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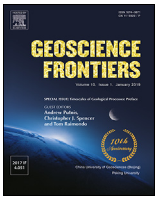

Editorial

Timescales of geological processes: Preface

1. Introduction

One of the major challenges in Geoscience is to understand how the formation and evolution of the Earth System are governed by timescales – that is, how the various geological processes that continue to contribute to its present-day structure and composition operated in the deep past. The traditional view of such processes refers to events that occur at immense spatial scales and over hundreds of millions of years, constrained in most cases by the ages of rocks determined using isotopic dating methods or the fossil record. However, the modern view of geological processes has increasingly acknowledged that their durations can be significantly shorter than previously thought possible, or indeed detectable without recent analytical innovations. Earthquakes are a prime example of rapid, high energy and episodic events that have a profound effect on subsequent processes such as metamorphism, fluid transport, and ore formation – the evidence of which is written in microstructures, compositional zoning, and P-T records. Experimental studies have also revealed that the reaction rates between fluids and rocks can be extremely rapid relative to geological timescales. This has led to the notion that geological processes are not necessarily continuous over millions of years but may, in fact, be sporadic, with long periods where essentially no reactions take place punctuated by periods of intense activity.

Understanding the coupling of slow processes on a large spatial scale (e.g. orogenesis) with rapid processes taking place on a local scale (e.g. fluid-mineral interaction) will engage geoscientists for generations to come. Our present focus is to define the central issues relating to the timescales of Earth's evolution and the mechanisms underlying the processes of change. This encompasses topics as diverse as terrestrial planet formation and evolution, orogenesis and metamorphism, metasomatism and fluid flow, crystal growth and element transport, ore formation and weathering. In 2017, these issues were among those considered as part of the "Timescales of Geological Processes" theme for the annual TIGeR Conference organized at Curtin University (Perth, Australia) – details of the presentations and abstracts can be found on the Institute for Geoscience Research website (tiger.curtin.edu.au/conferences/). The present Special Issue of *Geoscience Frontiers* is a subset of the presentations delivered, giving a broad cross-section of the topics addressed and their contribution to our improved understanding of geological timescales.

2. Contributions in this special issue

In this Special Issue of *Geoscience Frontiers*, we assemble thirteen contributions spanning a wide array of topics relating to the timescales of geologic processes, from rapid fluid flow to long-term evolution of the continental crust. In the summaries below, the contributions are approximately ordered from shortest to longest timescales.

The first paper by Scarlett et al. (2019) examines terrestrial oil seeps from the Caribbean region using a novel method of gas chromatography coupled to a time of flight mass spectrometer. They note that although the timescale of oil formation is generally measured in millions of years, the degradation of oil occurs within months to years in anaerobic and hours to days in aerobic conditions. Therefore, defining the degree and driver of biodegradation is a significant issue, in that biodegraded oil such as that found in terrestrial oil seeps will become increasingly important as Earth's reserve of low-density oil decreases.

The second contribution by Renard et al. (2019) performs in situ Atomic Force Microscopy experiments on carbonate minerals to capture the dissolution and precipitation of new minerals through time. They found that various hazardous elements will be sequestered in a stable solid phase by the calcium released during dissolution. Theoretical scaling of their experiments provides a framework to characterize the time-scale of the boundary layer within which the carbonate dissolution and precipitation can occur on the order of seconds to minutes. The authors state these results imply that many carbonate-fluid reactions are controlled by local thermodynamic equilibria rather than equilibrium of the whole system.

Continuing on the theme of mineral-forming reaction times, Zhao et al. (2019) provide new constraints on the mechanism and kinetics of the replacement of magnetite by hematite in hydrothermal conditions. They further elucidate the relative effects of redox and non-redox processes on this transformation. Using textural and chemical criteria, the authors point out that the kinetics of magnetite to hematite replacement is driven primarily by the temperature and solution parameters rather than the presence of oxygen. These results lay the foundation of future research to constrain the reaction pathways and timing of hematite formation in natural magnetite occurrences.

Trepmann and Seybold (2019) explore the control of dissolution-precipitation of mineral veins by low and high stress-loading rates. Through the investigation of microstructures, the authors argue that micro-shear zones, sub-basal deformation

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lamellae, short-wavelength undulatory extinction, and recrystallized grains in fracture-fill veins allow constraint of the stress loading-rates. This contribution provides empirical evidence that microstructures in quartz veins reflect episodes of cracking and sealing during dissolution-precipitation creep of the host rock on a timescale of tens to hundreds of years. Importantly, the authors provide a novel way to use quartz microstructures to distinguish various stress histories.

Discussing trace element mobility, Fougerouse et al. (2019) use atom probe microscopy to investigate the mechanisms responsible for the formation of trace element enriched nanoclusters and Pb enriched microstructures in pyrite. The data presented herein provide a mechanism for the trapping and retaining of ex-situ Pb within pyrite during deformation, and suggest that differing Pb isotopic compositions found along deformation microstructures are related to discrete geologic events. The authors highlight that the formation of these structural and chemical features in pyrite challenges the assumption that pyrite remains unchanged from the time of crystallization and is unaffected by alteration processes.

Seydoux-Guillaume et al. (2019) provide further evidence of nanoscale chemical changes using atom probe tomography and transmission electron microscopy. They report nanoscale isolation of two different geochemical reservoirs within a single monazite grain identified by two chemically distinct types of nanoclusters with distinct Pb isotopic signatures. Curiously, this nanoscale resetting is present in an apparently undisturbed monazite grain and highlights what without high-resolution investigation, such disruption of the Th/Pb isotopic system would not be seen. This study provides an important first step in developing a rigorous workflow for nano-geochronology and nano-thermochronology.

Moving into economically important mineralization, Barnes and Robertson (2019) discuss the kinetics that plays a major role in magmatic ore-forming processes and how the formation of well-equilibrated, high-tenor ores require multi-stage recycling in long-lived trans-crustal conduit systems. The authors discuss the timescale of processes ranging from minutes to hours with magma flow and sulfide droplet settling, extending to thousands and millions of years with tectonic-driven seismic pumping and deformation. This work proposes that high-R factor ore-forming systems such as those at Noril'sk-Talnakh are analogous to a long-lived, large scale, magmatic elutriation column that keeps sulfide liquids suspended in magma over long equilibration times and allows for extreme enrichment in Ni-Cu-PGE ore deposits.

Fielding et al. (2019) deliver a synthesis of pyrite geochemical maps and in situ xenotime geochronology to constrain the regional-scale drivers for hydrothermal gold mineralization. This work provides evidence that U-Pb geochronology of hydrothermal xenotime can not only precisely date the timing of gold mineralization, but can lead to better understanding of the fundamental controls on gold mineralization at a regional scale. These provocative findings challenge previous interpretations of the timing and style of gold mineralization at the Mount Olympus deposit and propose that Carlin-type ores can form in a wide variety of intracratonic settings. The findings of Fielding et al. (2019) highlight how the integration of the tectonic evolution with the geochronology of hydrothermal minerals connected to ore-forming processes can, in turn, improve regional-scale exploration targeting for gold mineralization.

Using trace element and sulfur isotope composition of pyrite, Wu et al. (2019) provide insight into the relative timescale and origin of the gold deposits from the West Qinling Orogen of China. The authors demonstrate that the geochemical evidence presented is consistent with fluids sources derived from Ni- and Se-rich carbonaceous sediments and discount the involvement of magmatic fluids. A synthesis of regional tectonics and orogenic geochronology provides a framework to better understand the structural regime that facilitated the gold mineralization and implies the far-field effects of subduction on the continental interior extended thousands of kilometers away from the continental margin.

Tessalina et al. (2019) address the controversy between constraining the chronology of geologic events through biostratigraphy and isotope geochronology through a reassessment of the recent radiometric dating of sulfide mineralization and new U-Pb geochronology from various VHMS deposits. These new data provide a solution to the previous chronologic discrepancies that extend the timespan of hydrothermal activity in the Ural Mountains and require a reevaluation of the tectonic affinity of the VHMS deposits. Nevertheless, these new data call into question much of the previous work on similar age VHMS deposits along the ancient Pacific subduction margins. This study lays the foundation for future geochronological work to better understand the chronology and timescales of VHMS deposit formation.

Changing tact to the longer timescales of tectonic processes, Pourteau et al. (2019) constrain the oceanic subduction history of the Sivrihisar Massif of Turkey using Lu-Hf dating of garnet. Their results reveal a 15–20 Myr duration of cooling within the ancient subduction interface. Metamorphism took place over this interval with a progressively-decreasing thermal gradient from $\sim$45 °C/km at $\sim$104 Ma during subduction initiation to $\sim$7 °C/km at $\sim$87 Ma during continental subduction. These results suggest that the high-pressure, low-temperature rocks were not exhumed episodically as was previously thought, but rather were exhumed continuously via return flow. The timescale presented by Pourteau et al. (2019) implies long-lived metamorphic processes associated with the evolving thermal structure of a subduction zone.

Gromard et al. (2019) address a long-standing controversy relating to prolonged intracontinental tectonics in central Australia. New structurally-controlled geochronology indicates that orogenic activity previously thought to be correlated with the Peterman Orogeny (580–520 Ma) is actually associated with two previously unrecognized tectono-metamorphic events that occurred at $\sim$715 Ma and $\sim$630 Ma. This new interpretation is built upon the geochronology and thermochronology of multiple mineral phases that constrain events from high-temperature metamorphism in the mid-crust to exhumation at the surface and provides an excellent example of revealing the timescale of mountain building processes using a multi-faceted approach.

The final contribution deals with the longest timescale in this Special Issue, where Hawkesworth et al. (2019) provide a succinct review of the rates of generation and growth of the continental crust. Bringing together a wide array of data from volcanic output and spatial extent of granitoid rocks to large compilations of zircon data and geochemistry of mafic rocks, the authors explore plausible scenarios of crustal growth and changing rates of crustal generation. They propose that 65%–70% of the present volume of the continental crust was generated at a relatively high growth rate prior to 3 billion years ago. It is posited that this time heralded modern-style plate tectonics as the dominant mechanism for crustal growth, which has since proceed at a decreased rate.

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