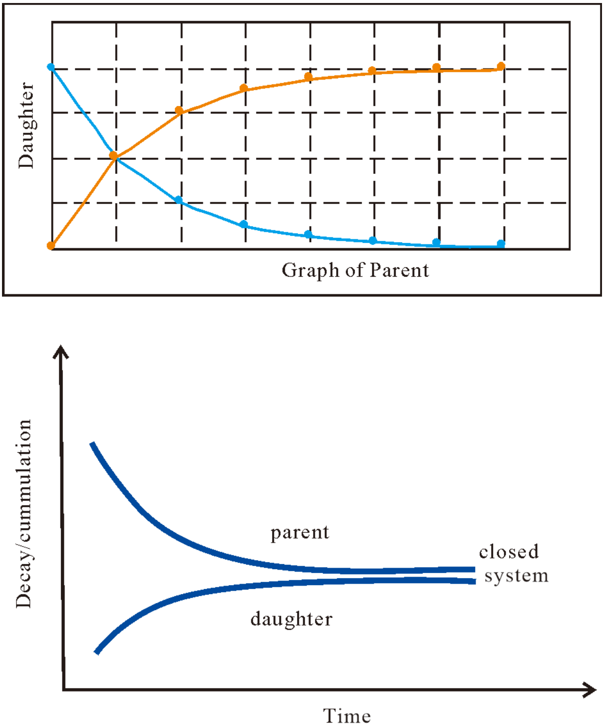

Figure 1-1 Plot for Graph of parent vs daughter, showing radioactive decay and ingrowth of parent and daughter nuclides (modified from Reiners et al., 2018).

short- and long-term isotope chronology (Figure 1-2). Long-term decay methods such as those of the $^{40}Ar/^{39}Ar$, U–Pb, Sm–Nd, and Re–Os systems are commonly used. Other methods include cosmic radiation damage or nuclear damage, knowledge of which has led to the development of fission track, (U–Th)/He, and younger-age dating methods. The discovery and calculation of isotopic decay form the basis of isotope chronology methods.

Diffusion. Isotope chronology can be used to date geologic events, processes, and environmental change, as well as for dating purposes in archeological research. Diffusion is a key component of natural environments and laboratory procedures, but the interpretation and significance of ages can vary depending on environmental conditions and geologic processes, even when using the same isotopic dating method on a particular mineral (Figure 1-3).

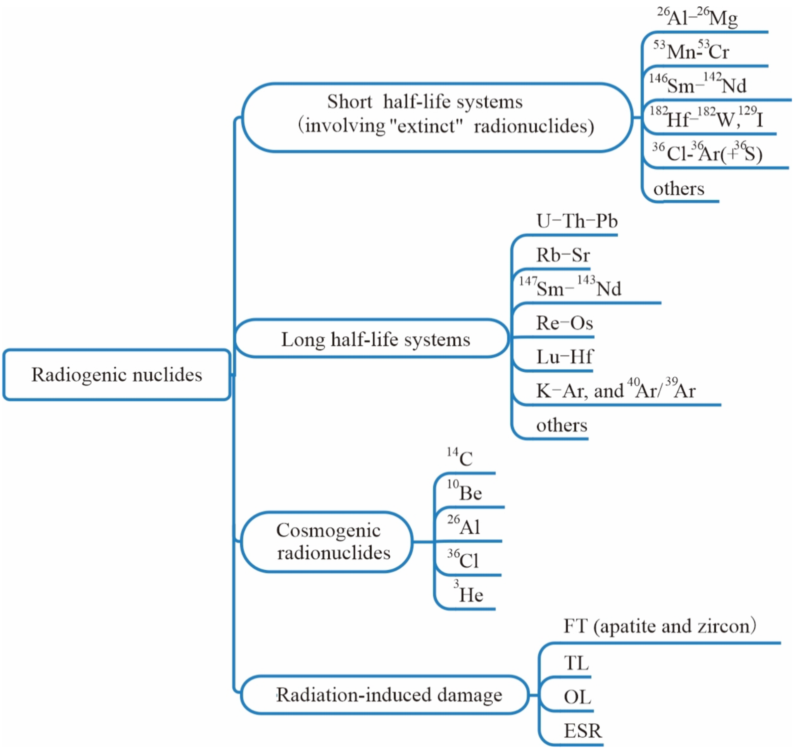

Figure 1-2 Divisions of radiogenic nuclides followed with decay constants (summary from Reiners et al., 2018, and references therein). They include short and long half-life radiogenic systems, cosmogenic radionuclides and radiation-induced damage systems.

This is an important consideration in current geologic studies and for making precise comparisons. Diffusion in natural environments is influenced by multiple kinetic factors, such as temperature, stress, fluid, and pressure. These factors can individually and collectively affect isotopic diffusion in tectonic, sedimentary, magmatic, and metamorphic settings. This book discusses these kinetic factors in more detail.

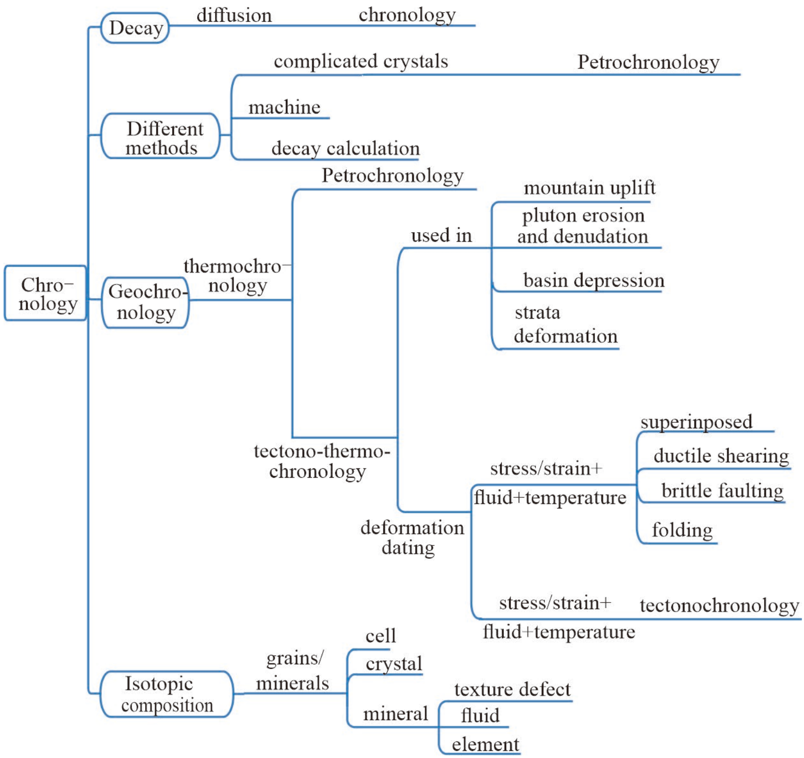

Figure 1-3 Constructions of chronology and developments. The knowledge-tree includes: from decay and diffusion to geochronology, different methods, from isotope chronology to tectonochronology, dating targets of isotopic compositions, and constraining factors etc.

Accumulation. Isotopic diffusion can be used for chronology in cases where parent and daughter isotopes reach equilibrium and the system is closed. The process of reaching equilibrium is cumulative for the daughter isotope, and the system must remain closed. If the isotopic system is opened or re-opened, it will no longer be in equilibrium, meaning that an accurate age cannot be determined. Instead, any ion or element loss/gain will result in an isotopic excess or loss.

Advances in methods and techniques. Modern techniques and analytical instruments have been developed to meet the demands of chronology and provide precise and accurate data using methods such as U–Pb and $^{40}Ar/^{39}Ar$ dating (e.g., Onstott et al., 1995; Vance et al., 2003; Mattinson, 2005; Cherniak, 2010; Schaltegger et al., 2015; Schoene and Baxter, 2017; Williams et al., 2017; Moser et al., 2018). The U–Pb dating method has been improved with the use of instruments such as TIMS, LA–ICP–MS, SHRIMP, and SIMS, and new instruments may be developed in the future. The $^{40}Ar/^{39}Ar$ method has also advanced, owing to the use of instruments such as MASS 1200, Micromass 3600, Micromass 5400, and ISOTOPX. These instruments are more precise and reduce diffusion in the laboratory by using multiple collectors. For example, in $^{40}Ar/^{39}Ar$ dating, ^{36}Ar, ^{37}Ar, ^{38}Ar, ^{39}Ar, and ^{40}Ar can be collected simultaneously instead of sequentially over several seconds. As instruments have improved, so too have the methods and calculations used in isotope chronology. The interpretation of age data has also evolved with these developments, leading to more meaningful and useful dating results.

1.1.2 Development of chronology

Isotope chronology. As mentioned above, decay is the basis for isotope chronology methods and instruments. This has been the foundation of isotope chronology since the beginning of the twentieth century to the present (e.g., Becker, 1908; Bateman, 1910; Barrell, 1917). The development of instruments has greatly improved over time. Since the initial discovery of chronological dating methods such as K–Ar and U–Pb, other isotope chronology methods have been developed, including $^{40}Ar/^{39}Ar$, Rb–Sr, Sm–Nd, fission track, ESR, TL, OL, and more recently (U–Th)/He.

Prior to the 1970s, isotope chronology was the main direct dating method used to develop chronostratigraphic charts and to constrain regional geological histories. Ages determined using isotope chronology were considered to be absolute, and geologists did not consider the effect of diffusion when using age data to represent the ages of magmatic and metamorphic events (Figure 1-4).

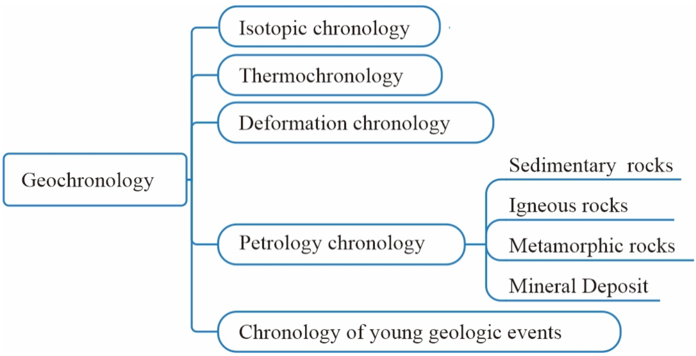

Figure 1-4 The main geochronology and its uses included. By the development, they are mainly composed of thermochronology, a short time development of tectono-thermochronology (not listed), petrochronology, defochronology, younger dating chronology (also same as cosmogenic radionuclides and radiation-induced damage methods), and criterion of age evaluation.

Thermochronology. Since the 1960s, especially following the milestone paper by Dodson (1973) on the concept of closure temperature, radiometric ages have been associated with temperature. For different methods, and even for the same minerals, ages can vary owing to the different closure temperatures of different isotopic systems. This stage of development of chronology is also known as thermochronology (Figure 1-

5). The basis of thermochronology is that a measured age is related to the closure temperature relevant to the isotopic system being used for chronological measurements, with the measured age (apparent age) corresponding to the time since when the dated material cooled below the closure temperature (Huntington et al., 2018) (Figure 1-6). Reiners et al. (2018) have provided a detailed review of this topic.

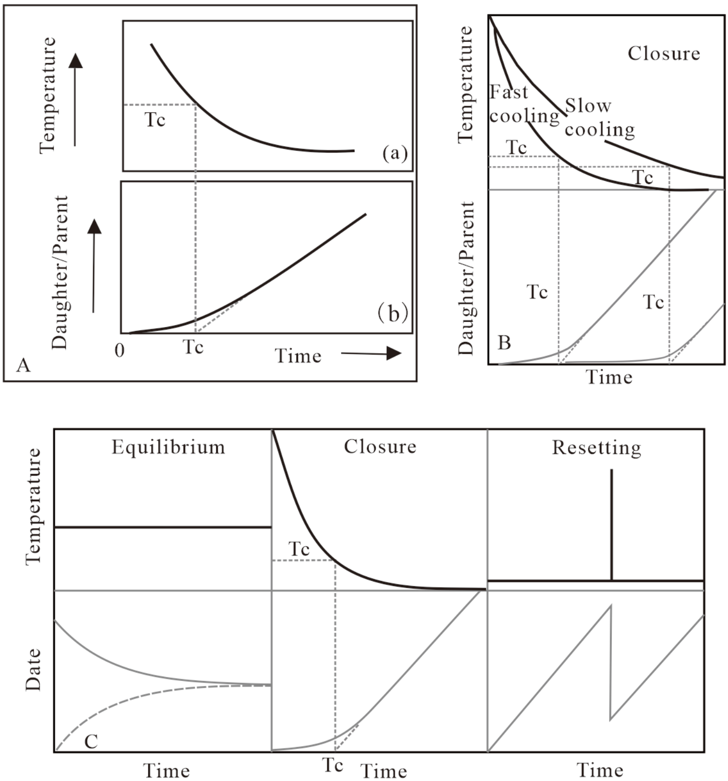

Figure 1-5 Closure temperature and temperature vs diffusion. A-closure temperature, the age reflects the duration of cooling time (from Dodson, 1973), B- two different cooling paths (from Reiners et al., 2018), C-end-member interpretations for thermochrometric cooling ages (from Reiners et al., 2018). In the figure, Tc-closure temperature, tc-the closure time.

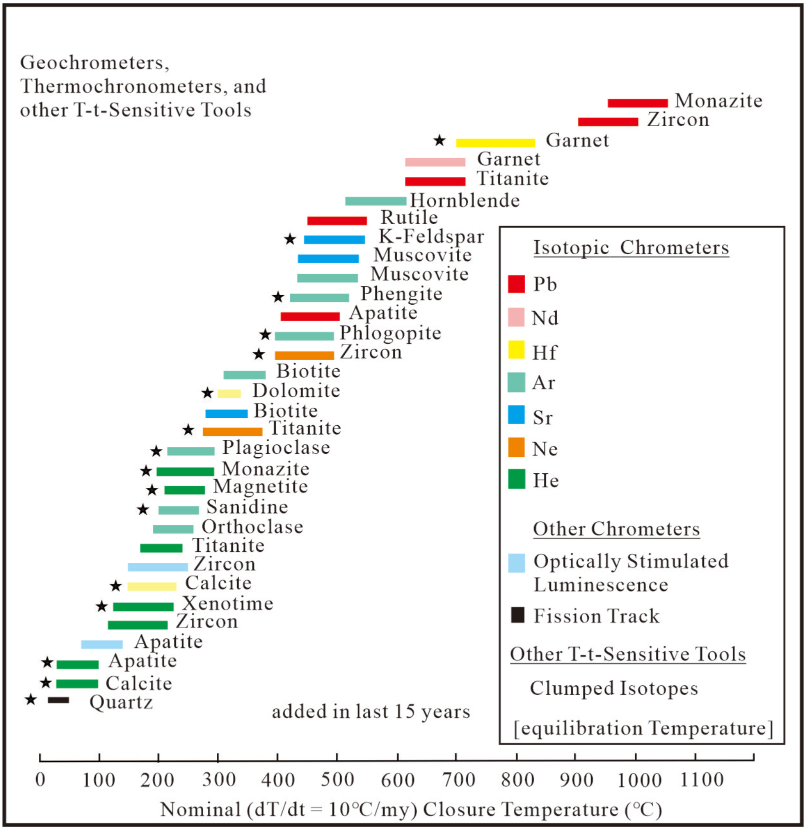

Figure 1-6 Geochrometers, thermochronometers, and other T-t-sensitive tools (from Huntington et al., 2018) developed so far.

Thermochronology is still widely used in the study of geologic evolution, particularly lower-temperature thermochronological methods such as apatite and zircon fission track analysis and (U–Th)/He analysis. These methods have been used to determine the timing, extent, and rates of mountain erosion/uplift, basin inversion, and reversal. In the late twentieth century, multi-diffusion domain (MDD) modeling and fission track were used together for the first time to reconstruct mountain uplift and evaluate erosion/uplift rates. Currently, geologists are using thermochronology to interpret tectonic events such as ductile shear deformation and fault timing via fission track dating and other thermochronological methods (Braun et al., 2006).

Petrochronology. Thermochronology is a useful approach for resolving the ages of different geologic events such as magmatism and mountain erosion/uplift; however, it is mostly limited to cooling histories, such as pluton emplacement and mountain erosion/uplift, and other events such as deformation, sedimentation, and metamorphism cannot be directly and precisely resolved. For U–Pb dating of zircon and other minerals, temperature and fluid flow can influence the inner parts and outer rims of such minerals after their original formation (e.g., Bickle and McKenzie, 1987; Glodny et al., 2008; Kohn, 2016), and these different domains of mineral grains can be dated separately. Elements or ions such as Pb and K can diffuse in different domains of mineral grains, resulting in different distributions of ions or elements within individual grains. With the use of 2D and 3D micro-mapping and laser systems, micro-spot dating can be combined with elemental diffusion to determine ages. This has led to the development of petrochronology during the last decade (Kohn, 2017; Kohn and Penniston-Dorland, 2017; Schoene and Baxter, 2017).

Tectonochronology. Tectonochronology is a recently developed and evolving approach within chronology and is the main focus of this book. Tectonochronology considers the stresses and fluids involved in isotopic diffusion, as well as the syn-kinematic and syn-sedimentation formation of minerals.

Tectonochronology systematically builds upon chronology, isotopic systems, mineralogy, petrology, structural geology, and micro-tectonics through the study of physical and chemical processes and interactions. This represents an advance in chronology from thermochronology to tectonochronology.

As a geologic concept, tectonochronology has its own typical and non-representative study targets with particular development rules. Its theoretical basis includes typical definitions, terms, principles, theories, propositions, and rules that form a logical system. It also has its own investigation and systematic dating methods. Therefore, tectonochronology is a rigorous scientific methodology, not just a laboratory technique.

1.1.3 Main kinetic controls on isotopic diffusion

Pressure and temperature are fundamental properties (or factors) in earth science, and temperature is the primary control referred to regarding isotopic diffusion and thermochronology. However, in addition to temperature and pressure, there are two other important factors in nature (i.e., stress and fluid), although these factors have not yet attracted sufficient scientific research attention with respect to isotopic diffusion and chronology. Stress and fluid flow, in addition to temperature and pressure, can influence isotopic diffusion.

Temperature. The development of isotope chronology has considered not only the precise measurement of ages but also the interpretation of age data with respect to geologic events. Temperature is a key factor to consider in the interpretation of isotope chronology data and with respect to the dating of geologic events. As a kinetic factor, temperature controls the rate of diffusion, which serves as a basis for thermochronology. Given this kinetic factor and the concept of closure temperature, age data can be associated with temperature, resulting in the determination of cooling ages. High-temperature thermochronological methods, such as zircon and monazite U–Pb dating, as well as lower-temperature thermochronological methods, such as hornblende, biotite, muscovite, K-feldspar $^{40}Ar/^{39}Ar$ dating, apatite fission track, and (U–Th)/He dating, have been used to study mountain erosion/uplift and sedimentary sources and transport. Rates of cooling or annealing and the interpretation of these data have been discussed