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ABSTRACT VOLUME

Rates and timing of Earth system processes

FAULT INITIATION, EXHUMATION, AND PROPAGATION DOCUMENTED BY LOW-TEMPERATURE THERMOCHRONOLOGY IN THE ANDEAN PRECORDILLERA, SAN JUAN, ARGENTINA

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The central Andean Precordillera, between 30-31°S, has experienced active faulting and deformation from the early Miocene to present driven by a flat-slab segment of the down-going Pacific Plate. Basic models for fault propagation, in this region, involve progressive eastward stepping of deformation; however, out-of-sequence faulting has been postulated. Furthermore, deformation appears to have started earlier in the northern part of this region and later in the southern part. We use apatite (U-Th-Sm)/He (AHe) low-temperature thermochronology to quantify timing of fault exhumation and fault growth patterns to test hypotheses about out-of-sequence thrusting and the southward propagation of deformation in the region. Nine vertical transects were collected in the eastern-most part of the Precordillera. Preliminary AHe data indicate complete and partial age resetting in middle to late Miocene sedimentary units, that were deposited, buried, and subsequently exhumed. AHe ages range between 30 - 2Ma and trend younger to the south, supporting previous suggestions of north to south deformation migration. Additionally, we use cosmogenic radionuclides (CRN) to assess modern erosion rates across the landscape. Initial erosion rates range from 22 – 1330 m/my, with generally lower rates in the north and higher rates to the south. Ongoing analysis and modeling of both thermochronologic and CRN data will help to constrain the recent exhumation and erosion history in the central Andean Precordillera and determine if combining these two techniques can be used to identify out-of-sequence faulting and changes in spatial patterns of tectonically driven deformation.

Advances in noble gas and solid state thermochronology

A DIODE LASER CONTROLLED APPARATUS FOR HIGH-PRECISION STEP HEATING EXPERIMENTS FOR 4HE/3HE THERMOCHRONOMETRY.

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We present a simple and low-cost apparatus for in-vacuum step heating measurements using a 75W Diode laser heater source, which we developed at the 4He/3He thermochronometry facility of the University of Potsdam in the framework of the ERC-funded COOLER project. The sample is wrapped in a Pt foil and located in an Alumina crucible connected to a K-type thermocouple for high-precision temperature control. The sample is placed near the thermocouple head for maximum accuracy. The thermocouple allows calibration of temperature measurements with an IR pyrometer for temperatures >300 °C. Laser heating is performed on the Alumina crucible with indirect sample illumination to reduce temperature gradients, temperature set-point overshoots, and ramping times. Laser and PID temperature controls are carried out by a custom LabVIEW program. The crucible is connected to a noble-gas preparation line and the gas released from the sample is purified and analyzed on a Thermo Scientific Helix SFT™ multi-collector mass spectrometer. In experiments with set points between 100 and 1000 °C, this apparatus can achieve set point temperatures from room temperature in 100-200 s, with no set-point overshoot. Preliminary step-heating experiments performed on proton-irradiated Durango shards indicate that the measured temperatures are precise and reproducible to less than 2 °C.

Celebration of the research achievements of Rod Brown

CONSTRAINING THE EARLY MIOCENE COOLING PULSE OF GRANITIC INTRUSIONS ALONG THE NE OF IRAQ-BORDER BY USING JOINT APATITE/ZIRCON U-TH-SM/HE, AND FISSION TRACK DATING APPROACH.

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Along the NE of the Kurdistan Region of Iraq there are only few minor granitic intrusions with crystallization age ranging from ,96 to ,46 Ma. These acidic emplacements are typically found in the eastern Iraq part on the Arabian plate. However, in Shlair, Iraq, they are also found in the Sanandaj Sirjan Zone, which is part of the Iranian/Eurasisan plate and extends into NW Iran. Recent zircon (U-Th)/He published data (e.g., Ismail et al., 2020) of granitoids in Penjween area, on the Arabian Plate in eastern Iraq, reveals a cooling pulse in Miocene, which is linked to shallow break off in the oceanic slab during subduction beneath the Eurasian plate since the Late Cretaceous. Here, we present combined apatite/zircon U-Th-Sm/He and fission track dating of the Shalair and Penjween granitoids in order to better constrain the regional extent of the Miocene cooling pulse. We investigate the timing and spatial relationship of this cooling pulse across the Arabian and Iranian plates to determine either the cause of Miocene cooling is driven by regional tectonic cooling due to the slab break off or out-of-sequence thrusting.

Developments and challenges in (U-Th-Sm)/He thermochronology

PALEOEARTHQUAKES IN THE ROCK RECORD: CAN THE ZIRCON (U-TH)/HE SYSTEM BE RESET BY SHALLOW SEISMIC SLIP?

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Helium diffusion kinetics in zircon are estimated from laboratory experiments and extrapolated to transient events and geologic timescales. In principle, the zircon (U-Th)/He (ZHe) system should be sensitive to earthquake thermal histories, and we test this hypothesis with high-spatial resolution ZHe thermochronometry adjacent to pseudotachylytes emplaced along the West Salton Detachment fault (WSDF) in southern California. Prior regional thermochronometry data suggest shallow pseudotachylyte formation at ambient temperatures low enough for wall rock zircons within 1 cm of the pseudotachylyte contact (i.e., thermal boundary layer) to be thermally reset by elevated temperatures from pseudotachylyte emplacement. New ZHe dates from within the thermal boundary layer above and below the pseudotachylyte overlap and range from ,46-101 Ma over ,450-2050 ppm eU (n = 26 analyses). New apatite (U-Th)/He (AHe) data from some of these same samples are ,28-51 Ma and ,30-50 ppm eU (n = 7 analyses). Our data overlap with previously reported AHe and ZHe data from WSDF hanging wall rocks, indicating pseudotachylyte was emplaced in the hanging wall and does not delineate the WSDF interface. Because our ZHe dates from within and outside the thermal boundary layer overlap, the ZHe system was not reset by pseudotachylyte emplacement. Ongoing thermochronometric and experimental work evaluates whether pseudotachylyte formed at depths where ambient temperatures were too high to record this process, temperatures in the thermal boundary layer are not as high as predicted from preliminary numerical models, or He diffusion in zircon is less sensitive than expected for short-duration, high temperatures characteristic of earthquakes.

Developments and challenges in fission-track thermochronology

FACTORS AFFECTING FISSION-TRACK COUNTS AND MEASUREMENTS IN DURANGO APATITE

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The fission track method is a geochronological tool for determining the ages of rocks and for retracing their thermal histories. It is based on counting and measuring the damage trails from uranium fission in minerals. Samples containing fission tracks must be etched in order to observe them with an optical microscope. However, the relationship between the damaged trails and the etched tracks is not well understood, as the current etch models cannot explain the variable track shapes in different apatite faces and crystallographic orientations, or their composite geometries, consisting of a channel connected to an etch pit at their intersection with the surface. We carried out step-etch experiments on prism faces of the Durango apatite (5.5 M HNO3 at 21 °C), monitoring the evolution of the shapes and the dimensions of individual horizontal fossil confined tracks. This enabled us to calculate the apatite and track etch rates and the effective etch time of each confined track, i.e., the true duration for which it has been etched after being intersected by a surface track. Step etch experiments on surface tracks and comparative track counts in transmitted and reflected light showed that even in prism faces track counts are not lossless. These results constitute the framework of a model of fission track etching in apatite based on the principles of crystal growth and dissolution. This leads to an improved understanding of the factors affecting track counts and measurements, and provides a rationale for proposing more efficient and less restrictive dating protocols.

Rates and timing of Earth system processes

Low-temperature thermochronology on the eastern margin of the Parnaíba Basin (NE Brazil) – did sea way paths exist between the Cretaceous Parnaiba and Araripe basins?

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The sedimentary basins of Northeast Brazil trace the history of the paleocontinent Gondwana. The currently separated Parnaiba and Araripe basins record equivalent Cretaceous sequences, suggesting that an epicontinental sea advanced over the northern portion of current South America connecting these basins. Ordovician-Silurian basal units of the eastern margin of the the Parnaíba Basin are uplifted to >1,000 m above sea level, forming the contemporary table relief of the Serra de Ibiapaba. The timing of this uplift and whether it played a role in connecting the Parnaíba and Araripe basins are hitherto unknown. This work aims to determine the thermal history of burial, denudation and exhumation of the eastern margin of the Parnaíba Basin through apatite (AFT) and zircon fission track (ZFT) thermochronometry. We present preliminary results on ten samples between the Parnaíba and Araripe basins. AFT central ages range from 316 to 140 Ma and mean track lengths from 11.6 to 13.5 µm. ZFT ages range from 427 to 513 Ma. Younger AFT ages seem to be linked to reactivation of continental shear zones, such as the Transbraziliano lineament, along the northeastern border of the Parnaiba basin. The southern portion of the basin does not record Meso-Cenozoic cooling ages, implying a distinct evolution of the basin margin. Additional AFT analyses are ongoing in order to provide robust models for the thermo-tectonic evolution of the area that might potentially answer the enigma of the Cretaceous Parnaíba – Araripe connection.

Rates and timing of Earth system processes

MULTI-METHOD THERMOCHRONOLOGY OF EXTENSIONAL FAULT ZONES – A CASE STUDY OF THE WAKONAI SHEAR ZONE IN THE ACTIVE GOODENOUGH ISLAND METAMORPHIC CORE COMPLEX OF EASTERN PAPUA NEW GUINEA

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The Wakonai shear zone is an extensional detachment fault that separates upper-plate oceanic lithospheric fragments from lower-plate high and ultrahigh pressure (U)HP metamorphic rocks of the Goodenough metamorphic core complex. Thermochronology (Lu-Hf garnet, U-Pb zircon, 40Ar/39Ar white mica, biotite and K-feldspar, AFT, AHe) of mylonites documents the ductile-brittle shear zone evolution. Data interpretation requires assessing the rate-limiting daughter product loss mechanisms of minerals in each case. Relict minerals (68 Ma garnet porphyroclasts) were incorporated into the shear zone via subduction erosion of the hanging wall. Zircons inherited from footwall mylonitic (U)HP gneisses yielded ,80-160 Ma U-Pb ages on cores and ,2.8 Ma metamorphic rims. Most 40Ar/39Ar ages for white micas (2.0–1.5 Ma), biotites (1.7–1.0 Ma), and K-feldspars (1.8-1.4 Ma) constrain the timing of synkinematic (re)crystallization during ductile shearing. However, K-feldspar porphyroclasts within one mylonite sample yielded an 40Ar/39Ar age gradient of ,8.0–1.0 Ma, capturing the timing of UHP metamorphism and subsequent cooling/exhumation. Post-kinematic crystallization of biotite yielded complex 40Ar/39Ar spectra with age gradients from ,1.45–0.87 Ma. Exhumation above the brittle–ductile transition is constrained by AFT (0.7–0.8 Ma), and AHe ages (0.5–0.7 Ma). This integrated data set thus records the upper and lower plate evolution, as well as the timing and duration of ductile shearing followed by brittle deformation. Exhumation continues today on seismically active normal faults.

Developments and challenges in fission-track thermochronology

THERMOCHRONOLOGICAL CONSTRAINTS ON THE THERMAL EVOLUTION OF MAGMATIC ROCKS ASSOCIATED WITH CHELOPECH AU-CU DEPOSIT, BULGARIA

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The Chelopech high-sulphidation epithermal Au-Cu deposit in Bulgaria is part of the Panagyurishte Ore District situated within the Late Cretaceous Apuseni-Banat-Timok-Sredna Gora metallogenic belt. The time of the magmatic and ore-forming events in the Chelopech area were previously well constrained by zircon U-Pb geochronology at 92.5–91 Ma.

Here we provide the results of the first apatite fission-track (FT) together with biotite and amphibole 40Ar/39Ar multiple single grain fusion analysis on the Late Cretaceous magmatic rocks associated with the Chelopech Au-Cu deposit. These rocks were sampled in aim to reveal the post-magmatic/metallogenic evolution of the area, which includes a Late Cretaceous–Paleocene (Late Alpine) compression followed by an Eocene-Miocene extension.

The obtained results reveal at least three major cooling episodes since the Late Cretaceous. The 40Ar/39Ar weighted mean ages of 92.12 ± 0.60 Ma (amphibole) and 89.17 ± 0.34 Ma (biotite) are interpreted as representing the time of cooling below ,300 °C after the emplacement of the sampled magmatic bodies. Four rock samples yield apatite FT ages between 48.6 ± 4.1 Ma and 37.7 ± 3.7 Ma. The confined mean track lengths are between 13.83 ± 1.53 μm and 14.46 ± 1.09 μm. Modelling of the apatite fission track data using HeFTy software revealed two stages of rapid cooling below ,120 °C – the first one between 52 and 45 Ma probably related to the syn- to post-Late Alpine thrusting denudation and the second one between 38 and 35 Ma triggered by the post-orogenic middle to late Eocene extension and exhumation.

Rates and timing of Earth system processes

DEFORMATION, UPLIFT AND EXHUMATION ACROSS THE NORTHERN SECTORS OF THE IRANIAN PLATEAU: INSIGHTS FROM LOW-TEMPERATURE THERMOCHRONOLOGY DATA AND INTERMONTANE BASINS FILL UNITS

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The Iranian Plateau represents a NW-SE striking, elongated, thickened, elevated and arid morphotectonic feature of the Arabia-Eurasia collision zone. The southern plateau margin includes the High Zagros Mountains and the plate suture zone, while the northern one consists of the Urumieh-Dokhtar Magmatic Zone and the western Alborz-Talesh Mountains. The plateau interior is characterized by low-topographic relief with several, mostly internally drained, intermontane sedimentary basins. The backbones of these basins include the Sanandaj-Sirjan Zone. Plateau uplift commenced after ~17 Ma as documented by Lower Miocene shallow-water marine sediments of the Qom Formation within the plateau interior. Nevertheless, the history of plateau development is poorly known.

Here we combine new low-temperature thermochronologic data (apatite fission- track and apatite (U-Th-Sm)/He), from the northern plateau and its interior with structural, stratigraphic, and available thermochronology data. This compilation shows that after a mild phase of post late Eocene contractional deformation, collisional deformation started in the early Miocene (~20 Ma) along the plate suture to the south and in the middle Miocene (~16 Ma) in the Talesh-Alborz Mountains to the north. Around 12-10 Ma, deformation jumped in the plateau interior without a specific pattern of fault propagation. Upper plate deformation occurred through the reactivation of older NE-dipping structures leding to the topographic growth of several mountain ranges spanning a wavelength of ~50-60 km, in association with plateau compartmentalization and intermontane basins development. There, basin filling processes inhibited intrabasinal deformation and faulting along the major range-bounding faults producing the smoothed, low-relief landscape typical of an orogenic plateau.

Advances in noble gas and solid state thermochronology

A MULTI-METHOD (LU-HF, U-PB, RB-SR, FT) APPROACH TO CONSTRAIN 1 BILLION YEARS OF THERMAL HISTORY (RUDALL PROVINCE, AUSTRALIA)

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The thermal evolution of metamorphic belts is often studied by phase equilibria P–T–t modelling, accompanied by petrochronology. However, thermal histories can be complex and multiple overprinting high-temperature (>,650°C) events make establishing and resolving relationships between dates and P–T events challenging.
The Rudall Province (RP) is a Palaeo- to Mesoproterozoic metamorphic belt, located between the West Australian Craton and Percival Lakes Province. Given its location between two major lithospheric blocks, the RP represents a key area for understanding the Proterozoic assembly and subsequent tectonic history of Australia. Several studies have been carried out with the aim of understanding the temporal Palaeo- to Mesoproterozoic history; however, much of its thermal history is yet to be linked to temporal data. Here, we present new in situ garnet Lu–Hf, biotite and muscovite Rb–Sr, titanite and rutile U–Pb dates, as well as apatite Lu–Hf, U–Pb and fission tracks results from RP metamorphic assemblages, aiming to reconstruct a full thermal history using a comprehensive set of high to low temperature geo- and thermochronological systems. Resulting garnet and apatite Lu–Hf dates range between c.1.72 and 1.24 Ga, whereas apatite U–Pb and muscovite Rb–Sr dates range between c.1.30 and 1.17 Ga. Biotite Rb–Sr dates of c.627 Ma reveal a subsequent resetting event and the AFT dates record an even younger thermal event occurred during the Devonian. In conclusion, our study highlights that multiple geo- and thermochronometers identify different thermal events allowing a reconstruction of nearly one billion years of thermal history.

Rates and timing of Earth system processes

APPLICATIONS OF QUANTITATIVE THERMOCHRONOLOGY AND GEOMORPHOLOGY TO DISCRIMINATE BETWEEN TRANSIENT AND STEADY-STATE TOPOGRAPHY: CASE CHICAMOCHA RIVER, EASTERN CORDILLERA OF COLOMBIA.

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In this research, we combine detrital thermochronology, quantitative geomorphology and 3D thermokinematic modelling in order to study the exhumation and topographic relief development of the Chicamocha River basin. The study area is influenced by the Bucaramanga sinistral fault in the Colombian Eastern Cordillera. Six detrital fission track ages from tributaries of the Chicamocha River were used to determine exhumation/erosion rates assuming steady-state or time-varying topography. In addition, the topography of the study area was analyzed using the Hotspot and Cluster Analysis (HCA) of Hack's stream length index (SL), which enables us to detect transient signals related to landsliding, lithologic variability, or tectonic processes. A total of 175 SL-HCA anomalies were discriminated on the western side of the Chicamocha River where gigantic landslides are present. This topographic analysis reveals knickzones where higher erosion rates are expected. This favors the hypothesis that the area has spatially variable topographic conditions over time. Finally, we compare observed and predicted cumulative detrital age distributions derived from 3D thermal-kinematic inversions assuming the two different topography conditions (steady and transient). Exhumation rates in the study area evolved from ,2 km/m.y. between ,40 and 30 Ma, decreasing to values below 0.1 km/m.y. from 30 to 25 Ma, before increasing to 0.5 km/m.y. from ,20 Ma to the present.

Rates and timing of Earth system processes

ESTIMATION OF EROSION RATE PARAMETERS FROM INVERSE MODELLING OF RIVER PROFILES AND THERMOCHRONOLOGICAL DATA

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The Earth's surface topography reflects the long-term competition between tectonic and climate-driven surface processes. River profiles, in particularly, at the scale of a catchment, can be inverted to estimate first-order uplift histories and/or lithological specific erodibilities. Geochemical data with sensitivities to different time scales, such as thermochronological ages and cosmogenic nuclide concentrations, can be combined in numerical models with river profile analyses to calibrate models and extract the uplift histories of landscapes. However, the estimation of a complete denudation record through time remains challenging, especially in landscapes where river captures and drainage reorganizations have strongly perturbated the river system.
In this study, we perform inverse modeling of river profiles and thermo- and geochronology data (i.e., low-temperature thermochronology and cosmogenic nuclides) to infer erosive parameters and the topographic history of different settings. The numerical model allows the prediction of river profiles, thermochronological ages (e.g., apatite and zircon fission track and (U-Th)/He ages), cosmogenic nuclide concentrations, and simplistic river captures. Variability in both rock uplift history and erodibility of different lithologies are accounted for. The model algorithm utilizes an efficient inverse modeling scheme "Simulation-Based Inference" to resolve unknown parameters such as uplift or erodibility of the different lithology. We present results for different main catchments of Germany where specific uplift and erodibility parameters reproduce river profiles and thermochronological data. Moreover, river capture events allow better prediction of the observed data, and therefore, parameters controlling erosion rate.

Improvements in handling and modeling low temperature thermochronological data

PECUBEGUI: A USER INTERFACE FOR PECUBE INCLUDING SAMPLE-SPECIFIC MULTI-KINETIC THERMOCHRONOMETER PREDICTIONS

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Thanks to its ability to predict spatially distributed thermochronometric data from the evolution of surface topography and/or fault-kinematic scenarios, the thermo-kinematic code, Pecube (Braun, 2003; Braun et al., 2012), has become widely used by the community over the past two decades. The diverse utility of Pecube to constrain the timing and rate of relief development, paleo-topographies, and structural-kinematic histories of major faults, as well as to guide sampling strategies, has greatly contributed to advancing the quantitative interpretation of thermochronometric data. Despite its wide use, the current version of Pecube has two main drawbacks: (1) it requires the use of line-input on a terminal; and (2) it includes only first-order diffusion models for the apatite and zircon (U-Th)/He thermochronometers as well as outdated apatite fission-track annealing models.

Here, we present the first friendly user interface for Pecube, called PecubeGUI. The interface has been developed not only to facilitate and guide users through each Pecube input parameter, but also to check model consistency and to plot and export model outcomes such as age-elevation plots, 2D maps of ages, or spatially varying depths of specific isotherms. Furthermore, PecubeGUI incorporates an updated version of Pecube that includes (1) a set of radiation-damage dependent diffusion models for apatite and zircon (U-Th)/He, (2) multi-kinetic annealing models for the apatite fission-track thermochronometer, and (3) 4He/3He thermochronometric modelling capabilities. In this presentation, we discuss the main tools the PecubeGUI interface offers, along with some tutorials on how to use it.

Rates and timing of Earth system processes

TRACING WESTERN ALPS MOUNTAIN BUILDING AND HIGH MOUNTAIN BIODIVERSITY SINCE THE EARLY-MID MIOCENE

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Mountain belts are biodiversity hotspots because of the large range of ecological habitats they offer to plant and animal species. The species richness is caused by the adaptation and diversification of species under changing climate conditions during the evolution of the mountain belt. Higher mean elevations and increased ruggedness of the terrain caused by erosion is favorable for species richness. Furthermore, mountain belts may act as formidable barriers or pathways for species migration over millions of years. As macroevolutionary processes are taking place at or above the species level also on millions of years time scales, it is of importance to study the evolution of mountain biodiversity and the long-term erosional record of mountain belts jointly.

Here we present a study on the long-term erosional evolution of the Western Alps and the development of plant species richness of sky islands flora in the alpine zone above the current tree line elevation of 2000-2200 m. As many species depend on the type of soil or lithology they grow on, the removal of calcareous sedimentary cover units and the exposure of siliceous crystalline basement rocks is important for species evolution. We used detrital geo-thermochronology on granite pebbles, sand and sandstone deposited in modern river and foreland basin environments to trace the first appearance of sediments derived from the external crystalline massifs in the foreland basin and to determine erosion rates. Together with pollen analyses and sequencing of chloroplast genomes, all this information will be coupled with landscape evolution models.

Rates and timing of Earth system processes

APATITE FISSION TRACK THERMOCHRONOLOGY AND TRACE ELEMENT ANALYSIS APPLIED TO THE PEIXE RIVER/BRASILIA BELT IN SE BRAZIL: CONSIDERATIONS ON PROVENANCE AND MINERAL FERTILITY

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Fission-track (FT) dating applied to modern river sediment (MRS) can provide important information on the provenance, fertility, and exhumation of sediment sources. Apatite, unlike zircon, commonly represents first cycle detritus. Apatite can host a wide variety of trace elements in its crystal structure, many of which (the REE, Sr, Y) are provenance diagnostic and allow the identification of sediment sources in alluvial systems, particularly when integrated with FT and U- Pb dating. The Peixe River, part of the Mogi Guaçu River Hydrographic Basin, is located in the southern Brasília Belt, northeast of the State of São Paulo, Brazil. It is about 50 km long, crossing several lithologies, mostly composed of gneissic and granitic rocks, formed from the Archean to the Neoproterozoic. This portion of the Mogi Guaçu River basin has the highest slopes, linked to a strong structural control. During fieldwork, samples were collected from both bedrock and MRS along the Peixe River, to apply apatite FT-thermochronology, U-Pb dating and trace element analysis by Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS). Through the preliminary data is possible to study the origin and exhumation of these sediments, correlate the trace elements with FT ages and indicate the fertility yield of the Peixe River sub-basin.

Improvements in handling and modeling low temperature thermochronological data

RESPONSE OF LOW-TEMPERATURE THERMOCHRONOMETERS TO MAGMATIC REHEATING: INSIGHTS FROM TAKAB METALLOGENIC DISTRICT OF NW IRAN, (ARABIA-EURASIA COLLISION ZONE)

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The challenge in interpreting low-temperature thermochronology (LTT) data in magmatic provinces is differentiating rapid cooling following transient perturbations of the geotherms (reheating) from exhumational and tectonic cooling. The Takab Range Complex (NW Iran) is a basement-cored range within the Arabia-Eurasia collision zone that experienced voluminous Eocene to Miocene magmatism and mineralization. Our new apatite and zircon (U-Th-Sm)/He (AHe and ZHe) and apatite fission-track (AFT) data, together with field observations and a re-evaluation of available geochronology data document a complex geological and thermal history that includes multiple episodes of Cenozoic exhumation. To explain the occurrence of overlapping AHe, ZHe and AFT ages that are coeval with early-middle Miocene subsidence, sediment burial, volcanism and mineralization, we designed a numerical thermal model using the TOUGH2 code (Transport Of Unsaturated Groundwater and Heat). The model broadly quantifies the thermal effect (transient heating and cooling) of a magmatic intrusion on almost impermeable (conductive) and permeable (convective) systems. Results show a significant perturbation of the geothermal field with similar maximum temperatures but different duration of heating/cooling for the two models. The resulting time-temperature paths were then imported into HeFTy to test whether the modeled thermal perturbations could reset LTT data and explain our ages. The modeled paths show that around shallow intrusions, the thermally influenced zone is wide where the AHe system is reset. AFT and ZHe ages are only reset under certain circumstances. Specifically, as rock permeability diminishes, the heating time increases and a transition from partially to fully reset AFT and ZHe ages occurs.

Developments and challenges in fission-track thermochronology

TOWARDS FULLY AUTOMATED DIGITAL FISSION-TRACK ANALYSIS THROUGH ARTIFICIAL INTELLIGENCE

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Recent attempts to develop digital fission track (FT) identification routines using artificial intelligence (AI) techniques have yielded promising results, clearly illustrating their potential to improve analytical automation. Yet, limitations in performance and applicability persist, with mean statistical recalls for relatively simple-to-analyse apatites like Durango being comparable to that of conventional segmentation algorithms1. This is likely due, in part, to being trained on relatively small datasets (40-108 grains) comprised of primarily young, rapidly cooled and low-uranium apatites (Durango) and implanted micas, with low track densities and ideal optical properties (limited spurious surface and intracrystalline features).

Here, we present a new open access machine learning algorithm for automatic detection of surface-intersecting FTs in apatite and mica trained on 5,722 image sets from 283 rock samples from around the globe. Preliminary results already outperform all previous automated counting algorithms, which we largely attribute to use of a significantly more comprehensive training set spanning a broader range of track densities, etch-pit diameters and underlying track length distributions. It also differs by operating in 3-dimensions through use of the full transmitted image stack, as well as the reflected light image, unlike all previous models which are restricted to using surface reflected and transmitted images alone.

The new AI-FT algorithm can be used in FastTracks Version 4, which now enables users to choose from a range of automated fission track identification algorithms for analysis, allowing AI-FT algorithms developed by different laboratories to be further tested using the same analytical software on the exact same datasets.

Rates and timing of Earth system processes

EXHUMATION AND TOPOGRAPHIC EVOLUTION OF THE CHIAPAS MASSIF COMPLEX (SOUTHERN MEXICO) CONSTRAINED BY THERMOCHRONOLOGIC DATA MODELING ALONG VERTICAL PROFILES.

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Thermochronometry is used to better understand the processes responsible for Cenozoic magmatism and exhumation of the Chiapas Massif Complex (CMC) that spans a diffuse triple junction between the Caribbean, North American and Cocos plates. A combination of zircon U-Pb, apatite fission tracks, (U-Th-Sm)/He and numerical modeling show contrasting histories. Exhumation started earlier in the south (,16 Ma) relative to the north (,9 Ma). Northern exhumation is related to activity on the Tonalá fault system, while to the south it may be correlated with transpressive deformation in the Sierra de Chiapas. The southern block also experienced significant topographic growth from ,5 Ma to ,1 Ma followed by intense erosion. Overall, the pattern of uplift is in agreement with the 'closing zipper' model in which a forearc sliver is progressively incorporated to the North American plate. Thermal models also support a Pleistocene decrease in topography consistent with independent paleoenvironmental and geomorphologic evidences.

Improvements in handling and modeling low temperature thermochronological data

COMBINING LOW-TEMPERATURE THERMOCHRONOLOGY WITH 3-D PROBABILISTIC KINEMATIC MODELING INCLUDING UNCERTAINTIES IN THE EASTERN ALPS

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To understand the exhumation history of the Alps and its foreland, it is important to accurately reconstruct its time-temperature evolution. This is often done employing thermokinematic models. However, one problem of many current approaches is that they rely on prescribed geometric structures at depth without considering their uncertainty.
Therefore, the aim of this work is to compare low-temperature thermochronological data with a 3-D probabilistic kinematic model. To this end, we combine 3-D kinematic forward modeling with a systematic random sampling approach to automatically generate an ensemble of kinematic models in the range of assigned uncertainties. These can later be used to obtain a 3-D probabilistic exhumation map, from which exhumation values for the sample positions of thermochronological data can be interpolated, and compared to estimates made solely from thermochronology. In a next step, the uncertainties assigned to the kinematic model can be updated with the thermochronological data, to obtain an even more robust model.
We apply this approach to the Bavarian Subalpine Molasse, which is particularly suited as a test case, as it connects the Alpine orogen with its foreland, and should shed light on the strain distributions during the latest stages of Alpine mountain building.
Preliminary results using previously published data show that the estimated exhumation from the modeling can serve as a constraint to thermochronological interpretations, leading to a reduction in uncertainty. In a next step, we will use our own (U-Th)/He measurements to obtain an integrated picture of foreland evolution and associated uncertainties over space and time.

Rates and timing of Earth system processes

RECONSTRUCTION OF THE EXHUMATION HISTORY OF THE HELVETIC NAPPES IN SW SWITZERLAND BY LOW-TEMPERATURE THERMOCHRONOMETRY, STABLE AND CLUMPED-ISOTOPES

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The study area is located between culminations of late Variscan crystalline basement to the W (Mont Blanc-Aiguilles Rouges massifs) and to the E (Aar-Gastern massifs) and constitutes an axial depression in the Helvetic nappes, which overly this basement and were previously stacked during the Alpine orogeny. Exhumation of this nappe-stack through the brittle-ductile transition involves a series of time- and temperature-dependent processes that typically also involve hydrous fluids. To constrain the time and temperature history of these processes, stable isotope data, carbonate clumped-isotope thermometry, and low-temperature thermochronology data (AFT, ZHe) were combined.

Single grain ZHe ages indicate partial to possibly complete resetting in the lower Helvetic nappes at about 17 Ma, while upper Helvetic units were only buried to temperatures and for a time period insufficient to fully reset the ZHe system. Modelled cooling curves provide absolute ages for clumped-isotope temperatures determined from different fault and vein structures. Two trends observed in the stable isotopes are interpreted to be related to hydrothermal fluids during nappe emplacement and progressive opening of a hydraulic system during the subsequent transition from ductile to brittle deformation. Results reveal a wide range of clumped-isotope temperatures associated with deformation from about 220°C in calc-mylonites to 60°C in late fault cataclasites. Temperatures recorded in the shear zones associated with major high-angle brittle-ductile structures are interpreted as minimum dynamic recrystallisation temperatures. Calcite- and matrix-supported massive cataclasites show lower temperatures with decreasing relative age, indicating progressive exhumation in accordance with the structural history established from field observations.

Rates and timing of Earth system processes

OROGENIC SCALE THERMOCHRONOLOGY AS PROXY FOR EROSION SHOWS MONSOON INTENSITY CONTROLS THE SIZE OF MOUNTAIN BELTS

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Low-T-thermochronology applied at a regional scale to mountain belts and foreland basins can serve as a proxy of orogen scale erosion and help decipher the controlling factors on mountain building. We here present a comparative study of thermochronological ages from the Andes and Himalayas, which when integrated with other data reveal that monsoon intensity-controlled erosion can explain the difference in size between the two major mountain belts on Earth. The Central Andean and Himalayan orogenic belts provide an ideal natural experiment to test the potential role of climate and erosion in controlling orogeny. Approximately equal in age and along-strike length, both orogens are forming in plate-marginal convergent tectonic settings. The Central Andes orogenic wedge is volumetrically and aerially nearly two times larger than the Himalayan orogenic wedge, despite the Himalaya having accommodated two to three times more tectonic shortening. The Himalaya exports four times more sediment owing to much greater erosion rates as signified by widespread Cenozoic metamorphic rocks and very young (<10 Ma) low-temperature thermochronologic ages. The Central Andes are thermochronologically old (mostly >20 Ma), expose no Cenozoic metamorphic rocks, and are mantled by volcanic and sedimentary rocks, attesting to shallow, slow erosion. Lag times from detrital thermochronology show that erosion rates are up to five times higher for the Himalayas than for the Andes during foreland basin deposition. We conclude that greater intensity of the Indian Monsoon relative to the South American Monsoon since Oligocene time accounts for the differences in orogen size and characteristics.

Rates and timing of Earth system processes

INVESTIGATING ISLAND ARC EXHUMATION MECHANISMS – A DETAILED LOW-TEMPERATURE THERMOCHRONOLOGIC STUDY OF ADAK AND KAGALASKA ISLANDS, ALEUTIAN ISLANDS.

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Adak and Kagalaska form part of the central Aleutian Island arc and have been extensively studied to understand magmatic processes because they expose three plutons with varied chemistry and crystallization ages. The Hidden Bay (calc-alkaline) and Finger Bay (tholeiitic) plutons on Adak were emplaced between 37-30 Ma and the Kagalaska pluton (calc-alkaline) was emplaced at ,14 Ma. Previous models relate pluton emplacement depth and chemistry, proposing that calc-alkaline magmas stalled in the upper 5 km of the crust whereas tholeiitic magmas reach shallower crustal levels. Although these plutons have been extensively characterized geochemically and using high-temperature chronometers, their low-temperature exhumation history is less well constrained. We use apatite and zircon (U-Th)/He, apatite fission track, and Al-in-hornblende geobarometry to evaluate the exhumation history of Adak and Kagalaska. We analyze six samples from the Hidden Bay pluton and four samples each from the Finger Bay and the Kagalaska plutons.
With this dataset, we aim to resolve the time-temperature history of these islands and relate potential exhumation mechanisms. We will also test whether these plutons' emplacements depths and exhumation rates vary systematically with composition. Our preliminary data suggest that the zircon and apatite helium chronometers likely record different processes. Zircon helium ages of the Hidden Bay pluton coincide with periods of magmatic lulls and arc migration at ,20-25 Ma. Apatite helium ages of the Hidden Bay, Finger Bay, and Kagalaska pluton are all ,5-6 Ma, suggesting a significant late Miocene exhumation event and a plate scale or climatic exhumation mechanism.

Rates and timing of Earth system processes

TIMING AND DRIVERS FOR CENOZOIC EXTENSION AND BASIN EVOLUTION IN THE SEVIER OROGENIC BELT OF THE WESTERN UNITED STATES FROM DETRITAL THERMOCHRONOMETRY

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The spatial and temporal distribution of surface-lowering extension provides insights into the mechanisms that drive orogenic collapse, as well as the genesis and structure of the original orogen. Sedimentary basin evolution is directly coupled to crustal deformation, and the earliest thermal records of exhumation now reside in basin strata. In the hinterland and wedge-top of the Sevier orogenic belt, western U.S., a variety of Eocene basins formed from localized post-orogenic extensional deformation. The timing, magnitude, and distribution of sedimentation are critical to understanding of the drivers for collapse. We used detrital zircon (U-Th)/(He-Pb) double dating of Paleogene terrestrial strata in western Montana and northeastern Nevada to quantify the timing and magnitude of exhumation and explore the linkages between tectonic unroofing and basin evolution across the orogen. In both settings, lacustrine deposition, increasing paleohydrologic isolation, and local volcanism coincided closely to a shift from extra-regional to more highly exhumed proximal sources. In the Deer Lodge Valley, Montana, DZHe ages show rapid cooling between 65-55 Ma and <10 Myr sediment lag times in proximal early Eocene basal strata. In the Elko Basin, Nevada, lag times progressively decrease from >100 Myr to <10 Myr starting at 44 Ma as unroofing accelerates and the basin becomes increasingly evaporative, with rapid cooling from 42-40 Ma. We attribute the migration of accelerating exhumation, expansion and ponding of sedimentary basins, and volcanism across the Eocene to record the thermal and isostatic effects of Farallon slab rollback and accompanying or subsequent removal of the lowermost mantle lithosphere.

Improvements in handling and modeling low temperature thermochronological data

THE NORTH DOBROGEA OROGEN REVISITED: LATE MIOCENE STRUCTURAL REACTIVATION ALONG THE TRANS-EUROPEAN SUTURE ZONE

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The Northern Dobrogea orogen (NDO) is the southeastern termination of the Trans-European Suture Zone, the most prominent tectonic boundary of Europe, affected by multiple superposed deformation episodes in the Paleozoic and the Mesozoic. Contrary to the widely held notion that the NDO has not experienced significant deformation since the Cenomanian, our (U-Th)/He analyses on apatites from Precambrian, Paleozoic, and Triassic basement and cover rocks indicate consistently a discrete episode of cooling/exhumation during the Late Miocene. Such episode is not chronologically and spatially coherent neither with the progressive eastward migration of the Carpathian forebulge nor with the hypothesized break-off of the Moesian slab in the Vrancea zone. Late Miocene NDO exhumation can instead be placed in a larger framework of coeval intraplate compressional deformation affecting a wide area ranging -east to west- from the Greater Caucasus to the Romanian continental shelf. We posit that the mild structural inversion of inherited structures in the study area is a distant echo of the Arabia-Eurasia hard collision, some 1,200 km away. Low-temperature thermochronological data for the Eurasian foreland north of the Bitlis- Pütürge suture zone of SE Anatolia suggest that the tectonic stresses related to the Arabian collision were transmitted efficiently over large distances, focusing preferentially at rheological discontinuities located as far as the northern shores of the Black Sea.

Rates and timing of Earth system processes

CENOZOIC EXHUMATION OF THE MCCOY BASIN AND SURROUNDING REGIONS: INSIGHTS INTO LARAMIDE FLAT SLAB SUBDUCTION

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Late Jurassic–Eocene time in the North American Cordillera was characterized by dramatic tectonic, paleogeographic, and paleoenvironmental changes including the transition from normal to flat-slab subduction. The development of the southwestern segment of the Cordillera as recorded by the McCoy basin, Maria fold-thrust belt, Mule Mountains thrust system, and the underplated Pelona-Orocopia-Rand schist during Late Cretaceous–Eocene Laramide flat slab subduction is poorly understood compared to the rest of the Cordilleran system. The elements represent natural laboratories for understanding the Late Cretaceous–Eocene tectono-thermal history of the southwestern U.S. We resolve the amount of post-depositional heating due to burial and the timing of regional cooling and exhumation of the McCoy basin and surrounding regions using zircon (U-Th)/He (ZHe) thermochronology, which allows for determination of the time-temperature history of basin strata through the ,130–190ºC temperature window. We present 86 new single-grain ZHe dates from sandstone samples collected at the base, middle, and top of the ,7 km thick McCoy Mountains Formation and basement samples from the Mule Mountains, Little Maria, and Plomosa Mountains in southern Arizona and southern California. ZHe dates suggest that by the early Cenozoic (,60–55 Ma), regional cooling and exhumation associated with tectonic processes related to flat-slab subduction were underway in the southwestern U.S. Determining the thermal history of the McCoy basin and surrounding has implications on our understanding of tectonic processes such as underplating and regional exhumation associated with the Pelona-Orocopia- Rand schist.

Developments and challenges in fission-track thermochronology

EFFICACY AND REPRODUCIBILITY OF IMAGE-BASED APATITE FISSION-TRACK TRAINING

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We report results from seven analysts for evaluating the efficacy and data reproducibility of a newly-developed digital apatite fission-track (AFT) training module using a semi-automated image- based approach. The module is based on seven well-characterised apatites (e.g. Durango, Fish Canyon and Bergell) and is designed to equip trainees with the necessary skills and knowledge for AFT age determination and length measurement. The module comprises a cloud-stored image package containing >400 grains, >500 lengths, >23,000 Dpars and supporting documentation. All analyses can be displayed as overlays over images allowing follow-up reviewing.

Analyst-produced AFT ages showed noticeable variance from sample median ages and suggest that region of interest determination and shallow track identification are important factors contributing to age dispersion, especially for lower track density samples, while grain selection cannot be overlooked. Mean track length data reproduced within ±1 sd and review of images suggests that variability is due to how track ends are defined. Dpar data is noticeably scattered, possibly due to variations in settings for manual or automated measurements. Average Dpar values measured automatically by all analysts, showed similar trends but with some variability, implying that the implementation of standardised calibration could improve reproducibility.

The image-based AFT training module enables the first-ever visual diagnosis of potential individual analytical biases down to the single grain and length level within an average of ,30 working hours on a personal device. This approach provides efficiency and flexibility for intra-lab training routines, thereby offering improved analytical rigour and transparency at a community level.

Developments and challenges in fission-track thermochronology

MCCLURE MOUNTAIN APATITE, A CONTROL MATERIAL FOR LA-ICP-MS AFT – U-PB DOUBLE DATING AND BEYOND.

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LA-ICP-MS has become increasingly popular for fission-track (FT) dating, allowing the routine combination with U-Pb dating. The latter always uses a quality control standard and the community is looking for a material that could be used for both U-Pb and FT quality control. The McClure Mountain (McCM) apatite is proposed as a candidate as it is widely used for U-Pb standardization. We present the results of LA-ICP-MS FT dating for McCM apatite, with a total of 238 grains analyzed over 13 analytical sessions using single-round spot of 30µm, square spot of 40µm and mapping approach. Apatites show a track density of 0.75- 3.5 ×106tracks/cm2, which is high enough to provide well constrained ages with a low number of counted grains, but also low enough to be easily counted. The overall central-age is 254.1±5.1 Ma (2σ) with a dispersion of 4.3% and a p(χ2) of 0.26. For all sessions, central-ages are in accordance with the overall value and U-Pb age agrees with the reference age. We therefore argue that McCM apatites can be used for double dating quality control, the analysis duration only increasing by the short time required for FT counting. Additionally, trace element concentrations were also measured and the results show that, despite some inter grain variability, the McCM apatite could also be used as quality control for elemental concentration reduction. Finally, we performed data inversion together with other low-temperature-thermochronometers (ZHe, AHe) using latest helium diffusion model. Results suggest the potential of McCM as AHe standard too.

Developments and challenges in (U-Th-Sm)/He thermochronology

ESTABLISHING A RAPID PROTON IRRADIATION PROTOCOL FOR 4HE/3HE THERMOCHRONOLOGY

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The synthesis of uniform and high concentrations of 3He within geologic materials via proton bombardment is paramount for 4He/3He thermochronology and the quantification of helium diffusion kinetics. As the number of laboratories with 4He/3He analytical capabilities grows, it is essential to expand the accessibility of proton irradiations and to improve the efficiency of irradiation-to-measurement protocols. Here, we summarize the results of recent efforts to establish a European-based facility for routine proton irradiations dedicated to 4He/3He thermochronology. To date, we have conducted four irradiation experiments at the Helmholtz Zentrum Berlin (HZB), and a single irradiation at the Paul Scherrer Institute (PSI). Internal shards of Durango apatite were irradiated in all experiments to assess the uniformity of synthesized 3He. Whereas the PSI irradiation utilized a protocol most similar to previously established methods, HZB irradiations were conducted following a newly established procedure involving in-vacuum irradiations intended to maximize the proton flux. Using newly measured 4He/3He profiles from Durango apatite irradiated at the Francis H. Burr Proton Therapy Center as an experimental control, we assessed the suitability of each HZB and PSI irradiation to produce similar Durango 4He/3He profiles with sufficient 3He concentrations. We will discuss the benefits and limitations of each irradiation protocol in terms of 3He uniformity, 3He dose, and efficiency. Furthermore, we demonstrate how HZB irradiation results can be, in part, replicated using computer simulations, which permits the use of simulations to inform how future irradiations may be modified to improve the uniformity of the 3He dose across the irradiation target.

Rates and timing of Earth system processes

THERMOCHRONOMETRIC CONSTRAINTS ON THE TECTONIC EVOLUTION OF THE CENTRAL CORDILLERA OF HISPANIOLA, DOMINICAN REPUBLIC

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The Greater Antilles island of Hispaniola lies along the Northern Caribbean Plate Boundary (NCPB) between Cuba and Puerto Rico. The tectonic evolution of the NCPB is marked by the late Eocene transition from a subduction to a transform margin, leading to transpressional deformation and uplift of the Central Cordillera. In the Late Miocene–Early Pliocene, an oceanic plateau accreted to southern Hispaniola, rejuvenating shortening and uplift in the Central Cordillera and southern ranges. However, the precise timing of these deformational episodes and the structural and exhumational response within central-southern Hispaniola remain poorly constrained. For this purpose, we performed apatite and zircon (U-Th)/He dating on rocks across central-southern Hispaniola. We integrated these analyses with digital elevation models, field data, and existing geological constraints to reconstruct the structural evolution of the Central Cordillera and southern Hispaniola. ZHe dates cluster in two groups, 53–43 Ma and 38–23 Ma, structurally offset within the central Cordillera, reflecting a pulse of exhumation and progressive deformation associated with plate reorganization. AHe dates range from 3–26 Ma and correlate with structural position, which we interpret as fully to partially reset by the late Miocene accretion event. From the distribution of these data, we constrain the structure of the mountain belts and use erosional surfaces and synorogenic strata to provide additional insights into regional deformation and exhumation patterns. In summary, ZrHe dates may provide new age control on the onset of transpression following the late Eocene plate reorganization, whereas ApHe data track exhumation resulting from late Miocene accretion.

Advances in noble gas and solid state thermochronology

AR DIFFUSION IN CLAY MINERALS FOR EARTHQUAKE THERMOCHRONOLOGY

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K-Ar dating of potassium-bearing clay minerals provides a potential chronometer for major earthquakes, through a combination of new mineral growth and resetting during frictional heating. A key ingredient in modeling this behavior is understanding the diffusion of Ar in clay minerals during frictional heating by earthquakes. These mineral systems present a number of challenges, including changes in the minerals during heating and the complex, polycrystalline nature of the samples, which make traditional laboratory diffusion experiments difficult. However, earthquakes provide a major advantage in that the heating lasts only seconds to minutes, meaning that orders-of-magnitude extrapolation of diffusivity from experimental timescales is unnecessary. We show Ar diffusion data from heating of both clay mineral standards and fault rocks to simulate the temperature and duration of major earthquakes, allowing us to model the parameters under which the K-Ar system is partially or completely reset in these minerals.

Developments and challenges in fission-track thermochronology

AFT DATING OF CLINKER ON BLACK MESA, NAVAJO NATION

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A 7-km wide circular structural feature on Black Mesa, Navajo Nation has been proposed as representing an impact structure that formed in conjunction with nearby melt breccias. Some outcrops of mostly siliciclastic Mesaverde Group rocks on Black Mesa display various post-depositional thermometamorphic textures like melt brecciation and fusion of sand grains. Apatite fission track (AFT) analysis was applied to melt breccias and nearby unmelted sandstones to determine the post-depositional thermal histories of selected outcrops. For breccia sample 1: apatite is sparse, most AFT ages ≥stratigraphic age (95%CI). Breccia 2B: apatite is sparse, 12 AFT ages ≥stratigraphic age. Breccia 4B: 25 of 78 AFT ages ≤25 Ma, pooled age <1 Ma. For unmelted sample 2A: 2 of 78 AFT ages ≤25 Ma, pooled age = stratigraphic age. Unmelted 3: 54 AFT ages ≥stratigraphic age. Unmelted 4A: 15 of 87 AFT ages ≤25 Ma with pooled age ≤24 Ma. Sparse apatite may indicate loss due to thermal decomposition.

Our <1 Ma AFT pooled age for partially melted rocks on Black Mesa supports very recent melting, probably from an underground coal fire. Our evidence therefore supports an interpretation as clinker and contradicts the impact hypothesis at these outcrops.

Fieldwork on the Navajo Nation was conducted under a permit from the Navajo Nation Minerals Department. Any person(s) wishing to conduct geologic investigations on the Navajo Nation must first apply for and receive a permit from the Navajo Nation Minerals Department, P.O. Box 1910, Window Rock, Arizona 86515, and Telephone No. +1 (928) 871-6587.

Developments and challenges in (U-Th-Sm)/He thermochronology

BADDELEYITE (U-TH)/HE THERMOCHRONOLOGY – PROGRESS ON ANALYTICAL PROTOCOLS AND HELIUM DIFFUSION CHARACTERISTICS

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Baddeleyite (ZrO_2) is an accessory mineral that commonly occurs in a wide range of terrestrial and extra-terrestrial rocks, including mafic and ultramafic rocks (e.g., gabbros, basalts), alkali rocks (syenite, carbonatite), mantle xenoliths (from kimberlites), impact related rocks (tectites) and sedimentary deposits as detrital mineral grains. Incorporating significant concentrations of U (200-1000 ppm) and low common Pb, baddeleyite is routinely used for U-Th-Pb and U-Th-disequilibrium geochronology, providing information about its crystallization history. However, the potential and limitation of this mineral for (U-Th)/He thermochronology, providing information on cooling history as opposed to crystallization history, has not yet been fully explored.

Here, we report on our development of analytical protocols for conventional (U-Th)/He dating and combined U-Pb and (U-Th)/He "double-dating" of baddeleyite, both resulting in reproducible, internally consistent and geologically viable dates. We also present results from incremental He outgassing experiments performed on baddeleyite from different geologic environments, suggesting a thermally activated volume diffusion and closure temperatures in excess of 300 °C. The diffusion experiments also revealed some complexities, likely related to phase alterations during the heating, which were further explored by employing a combination of micro- and nanoscale characterization techniques, including FIB-HAADF STEM, and EBSD. Finally, we propose a potential mineral reference material of Neogene age that can serve to monitor the accuracy of baddeleyite (U-Th)/He dating.

Developments and challenges in (U-Th-Sm)/He thermochronology

POTENTIAL APPLICATION OF TIME-OF-FLIGHT SECONDARY ION MASS SPECTROMETRY (TOF-SIMS) IN (U-TH)/HE DATING WORKFLOWS

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Distribution of parent isotopes (i.e., U, Th, ±Sm) in minerals used for (U-Th)/He dating can significantly affect the accuracy and precision of (U-Th)/He data (e.g., 1). However, currently, distribution of parent nuclides is not routinely examined in (U-Th)/He dating workflows but instead homogeneity of parent nuclides is assumed, despite the fact that commonly dated minerals, such as zircon, often show zonation in uranium and thorium. In this paper, we utilize time-of-flight secondary ion mass spectrometry (ToF-SIMS) to illustrate a novel approach to characterize isotopic variations in minerals for (U-Th)/He dating. ToF-SIMS is essentially a non-destructive, surface analysis technique that is capable of generating 2D isotopic maps with ≤50 nm lateral resolution in a relatively short time (tens of minutes per crystal). We present a new, ToF-SIMS-based method for high-spatial resolution 2D mapping of uranium and thorium in minerals. We demonstrate how this approach can be used for improved alpha ejection correction of (U-Th)/He dates ultimately resulting in more accurate and more precise (U-Th)/He data, and also benefit (U-Th)/He based thermal history models through improved parametrization of input data.

1. Meesters & Dunai, 2002: Solving the production–diffusion equation for finite diffusion domains of various shapes: Part I. Implications for low-temperature (U–Th)/He thermochronology. Chemical Geology, 186(3-4), 333-344.

Developments and challenges in (U-Th-Sm)/He thermochronology

(U-TH-SM)/HE ANALYTICAL DEVELOPMENT AT GÉOSCIENCE RENNES : CONVENTIONAL AND RAMPED HEATING ANALYSIS

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Here we describe the new helium analytical capacity built at Geoscience Rennes, France, using an inhouse extraction system based on XY platform, an infrared laser, and a pyrometer/camera system for temperature control (range 250-1200 °C). The installation allows a laser-pyrometer coupling and so multiple forms of extraction (conventional/ramped/step heating). The gas purification system is flexible and can be adapted according to the mineral (apatite, zircon, Fe-oxide...). It consists of activated carbon, titanium foam (hot/cold), 2 SEAS GP50 Getters and a cryogenic "cold head" trap with a minimum temperature of 14°K. The helium analysis itself is performed on a PrimaPlus QMG220 quadrupole, with a quantification of 4He by spiking 3He (Gautheron et al. 2021). Chemical analyses are performed using standard concentration range on a triple-quadrupole mass spectrometer. This method allows us to measure concentrations down to 1 ppm for both REE and major elements on standard-sized crystals.
The poster provides an overview of the system and its capabilities, including standard ages and REE element concentrations (DURANGO and MK-1), cryogenic trap efficiency curve and experimental results from different extracting methods (conventional, direct analysis – ramped heating, cryogenic trap concentration). We reinforce the idea of “direct analysis – ramped heating” approach as a screening method to distinguish “perfect crystals” from “perturbed crystals” (e.g., inclusions, anomalous defects), and potentially we can obtain more detail about diffusion kinetics.

Improvements in handling and modeling low temperature thermochronological data

A NEW HELIUM DIFFUSION MODEL IN APATITE: IMPLICATION FOR DATA INVERSION AND SOLUTION FOR SOME ALFT- AHE INCONSISTENCY?

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In low temperature thermochronology, reliable interpretation of (U-Th)/He data is controlled by our understanding of helium diffusion in a crystal. For apatite, two models have been developed to parameterise the evolution of diffusion kinetics in apatite in terms of accumulated radiation damage: one based on the physical phenomenon (Gautheron et al., 2009) and the other calibrated on empirical observations (Flowers et al., 2009). However, results obtained from inverse thermal history modelling with these two models can differ and be inconsistent with other low thermochronological data (e.g., apatite fission tracks). In this contribution we present a new radiation damage-based diffusion model that combines the approaches of both the Gautheron and Flowers models.

Our new model is based on the theoretical diffusion model proposed by Gerin et al. (2017) but incorporates a new calibration from the available He diffusion experiment results. The Gerin et al. model is built on a theoretical understanding of the fundamental physical processes and predicts diffusion parameters for different levels of crystal lattice damage, using quantum calculus. We recalibrated this model through an empirical law based on real crystal mesh damage calculated from available experimental data.

To test the reliability of the revised model and to compare it to the existing models, here we present results of inverse modelling to highlight the benefits of the new model. Results are assessed in terms of the impact for “deep time” (>500 Ma) thermochronology, in which accumulated radiation damage can have a significant control on the inferred thermal history models.

Developments and challenges in fission-track thermochronology

MINERAL GRAIN LOCALIZATION AND CLASSIFICATION USING DEEP NEURAL NETWORKS

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Locating apatite and zircon mineral grains on a microscope mount is often one of the first steps in a thermochronology analysis, and it is often a tedious and time-consuming process. We propose a solution for locating and classifying mineral grains for analysis using only reflected light imagery from an optical microscope analyzed with deep learning segmentation and classification models.

We use the new Segment Anything Model (SAM) from Facebook Research as the basis for this grain detection system. When presented with a low magnification reflected light image, SAM segments the pixel data into grain-like objects and background masks. The grain-like objects are filtered to eliminate non-mineral grain objects or those of exceptionally poor quality. Finally, a convolutional neural network (CNN) labels the mineral type and quality of the grain-like objects. Mineral grain classes under study include various grades of apatite and zircon, and other phases such as quartz and barite.

By dividing the detection and classification task between SAM and a standard CNN, we eliminate the need for the tedious process of manually labeling the microscope image data to train a traditional object localization model. Nevertheless, even though SAM has not been explicitly trained for grain detection, we still obtain high quality position and shape data for the identified mineral grains on the image.

Analyses of test samples from both sedimentary and igneous rocks (Moenkopi Formation and La Sal Mountain laccolith, Castle Valley, Utah) show a classification accuracy of 90% for the overall system.

Advances in noble gas and solid state thermochronology

ZIRCON RAMAN THERMOCHRONOLOGY – REVISITED

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The potential of radiation-damage-based geochronology is long known, as best exemplified by the extensive use and detailed calibration of fission-track dating. Raman spectroscopy is capable to detect the accumulation of radiation damage in zircon, recorded by the correlation of alpha damage density with the widening and shift of Raman bands. Several studies described this relation, aiming at calculating 'Raman ages', e.g. [1]. The most recent approach to quantify damage accumulation provides individual age equations and closure temperatures for different bands of the zircon spectra [2], [3].

We expand on the calibration efforts of [2] by testing zircon crystals from more than two dozen rock samples with well-constrained thermal histories defined by U-Pb and low-temperature age constraints including ZFT, AFT, AHe, and organic maturation parameters.

We recognized an influence of the excitation laser wavelength and instrumental settings on the calibration of zircon Raman thermochronology and the need for self-calibration regarding the respective procedures. Similarly to illite 'crystallinity', U-Pb, and FT methods, measurements on natural reference materials seem to be an essential part of a proper calibration of Raman thermochronometers for each laboratory. In order to achieve reproducible data, we prepare and distribute a series of zircon samples that can be used for calibration.

[1] : Nasdala et al. (2001) https://doi.org/10.1007/s004100000235
[2] : Härtel et al. (2021) https://doi.org/10.1016/j.chemgeo.2021.120351
[3] : Härtel et al. (2020) https://doi.org/10.5194/gchron-3-259-2021

Developments and challenges in fission-track thermochronology

MACHINE LEARNING-BASED AFT ANNEALING PARAMETER RMR0 FROM C-AXIS-PROJECTED REDUCED MEAN LENGTH OF PARTIALLY ANNEALED 252CF-DERIVED FTS AND LA-ICP-MS-DERIVED CHEMICAL COMPOSITION DATA

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AFT annealing parameter rmr0 relative to apatite standard B2 (Carlson et al., 1999, American Mineralogist) is re-calibrated here using a combination of natural apatite mixtures from sandstones and selected standards. The standards include well-studied DR, FC, TI, and RN-like (Ca-F-apatite end-member). A machine learning approach is used that predicts rmr0 based on independent chemical composition data from LA-ICP-MS.

The c-axis-projected, reduced mean length of partially annealed 252Cf-derived FTs is measured and converted to rmr0 for each apatite grain studied. Absolute concentrations of Na, Mg, P, S, Cl, Ca, Mn, Fe, As, Sr, Y, 14 REEs, Th, U and relative concentrations of Al, Si, Sc, Br are determined for each grain by LA-ICP-MS using DR and other apatite species as matrix-matched standards. Of primary interest to rmr0 is: absolute Cl, Mn, Fe, Sr, ΣREEs, and annealing state of natural FTs (pre-annealed or not; t-T path dependence?); of secondary interest is relative Br, absolute Y, Th, U, and Pb-corrected UPb age (t-T path dependence?); of tertiary interest is everything else including the concentrations of individual REEs.

Machine learning regression techniques fit to the data include linear regression, random forests, dense neural networks, and support vector models. We compare the validation results between these regression techniques and examine the importance of each chemical composition feature as determined by the model training. The best performing model identified so far is a random forest regressor, with a 5-fold cross validation mean absolute error of 0.057 +/- 0.004 (1σ) on rmr0.

Rates and timing of Earth system processes

THE INFLUENCE OF CONTINENTAL RIFTING ON THE EVOLUTION OF TOPOGRAPHY AND DRAINAGE NETWORKS

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In Europe, Variscan massifs with relief differences exceeding 1000 m exist, among them the Black Forest and Vosges. They were formed during the Variscan orogeny and leveled to peneplains thereafter. Continental rifting in this region led to the uplift since the late Cretaceous and to rejuvenation of the existing topography. While the influence of continental rifting on the subsidence of the Upper Rhine Graben and the flexural uplift of the rift flanks, the Black Forest and Vosges, is well understood, the time evolution and magnitude of the uplift is not fully constrained.

In this study, we investigate the influence of continental rifting on the evolution of topography and its impact on drainage networks. We calculate various landscape metrics and combine these with existing and new low temperature thermochronological data to constrain the time evolution and magnitude of uplift. The results are used to develop conceptual landscape evolution models (LEMs) describing the influence of continental rifting on topography and river systems.

Results from morphometry and LEMs indicate that uplift is highest near the rift shoulders. These areas contain the drainage networks with the highest ksn values and the largest differences in across divide χ-gradients. The developed LEMs reveal the upstream adjustment of the bimodal river networks, including steep and low-gradient rivers. These results are in contrast with the observed thermochronological ages, which are highest at the rift shoulders and become progressively younger with increasing distance. This difference raises the question of how to compare long-term and short-term landscape development.

Developments and challenges in (U-Th-Sm)/He thermochronology

ZIRCON LASER-ABLATION DEPTH-PROFILE ANALYSIS USING PROTON-INDUCED 3HE AS A VOLUME PROXY

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Laser ablation (U-Th)/He methods have emerged as potential means for both the rapid determination of He ages, in particular for detrital thermochronometry, and the determination of spatially resolved intra-grain age distributions. Despite this potential, laser ablation techniques have been underutilized in the routine application for thermal history recovery from measurements of intra-grain diffusion loss profiles. In large part, this is linked to the uncertainty in determining ablation volumes and parent nuclide zoning in zircon. We are addressing these issues through the use of proton-induced 3He as a volume proxy and simultaneous 4He measurement. Differences in 3He yield between sample and standard spots can be attributed to the ratio of ablated volumes, allowing for age calculations when the age or 4He concentration of a standard are known. The low blank of 3He (,0.00008 pcc STP) allows for a depth resolution of up to 1 µm, albeit with a volume uncertainty of ,10%. To account for variations in proton-induced 3He concentrations, we used zirconia wafers as flux monitors in direct contact with both the sample and standard. We then measured the 3He signal across the monitor using laser ablation, and normalized the measurements against the ablated volume, which we independently verified both by white light interferometry and µ-CT. Precision and accuracy of in-situ (U-Th)/He dating demonstrably depend on both the uncertainties associated with volume determinations and the age standard (46.32 ± 1.27 Ma Sri Lanka zircon megacryst). Further efforts will focus on developing widely available mineral standards for future studies.

Rates and timing of Earth system processes

DRIVERS OF EASTERN ANDEAN PLATEAU INCISION FROM INTEGRATED THERMOCHRONOLOGY AND THERMO-KINEMATIC MODELLING

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Drivers of eastern Andean Plateau incision are controversially debated. Proposed drivers include Pliocene climate change, dynamically driven surface uplift, and long-wavelength surface uplift above deep basement structures. The evaluation of each mechanism has been hampered in previous studies due to a lack of along-strike data on the timing and magnitude of exhumation, structural geometries, and kinematic history.

We present three ,190-km-long and ,200-km-apart thermochronologic bedrock sample transects and two balanced geologic cross-sections across the Andean Plateau, Eastern Cordillera, and Subandes in southern Peru. Based on (i) age-distance and age-elevation patterns of >100 new thermochronologic dates (apatite and zircon (U-Th)/He and fission-track) from plateau, interfluve, and canyon sample locations; (ii) inverse thermal history model results; and (iii) flexural and thermo-kinematic modelling, we highlight similarities and differences in thermochronometric age patterns, exhumation magnitude, structural geometries, and shortening rates between sections.

Results show that the first-order thermochronometric age pattern is a function of rocks' vertical and lateral movement over basement ramps and resulting exhumational erosion. This pattern is superimposed with a regional and synchronous incision-related exhumation signal since the Pliocene. While this incision occurred independent of structural deformation, the exhumation magnitude and difference in interfluve and canyon thermochronometric ages require the presence of a tectonic contribution to exhumation. We conclude that uplift over a basement ramp in the Eastern Cordillera and a decrease in shortening rates since ,10 Ma set the stage for climate-enhanced incision to occur in southern Peru.

Rates and timing of Earth system processes

COMBINING RAMAN SPECTROSCOPY AND U-PB DATING ON ZIRCONS TO STUDY THE EFFECT OF A POLYPHASIC INTRUSION ON HOST ROCKS: AN EXAMPLE FROM THE ADAMELLO BATHOLITH (CENTRAL ALPS)

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To assess the potential of Raman spectroscopy combined with zircon U-Pb dating in provenance studies, we analysed the impact of multiple magmatic pulses in metamorphic country rocks and older magmatic bodies of the eastern Adamello area (Central Italian Alps). Five samples were collected along a traverse across the contact between plutons of different Eo-Oligocene ages and their Variscan country rocks.
We used Raman spectroscopy to estimate zircon metamictization, and LA-ICP-MS to measure U and Th contents and U-Pb ages.
Magmatic zircon ages show a younging trend from the South (Sostino pluton, 45.14±0.51 Ma) to the North (Val di Genova pluton, 34.17±0.35 Ma). By comparing the Raman bandwidths and peak positions with α-doses, we observe that the metamict state of magmatic zircons is consistent with the calculated α-doses, suggesting a full retention of the decay-related damage in the crystal lattice. Zircon from the Paleozoic country rocks shows high crystallinity coupled with high α-doses, suggesting that the thermal aureole of the Corno Alto pluton annealed their previously accumulated radiation damage. Indeed, their metamict state is consistent with damage accumulation over a shorter time than their U-Pb age, i.e. only records the radiation damage accumulated after the Eo-Oligocene intrusions.
We conclude that Raman spectroscopy can be used to characterize the zircon metamictic state and provide an independent validation of the age of a contact-metamorphic overprint, with potential applications to detrital studies.

Advances in noble gas and solid state thermochronology

DEFORMATION ENHANCED PB DIFFUSION IN APATITE

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Two series of experiments were conducted to assess Pb mobility in deformed apatite. Durango apatite single crystals were deformed in either compression or torsion using Paterson gas-medium apparatuses. Crystals deformed in compression at 300 MPa and 900 to 1100 °C were subsequently used in 1 atm diffusion experiments with a powder Pb source. Crystals deformed in torsion were coated in a Pb powder source. One was annealed at 300MPa and 1100°C for 5 hours; a second was deformed under the same conditions to a shear strain of 50%. Results from these two series document very different behavior of Pb in apatite. The Arrhenius parameter determined from the 1 atm diffusion experiments agrees with previous work by Cherniak et al., 1991, within experimental uncertainties. There is the possibility of small amounts of Pb traveling along fast paths, but such "tails" in profiles, if present, would not be resolvable using Rutherford backscattering spectrometry.

Results from the torsion experiments document very different behavior. The annealed sample does not show any measurable Pb beyond the Pb-apatite interface. In striking contrast, the deformed sample contains Pb at length scales >> 100 µm from the interface, but only within sub-grain regions. Electron microprobe analyses coupled with electron backscatter diffraction analyses document the close correlation of higher Pb concentrations, , 2 wt% PbO, with sub-grain bands. Image analysis further supports the strong correlation between sub-grain misorientation, lattice distortion, and higher Pb concentrations. These experiments confirm that Pb can be unexpectedly mobile in conjunction with appreciable crystal-plastic deformation

Rates and timing of Earth system processes

DETRITAL THERMOCHRONOLOGIC RECORD OF THE PLIO-PLEISTOCENE EXHUMATION OF TAIWAN

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Taiwan is a young arc-continent collisional orogen that exhibits very high modern erosion rates, up to 3-5 km/Myr. Despite the available very large thermochronologic dataset, it remains unclear when erosion rates in Taiwan reached the very high modern rates and if such high erosion rates were attained at different places and times across the island.
In order to investigate when erosion started to accelerate, we apply detrital zircon fission-track (ZFT) dating on samples from two stratigraphic sections in the Plio-Pleistocene foreland of western Taiwan and we integrate our data with previous ones from other foreland sequences on both sides of the orogen. We find that everywhere in the Early Pliocene detrital ZFT ages came from rocks that were not buried deep enough within the Taiwan orogen to be reset and that the first reset ZFT ages delivered to the basin appear in the Late Pliocene. From the Late Pliocene to the Present, reset ZFT ages appear and disappear several times up-section. The lag time, which is the time passed since zircons cooled through the closure temperature until their deposition, generally becomes shorter up-section everywhere, with shorter lag times observed in the east, and longer lag times in the southwest. We will model the ZFT data using a one-dimensional approach, in order to infer when fast surface uplift and erosion must have started to deliver the first observed reset ZFT ages in the late Pliocene foreland and how fast erosion must have been to give lag times of approximately 4-5 Myr.

Developments and challenges in fission-track thermochronology

APATITE FISSION TRACK THERMOCHRONOLOGY RECORDS OF MESOZOIC COOLING HISTORY OF THE SOUTHERN MARGIN OF ORDOS BASIN, NORTH CHINA CRATON

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The southern margin of Ordos Basin is adjacent to the Qinling orogenic belt by the Cenozoic Weihe graben. Since the Mesozoic, the region experienced Mesozoic intracontinental orogeny and the Cenozoic extensional deformation. It is thus a ideal place to explore the intracontinental tectonic evolution and basin-mountain coupling process in the north China. This study focuses on the Laolongshan-Shengrenqiao fault zone in the southern margin of the Ordos Basin. The apatite fission track analysis and thermal history inversion modeling were carried out on the two walls of the fault. Combined with the field geological characteristics of the area and a large number published thermochronological data, we conclude that the southern margin of the Ordos Basin mainly experienced three cooling steps: rapid cooling at , 205-190 Ma, slow cooling at 120-40 Ma and rapid cooling since , 40 Ma, which corresponded to two stages of compression uplift in the Qinling orogenic belt from the late Triassic to early Jurassic and late Early Cretaceous to Eocene, respectively, and rapid rift of Weihe graben since Eocene.

Celebration of the research achievements of Rod Brown

RIFT FLANK LANDSCAPE EVOLUTION IN THE TRANSANTARCTIC MOUNTAINS

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The geological evolution of the Transantarctic Mountain (TAM), one of the most extended mountain chains worldwide, has been long debated, especially regarding the surface and deep-seated processes that allowed the building of this unique high-elevation rift flank. Long-term tectonic history and the multi-phase ice sheet evolution shaped the glacial landscape along the Cenozoic. The resulting uplift and landscape evolution are therefore related to both regional long-term geodynamic and local short-term surface processes.

In this contribution we show preliminary data of samples prepared for low-temperature thermochronology (apatite fission track) from Convoy Range and Dry Valleys structural domains in southern Victoria Land. Partially reset Permian sandstone from the innermost portion of the Dry Valleys records the Mesozoic thermal evolution. A heating phase occurred after the Ferrar Dolerite onset and a cooling phase follows the inception of the Ross Sea extension. On the other hand, coastal samples reveal the complex interaction between glacial erosion along the Oligo-Miocene time interval and rift flank uplift. Samples, transversally distributed respect to the coastline, help to define different exhumation patterns, highlighting the role of extensional tectonics. Furthermore, thermochronological modeling and a comparison with the existing wide database of published fission track ages distributed all along the TAM allow to relate the exhumation patterns with topographic evolution.

Looking at the entire chain evolution through different observation scales represents the starting point to validate landscape reconstruction and sedimentary source to sink systems in light of the comprehensive West Antarctic Rift System geodynamic.

Celebration of the research achievements of Rod Brown

WHAT LIES BENEATH CONTINENTAL ICE SHEETS? APPLICATION OF DETRITAL THERMOCHRONOLOGY TO REVEAL THE THERMAL AND TECTONIC HISTORY OF INTERIOR CENTRAL EAST ANTARCTICA

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Cratons and continental interiors covered by ice sheets remain frontiers in earth sciences. To constrain the thermal/exhumation histories of these hidden geologic terranes requires relying heavily on detrital thermochronology. We apply AFT thermochronology and AHe dating on glacial erratics collected from high-elevation moraines inland of the Transantarctic Mountains (TAM) to investigate the thermal and tectonic history of interior East Antarctica buried under the East Antarctic Ice Sheet. Igneous boulders were screened using U-Pb zircon dating to select anomalous older samples (ages of 1.2–2.0 Ga) and exclude samples derived from local TAM basement. Source region is defined by ice velocity trends and sub-ice morphology, indicating boulders were glacially transported from central-interior East Antarctica, including the inland flank of the enigmatic Gamburtsev Subglacial Mountains. Only boulders were analysed, so AFT thermochronology can be fully exploited, utilizing kinetic parameters (confined track-length distributions and composition proxies) allowing inverse thermal modelling. Models constrain two thermal histories, for two zircon age populations (1.2–1.5 and 1.8–2.0 Ga), derived from different geologic terranes. Thermal histories are episodic and record evidence for significant tectonic events, including rapid cooling in the Cambro-Ordovician (Pan-African convergence), Jurassic (Gondwana supercontinent rifting) and Cretaceous (continental extension). If AFT data from boulders are treated as single-grain ages and plotted as a combined PDF, then only the youngest Cretaceous cooling episode has an obvious peak. Any possible age peaks associated with earlier exhumation episodes are obscured due to long-term residence in the PAZ/PRZ and/or burial between rapid-cooling/exhumation events.

Rates and timing of Earth system processes

CONTROL OF INHERITED STRUCTURAL FABRIC ON THE DEVELOPMENT AND EXHUMATION OF PASSIVE MARGINS – INSIGHTS FROM THE ARAÇUAÍ OROGEN (BRAZIL)

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The Araçuaí Orogen, in eastern Brazil, was formed during the Neoproterozoic—Cambrian amalgamation of West Gondwana. During the Meso-Cenozoic opening of the South Atlantic Ocean, the orogen developed as basement to the passive margin of South America and was progressively covered by thick offshore sedimentary basins, particularly the Espírito Santo, Mucuri, and Cumuruxatiba basins, in which hydrocarbon systems have been exploited. Our understanding of the Araçuaí Orogen's passive margin evolution, erosion, and sediment transfer to these basins ultimately depends on constraining the onshore exhumation in response to Meso-Cenozoic events. Here, new and previously published data from apatite fission-track (AFT) analyses and inverse thermal history modelling of (Pre)Cambrian basement rocks from the Araçuaí Orogen resolve three discrete basement cooling and associated erosional exhumation episodes. The rates at which these events unfolded vary spatially and are controlled by inherited structures. The Araçuaí Orogen experienced slower denudation rates in areas closer to the São Francisco Craton, which suggests that the tectonic reactivation and related surface uplift during the Meso-Cenozoic is in first-order controlled by lithospheric rigidity. Furthermore, the structural framework of the Paramirim and Pirapora aulacogens and NE-oriented shear zones in the orogen's southeast facilitated later reactivations. From the spatial pattern of denudation/exhumation of the Araçuaí Orogen during the Meso-Cenozoic, we draw inferences on the tectonic development of the offshore basins regarding their hydrocarbon potentials.

Developments and challenges in fission-track thermochronology

SPACE AND TIME INVERSION OF THERMOCHRONOMETRIC DATA WITH TRANSDIMENSIONAL PARAMETERIZATION

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There are multiple thermal histories that can produce very similar fission track datasets and to overcome this problem two approaches can be adopted. One approach is to favour simple thermal histories within a Bayesian framework. To parameterize thermal histories, points located in time and temperature are typically used and straight lines are interpolated between these points. The reversible jump Markov Chain Monte Carlo algorithm can be used to explore different values, and numbers, of the points describing thermal histories. The second approach is to link samples in space. This means that more data can be used to constrain model parameters. Here we present a new method in which the parameter space is represented by positions in latitude, longitude and time in the past. A parameter in the model is a point in this 3D space with a specific temperature. With 4 points in this space defining a tetrahedron, temperatures at any time or position within the tetrahedron can be extracted by linearly interpolating between the 4 points. To extract a thermal history for a sample, therefore, temperature values back through time are interpolated from tetrahedra made from the points distributed in the parameter space. The positions of the points and the numbers of points are sampled using the rj-MCMC algorithm. Geothermal gradients back through time are parameterized in the same way, allowing us to link samples from different depths or elevations.

Developments and challenges in (U-Th-Sm)/He thermochronology

CRYSTALLIZATION AGE ZONATION AND ITS EFFECTS ON (U-TH)/HE SYSTEMATICS IN JUVENILE ZIRCON

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In zircon double-dating (ZDD) of volcanic products <1 Ma, U-Th-Pb crystallization ages are employed to correct (U-Th)/He cooling ages for 4He deficits (or excesses) arising from 238U-230Th disequilibria (e.g., Schmitt et al., 2006, 2010; Danišík et al., 2012, 2017). These disequilibria originate from melt composition and U-Th fractionation upon crystallization, but the decay chain re-equilibrates during protracted zircon crystallization and magma chamber storage before eruption and cooling (Farley et al., 2002). Magnitudes and spatial distributions of 238U-230Th disequilibria affecting 4He budgets are therefore distinct for each zircon crystal. Disequilibrium corrections are commonly based on individual zircon rim crystallization ages in order to preserve the crystals for subsequent (U-Th)/He analyses, so that crystallization age zonation potentially causes significant over- or undercorrection of ZDD eruption ages. As ZDD targets very young crystals, in-situ laser ablation (U-Th)/He dating is impractical. Here, two approaches to account for protracted zircon crystallization are compared. The first, population-based approach quantifies the median U-Th disequilibrium crystallization age difference between zircon rims and interiors, and reduces the disequilibrium corrections in another (U-Th)/He dated population accordingly (Friedrichs et al., 2020, 2020, 2021). The second approach, employing individual zircon crystals sectioned to half-width to directly quantify their crystallization histories, investigates the resultant maximum and minimum eruption ages calculated from end-member rim and core crystallization ages (Marsden et al., 2021). These approaches show that eruption ages vary between 2% and 15% considering zircon crystallization age zonation, and that the dispersion of individual crystal corrected (U-Th)/He ages can be significantly reduced.

Developments and challenges in (U-Th-Sm)/He thermochronology

POPULATIONS IN APATITE (U-TH-SM)/HE SYSTEMS – INSIGHTS FROM A LARGE SINGLE GRAIN AGE DATASET

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Detrital thermochronologic datasets commonly show a spread in ages. Our detrital apatite (U-Th-Sm)/He (AHe) data from a single borehole in the northern Swiss Molasse Basin show ages ranging between 4 and 30 Ma in the upper 500 m, and ages ranging between 3 and 80 Ma for grains sampled from rocks below 1300 m. This spread and depth trend are counterintuitive, and total reset of the AHe system could be expected at greater depth, which is in agreement with existing apatite fission track data for the region. Age spread has been shown to be partly related to differences in effective uranium (eU) and grain volume. For our dataset, these correlations are weak and not sufficient to explain the observed age spread. Instead, we propose that the age spread roots in mixing of different provenance populations, as different pre-depositional thermal histories have been shown to influence diffusion kinetics. We employ eU and helium concentration derived closure temperatures (Tc) to statistically distinguish grain age populations. Using this method, Tc for individual AHe populations are inferred. Additionally, thermal history modeling recognizing provenance age populations reconciles previously conflicting interpretations where estimated exhumation magnitudes for the region ranged between 700 and 2000 m. Our models suggest exhumation of about 1050 m, starting slowly at 13 Ma and accelerating at 9 Ma. This questions a 5 Ma climatic event as driver of exhumation. Instead, we suggest that a deep seated process related to mantle dynamics may be responsible.

Developments and challenges in fission-track thermochronology

COMPOSITIONAL EFFECTS ON THE ETCH RATES, EFFECTIVE ETCH TIMES AND LENGTHS OF CONFINED FISSION TRACKS IN APATITE

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The fission-track method is a well-established technique for determining the ages of rocks and retracing their thermal histories, based on the trails of lattice damage left in certain minerals by the fragments of fissioned uranium nuclei. However, fundamental questions remain concerning the relationship between the original damage trails and the etched tracks that are counted and measured with an optical microscope. Our approach is based on step-etching of apatites with different chemical compositions. From consecutive measurements of the orientation, length width and taper of individual horizontal confined tracks we calculated the apatite etch rate vR, and the track etch rate vT, the rate of length increase vL and the effective etch time tE of each track.
Our samples are the Bamble, Panasqueira, Slyudyanka and Brazil apatites with compositions corresponding to Dpar = 1.5 – 4.6 µm. Polar plots of vR are constructed by mirroring the vR-data from 0 to 90° to the c-axis about the c-axis and the a-axis perpendicular to it. Raman measurements show that the position and bandwidth of the apatite v1-band is correlated with its anion composition and Dpar. The relationship between the Raman properties, Dpars and apatite and track etch rates are explored in order to ascertain which factors affect confined track selection, and how they bias the properties of the confined track samples used for Tt-modelling and the modelling results. A clear insight into the rela-tionship between etched and unetched tracks should also enable us to propose less biased but also less restrictive experimental protocols.

Developments and challenges in (U-Th-Sm)/He thermochronology

EVALUATION OF EIGHT ZIRCON SAMPLES AS POTENTIAL REFERENCE MATERIAL FOR (U-TH)/HE THERMOCHRONOMETRY

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The zircon (U-Th)/He (ZHe) system allows the reconstruction of thermal histories in the uppermost ,10 km of crust based on a closure temperature of ,160–200°C under cooling rates of ,1–100 °C/Myr and moderate radiation damage (Reiners et al., 2004). The Fish Canyon Tuff zircon, which has been used as reference material in several studies, may display strong U-Th zoning (Dobson et al., 2008). This issue has led to recent studies for evaluating other possible zircons as reference materials (e.g., Tibari et al., 2016; Yu et al., 2020; Kirkland et al., 2020; Wu et al., 2023; Härtel et al., 2023).

Here, we report results from eight prospective ZHe thermochronology reference samples <100 Ma and with lower radiation damage, selected from established ZFT/U-Pb international age standards and potential candidates in Japan. Samples tested include Buluk Tuff pantellerite (ZFT standard ,16 Ma); Mt. Dromedary monzonite (ZFT standard ,99 Ma), and OD-3 granodiorite (U-Pb standard ,33 Ma); Japanese rhyolitic samples included TRG04-21/TRG07-21 (,3 Ma), Site-43 (, 70 Ma), WSF1 (,20 Ma) and NST (,21 Ma). ZHe dating was performed on 30 zircon grains from each sample in order to evaluate their characteristics and age dispersion. Only samples TRG04-21 and Mt. Dromedary yielded concordant ZHe dates with respect to previously reported ages (e.g., Tagami et al., 2003), while others yielded concordant and/or significantly younger ages with moderate to higher dispersion. We plan to make zircon fractions available for round-robin interlaboratory testing from TRG04-21 which shows excellent potential as ZHe reference material.

Developments and challenges in fission-track thermochronology

TERMINATION CRITERION OF STEP-ETCHING IN MONAZITE FISSION-TRACK THERMOCHRONOMETRY: TOWARD THE REALIZATION OF ETCHING OF VARIOUS MONAZITES

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The monazite fission-track method has been expected to be a powerful tool as an ultra-low temperature (<50°C) thermochronometers (e.g., Weise et al., 2009). Jones et al., (2019) proposed the optimum for the MFT etching (6 M HCl at 90 °C for 60–90 min) by using 252Cf-derived semi-tracks of the Devonian monazite (Harcourt granodiorite, Australia).
In our preliminary experiments, spontaneous tracks in the Cretaceous monazites of Japan from Kibe granite (ca. 98 Ma: Skrzypek et al., 2016) and Sagawa granite (113–105 Ma: Ishizaka et al., 1966) were successfully etched within 90–120 min as FT densities attain a plateau. However, two Quaternary monazites in Japan, namely those from Kurobegawa granite (0.8 Ma: Ito et al., 2013) and Toya ignimbrite (0.1 Ma: Niki et al., 2022) yielded few and very thin (i.e., under-etched) spontaneous tracks even after step-etching for 600 min. Our results from Raman spectrometry and EPMA analyses suggested that less-damaged monazites tend to require a longer etching time. Therefore, we here propose a termination criterion for MFT step-etching: to etch until the thinnest track width reaches approximately 1.0 ± 0.5 μm, similar to that of zircon FT step-etching (e.g., Yamada et al., 1993). This 1-μm width criterion is valid regardless of monazite characteristics, e.g., radiation damage and chemistry. We have also attempted to verify whether or not this criterion works for monazites of different ages/chemistries, and also to examine the different etchants (e.g., 12M HCl or mixed acid) under various temperature conditions for Quaternary monazites.

Developments and challenges in fission-track thermochronology

Comparing LA-ICP-MS U measurements with the EDM in fission track thermochronology: some principles and some results

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There have been recent studies comparing fission track ages ob- tained using the LA-ICP-MS (laser) method of measuring uranium with the traditional external detector method (EDM). I will highlight some statistical issues, and potential pitfalls, that arise in such studies*, and point to some useful methods, illustrating them using data from an as yet unpublished study by Ian Duddy and Paul Green**.

In that study we have found, among other things, that:

- There was good agreement between the two methods for some samples, but poor agreement for others.
- The laser method did not always produce a reliable measurement.
- The analytical standard errors produced by the laser method do not properly reflect the measurement error. They are too small, and sometimes much too small.

These results suggest that more research needs to be done on the laser method before it can be used reliably in practice.

*In statistics, they are called method comparison studies.

**Thanks to Barry Kohn and Ling Chung (Melbourne University) for providing the LA-ICP-MS measure- ments and Marylin Moore (Geotrack International) for counting the fission tracks.

Improvements in handling and modeling low temperature thermochronological data

3D SPATIAL MODELLING OF THERMOCHRONOLOGICAL DATA REVISITED

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It is generally accepted that multiple sample thermal history modelling has advantages over single sample modelling. One advantage is that any real signal present should be reinforced while random noise will tend to cancel out, giving us more confidence in any inferred cooling/heating events. Vertical profiles are an obvious example where we expect the samples to have experienced a similar form of thermal history, with lower elevation/deeper samples experiencing higher temperatures than the higher elevation/shallower samples. Some years ago, Stephenson et al. (2006) explored an approach to group spatially distributed samples, again to reinforce and improve resolution of thermal history signals contained in the data. However, two closely spaced samples may have different thermal histories if faulting or fluid activity is important and so distance between samples in not necessarily a good criterion for grouping samples. The approach proposed by Stephenson et al. (2006) involves identifying partitions, such that the samples in each partition can be treated effectively as a vertical profile with a similar thermal history. Of course, we do not know these thermal histories in advance, how to partition the samples or even how many partitions there may be. Here we revisit this approach with the modification of allowing the complexity of the thermal history in each partition to adapt to the information in the data (as in the software QTQt).

Stephenson, J., Gallagher, K. and Holmes, C. (2006), Earth Planet Sci. Letts. 241, 557-570.

Developments and challenges in (U-Th-Sm)/He thermochronology

TROPICAL CRITICAL ZONE HEMATITE AND GOETHITE (U-TH)/HE GEOCHRONOLOGY: AN ARCHIVE OF THE CHANGE OF CLIMATE, GEODYNAMIC AND BIOGEOGRAPHICAL BARRIERS

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In quiescence areas of the tropics, lateritic and bauxitic covers form through intense weathering associated with high mean annual temperature and precipitation. While soluble elements including nutriments are leached from the basement rocks during weathering, insoluble elements such as Fe and Al are accumulated forming supergene minerals. With millions of years, thick lateritic profiles form, with a kaolinite-rich saprolite covered with a ferruginous duricrust containing mostly hematite and goethite. Under more intense weathering conditions (i.e. higher temperature and/or precipitation), kaolinite is leached and gibbsite and boehmite form bauxite with an Al-rich duricrust. Consequently, laterites and bauxites are formed and preserved only in low erosion areas, and will evolve in association with the water table fluctuations and change of geodynamic, climatic and biogeographical barriers. In this contribution, we will show how the use of hematite and goethite (U-Th)/He geochronology and a knowledge of He retention in hematite and goethite, coupled with mineralogical and geochemical analysis of different laterite and bauxite samples can be related with the change of climatic and geodynamic conditions over the Cenozoic. Examples from the Guiana Shield of the South American continent allow the identification of different weathering regimes through time related to climatic changes. In addition, in Central Amazonia, laterite also reflects geodynamic changes in paleofluvial dynamics and the formation of biogeographic barriers that correspond to bird speciation since the Pliocene. Thus, supergene products constitute an increasingly studied archive that sheds light on past processes in the evolution of the critical zone of tropical areas.

Rates and timing of Earth system processes

INCREASED EROSION ALONG THE SUTLEJ RIVER, NW INDIAN HIMALAYA, AT < 1 MA REVEALED BY APATITE (U-TH)/HE THERMOCHRONOLOGY DATA

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River erosion is considered as a major driver of localized exhumation in contractional systems and may be enhanced by tectonics, climate or hydrographic changes. Published thermochronological data across the Sutlej River region (NW Indian Himalaya), the third-largest erosive system in the Himalayan range, shows high exhumation rates (>2 mm/yr) during the last 3 Myr across a > 30-km-wide river anticline. It has been suggested that this significant and recent exhumation was largely driven by climate, but exhumation history at < 1 Ma is poorly understood. To constrain the last cooling events over the last ,100°C of rocks exposed, we acquired an extensive new apatite (U-Th)/He dataset (n= 349) along the Sutlej River and its main tributaries in the river anticline region. Contrary to previous thermochronology data that evidenced a zone of rapid cooling restricted to a large knickzone, our results and inverse modeling show an accelerated cooling (from 60-100°C to present-day temperature) at < 1 Ma related to a significant exhumation episode along the river course of the entire river anticline region. Similar and coeval exhumation is observed along the tributaries downstream and can be related to the enhanced erosion along the Sutlej River, which forced tributaries to accelerate incision in order to catch up with the level of the Sutlej River. Rather than climate, the rapid and focused exhumation along the Sutlej River was probably triggered by an increase in water discharge after the capture of the northeastern Zhada basin by the Sutlej River at ,0.8 Ma.

Rates and timing of Earth system processes

TECTONIC EVOLUTION OF THE PATAGONIAN BROKEN FORELAND: A SUMMARY OF LOW-TEMPERATURE THERMOCHRONOLOGICAL DATA

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The Meso-Cenozoic upper plate shortening episodes in Patagonia (during Cretaceous–early Paleogene and Miocene) have been related to changes of plate convergence settings and slab dynamics, and led to the development of the Patagonian Broken Foreland (PBF). However, little is known about the amount of regional unroofing of the PBF, as thermochronological studies focused mainly on the growth of the Cordillera. To unravel the significance of these shortening stages and examine the relationships between denudation processes and geodynamic evolution, we acquired thermochronological data from bedrocks and sedimentary deposits. We first acquired apatite fission tracks and (U-Th)/He data from the PBF, as well as hematite (U-Th)/He data for the Deseado Massif, then integrated for data inversion. A further set of data was focused on detrital apatite double dating (fission tracks and U-Pb) to analyze sediment provenance in the foreland basin since the Cretaceous. Overall, these studies point to a significant burial of foreland structures during the Jurassic followed by a substantial exhumation of the entire PBF from the Cretaceous to early Paleogene, triggered by a complex extensional setting (Deseado Massif), then a slab flattening event and finally the onset of a slab window. Unlikely, the Miocene cooling ages only recorded by hematite (U-Th)/He data and the provenance model reveal minor exhumation of the PBF through this period. Thus, the integration of our results illustrates the exhumation history experienced by the whole Patagonian foreland over the last 200 Myrs and provides key constraints for the reconstruction of a geodynamic model.

Advances in noble gas and solid state thermochronology

RESOLVING GEOLOGICAL HISTORIES USING THE NEW FACILITIES OF K-AR DATING AND CLAY SEPARATION AT GEORESSOURCES, NANCY

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Isotopic dating is a valuable method to constrain better the timing of lithospheric processes: geodynamic sequences, ore deposition and geothermal regimes. The K-Ar dating technique has the main advantage to be applied to ubiquitous K-bearing minerals that crystallize in various temperatures, from magmatic to low temperatures.

We present the new analytical platform, recently developed at the GeoRessources laboratory in Nancy (France), for K-Ar dating purposes. The potassium and argon quantitative analysis protocol has been validated on three reference materials from 24.2 to 420 Ma that give an age deviation of a maximum 1% from the published data. The first application of the method is the magmatic and hydrothermal processes from the Panasqueira Region (Portugal) related to Li-(Sn-W) granites. The ages recently obtained on muscovites allow for constraining the deposition ages, completing the hydrothermal scheme.

Clays are of significant interest among K-bearing minerals, considering that they are formed during various hydro-thermo-dynamic processes. Reliable K-Ar ages on illite-rich fractions are based on the proper separation of the illite along with morphological, mineralogical and crystallographic information. GeoRessources is now fully equipped for clays preparation, mainly with Stokes benches and a continuous flow centrifuge. Clays particles' mineralogical, morphological, and size analyses are performed using XRD, SEM, EDS, FTIR and laser diffraction.

The K-Ar dating platform, coupled with the clay laboratory, is a new asset for GeoRessources to constrain geological events' timing better. The first application of this coupling will be shown on illite-rich fractions in the well-documented uranium deposit in the Athabasca basin, Canada.

Celebration of the research achievements of Rod Brown

TRACKING MARGINS: A TRIBUTE TO THE LIFE AND WORK OF ROD BROWN

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Over a career that was all too short, Roderick Brown made many outstanding contributions to low temperature thermochronology. His PhD studies concerned the thermal evolution of the subaerial rifted margins of southern Africa, a topic that he went on to address from many different perspectives and returned to repeatedly throughout his career. Rod thought very deeply about his science and kept seeking more comprehensive answers that had eluded him to that point. He began with apatite fission track analysis, which remained at the heart of his interests, but he also saw that processes affecting the shallow crust at sufficient scale should also have a geomorphic expression. This led him to add an increasingly wide array of complementary techniques to his repertoire, often being the first to do so and usually involving long-term collaborations with others. These included quantitative estimates of erosion rates from cosmogenic radionuclides, geodynamic and thermal history modelling, his concept of 'backstacking' eroded crust, matching of sedimentary and erosional records, and apatite (U-Th)/He thermochronology. In the last of these he made important contributions to the vexed question of over-dispersion of apatite grain ages through his perceptive studies on the effects of grain breakage. Understanding the thermal histories of rifted continental margins has been a major theme in the evolution and application of low temperature thermochronology methods and is a field continues to develop to this day. Rod was a direct participant and key contributor to many stages of this progression.

Advances in noble gas and solid state thermochronology

APATITE LASER-ABLATION LU-HF - U-PB TANDEM THERMOCHRONOLOGY: A NOVEL METHOD TO CONSTRAIN HIGH TEMPERATURE THERMAL HISTORIES

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Apatite U-Pb dating has been frequently used in the last decade to constrain cooling histories through temperatures of ,350-500°C. However, apatite has the tendency to recrystalize easily in response to strain, metamorphism, or fluid flow, which might cause ambiguity in the interpretation of apatite U-Pb dates, recording either volume diffusion (thermal process) or recrystallization (chemical/mechanical process). This distinction is particularly relevant for old terranes that record complex thermal and deformation histories. The apatite trace element composition can provide further insights but often remains inconclusive. The apatite Lu-Hf system has a higher closure temperature (,660-730°C) than U-Pb and is therefore more robust to volume diffusion. Hence, Lu-Hf dates can better constrain the timing of apatite (re)crystallization and can serve as a reference for interpreting apatite U-Pb dates. In high-temperature systems (upper-amphibolite – granulite facies), the Lu-Hf system records cooling after peak metamorphism, while U-Pb dates often record younger lower-temperature events. Traditional Lu-Hf dating involves laborious chemical separation in specialized laboratories, making it challenging for routine application. The novel laser ablation Lu-Hf dating method can accurately obtain Lu-Hf dates at high spatial resolution, directly from grain mounts or rock blocks. Combining apatite U-Pb and Lu-Hf in the same grain or even the same ablation spot (tandem approach) allows more detailed high temperature thermal history reconstructions. Adding apatite fission track thermochronology, the three methods can potentially reconstruct high to low temperature thermal histories at the single-grain level. We will present case studies illustrating the power of the combined approach to reconstruct thermal histories.

Developments and challenges in (U-Th-Sm)/He thermochronology

Interpreting LA-ICP-MS in-situ (U-Th-Sm)/He data

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Whole grains are commonly measured to determine (U-Th-Sm)/He dates, although several studies have demonstrated that in-situ measurements produce reliable data. In-situ measurements are collected from one or more ablation pits within a grain and are potentially sensitive to different factors than whole grain analyses. Many of the differences between whole, and in-situ analyses stem from variations in the stopping distances of alpha particles produced by radiogenic nuclides. This results in complex spatial relationships between the product (He) and parent nuclides (U, Th, Sm), especially in grains with radionuclide zoning. This not only impacts conventional whole-grain (U-Th)/He analyses but also leads to variable in-situ ages, whereby in-situ dates collected at the center of grain can be older than whole-grain dates.

In this study, we have adjusted state-of-the-art production-ejection-diffusion models to be applicable to in-situ data. Our approach considers the full spectrum of stopping distances and cylindrical grain geometries. With this, we investigate (i) the relationship between in-situ ages and the location of ablation spots in the grain, and (ii) strategies for reconstructing cooling histories from in-situ (U-Th)/He data. Modeling the He distribution across a grain as a function of grain size, position and size of the ablation spot, and cooling history reveals that ages are primarily a function of the ablation pit distance to the grain rim. Therefore, as with whole-grain analyses, the grain geometry and the distance of the laser spot to the nearest prismatic face must be determined. Finally, we show the conditions when several He measurements, either within multiple grains or within a single grain (but at different distances to the grain rim), can be used to accurately reconstruct colling histories.

Rates and timing of Earth system processes

MESO-CENOZOIC EVOLUTION OF THE SOUTHERN CENTRAL TIAN SHAN, BASED ON APATITE AND ZIRCON (U-TH)/HE THERMOCHRONOLOGY

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The southern Central Tian Shan, marked by high elevation, high relief, and an uplifted relict landscape and intermontane basins, provides a natural laboratory to study the tectonic far-field response to the Indian-Asian convergence, as well as the interplay of topographic growth and climatic aridification since the Late Cenozoic. Previous thermochronology studies from the highest massifs of the southern Central Tian Shan (e.g. the Khan Tengri and Pobedi massifs) reported accelerated exhumation since the Late Miocene (, 10 Ma), linked to the reactivation of inherited structures propagating to the south, towards the Tarim Basin.

Little is known about the spatial distribution, timing and rates of erosion along the main fault structures in this region. To better address this question, we study exhumation associated with the Pobedi Thrust, a major Paleozoic fault with significant inferred Late Cenozoic reactivation. New apatite and zircon (U-Th-Sm)/He samples were collected along an elevation profile from both the hanging wall and footwall of the western branch of the Pobedi Thrust to quantify the low-temperature thermal history.

In contrast to the enhanced Late Miocene exhumation recorded in the Khan Tengri and Pobedi massifs, our samples around 100 km to the west indicate dominant Mesozoic cooling and little Cenozoic exhumation, despite the high topography. Our southernmost sample provides a hint of exhumation associated with the South Tian Shan thrust, showing Late Paleogene AHe ages. Our work indicates spatially variable exhumation along the Pobedi Thrust and provides insight into the complex Cenozoic tectonic evolution of the southern Central Tian Shan.

Developments and challenges in (U-Th-Sm)/He thermochronology

INTEGRATION OF NEW DIFFUSION DATA AND AN IMPROVED FUNCTIONAL FORM FOR THE DAMAGE-DIFFUSIVITY RELATIONSHIP IN THE ZIRCON (U-TH)/HE SYSTEM

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The radiation damage and He diffusivity relationship plays an important role in zircon (U-Th)/He thermochronology. The damage-diffusivity model of Guenthner et al. (2013) has been used in numerous geologic settings to constrain detailed thermal histories from complex zircon He datasets. Since this publication, new diffusion data from unzoned, crystallographically oriented zircon specimens with well-characterized degrees of radiation damage has been collected, and several uncertainties and limitations of the Guenthner et al. (2013) model have been suggested. Specifically, the original derivation of the damage-diffusivity relationship provided a single diffusivity term that potentially obscures the independent behavior of D0 and Ea across the damage spectrum. Here, I integrate recently published (Ginster, 2018) and newly reported diffusion data (see abstract by Sigat et al.) with the previous Guenthner et al. (2013) dataset. These data agree with the overall trend of the damage-diffusivity relationship as first described in Guenthner et al. (2013). A notable difference is the observation in the newer data of an initial increase in Ea followed by a decrease with damage accumulation, whereas Guenthner et al. (2013) reported constant values for Ea at low to moderate damage, followed by a decrease. I investigate the use of a modified damage-diffusivity parameterization to account for independent changes in D0 and Ea, and to provide a framework for sampling kinetic uncertainties. A trapping term is introduced to model the initial increase in Ea with damage accumulation, and a multipath diffusion framework is used for the decrease in both D0 and Ea at high damage.

Rates and timing of Earth system processes

NO CONNECTION BETWEEN THE UPPER YANGTZE AND RED RIVERS IN THE CENOZOIC

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The Yangtze River is the largest river in Asia and its evolution has been a subject of debate for more than a century. The formation of the First Bend is widely recognized as a key drainage reorganization event that led to the birth of the modern Yangtze River. In this study, we use new detrital rutile U-Pb ages to constrain the sedimentary provenance of the Cenozoic deposits in the Jianchuan Basin. Our results show that detrital rutile U-Pb ages of the Eocene sandstones from the Jianchuan Basin are distinct to those of the Jinsha River (main stream of the upper Yangtze River), indicating that the Jinsha River is unlikely to have flowed through the Jianchuan Basin since the late Eocene. Moreover, the characteristic young zircon age signature (50-60 Ma) of the Jinsha River is also absent in the Jianchuan Basin, which is consistent with the rutile data. Our rutile data and previous detrital zircon data do not support a connection between the upper Yangtze and Red rivers via the Jianchuan Basin since the late Eocene.

Rates and timing of Earth system processes

NORTHEASTERN TIBETAN PLATEAU GROWTH AND DYNAMICS IN THE OLIGOCENE-MIOCENE: CONSTRAINTS FROM COMPREHENSIVE APATITE GEO-THERMOCHRONOLOGICAL AND GEOCHEMICAL DATA

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Spatial and temporal constraints for mountain building on the northeastern Tibetan Plateau are of great significance for understanding the geodynamics of plateau growth. Several competing hypotheses have been proposed to elaborate the mechanisms of Tibetan Plateau outward growth, including oblique subduction, mantle lithosphere removal and middle-lower crustal flow. These tectonic models predict different spatiotemporal patterns of deformation on the margin of the Tibetan Plateau. Here we integrate new apatite U-Pb, fission-track, and rare-earth element provenance indicators from the Oligocene-Miocene sedimentary sequences in two representative sections of the Xunhua Basin to reestablish a framework of drainage reorganization and topographic evolution of the Xunhua region since the Oligocene. The apatite datasets coupled with paleocurrents suggest three provenance transitions at ca. 28 Ma, ca. 20 Ma, and ca. 12 Ma, that indicate topographic growth of the West Qinling, Laji Shan, and Jishi Shan, respectively. The results integrated with published works suggest that deformation expanded northward from the southern margin of the northeastern Tibetan Plateau since the Oligocene. In contrast to Oligocene-middle Miocene growth of east-west trending ranges, the middle-late Miocene appearance of north-south trending ranges indicates a change in shortening orientations within a regional stepover on the northeastern Tibetan Plateau. This kinematic change is attributed to sinistral strike- slip along the East Kunlun, Haiyuan, and West Qinling faults in the middle-late Miocene. Thus, our findings support oblique subduction beneath the northeastern Tibetan Plateau, leading to extensive deformation in the region during outward, south to-north, stepwise growth and a plateau-wide change in kinematic style.

Advances in noble gas and solid state thermochronology

TESTING THE LABORATORY-BASED ZIRCON RAMAN CLOSURE TEMPERATURE: THE DULUTH FC1 ZIRCON

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Zircon Raman dating is an emerging thermochronological method based on the accumulation of α-radiation-damage. It uses the Raman bandwidth to quantify the lattice damage and combines it with U and Th measurements to calculate an apparent age. The method's closure temperature (Tc) has been determined from laboratory-based annealing experiments. Still, these estimates result from extrapolating the annealing kinetics over several orders of magnitude of time. There is thus a need to test them on samples with a well-defined, geological cooling histories. We dated the Duluth Complex sample FC1 using radiation-damage estimates from three Raman bands. We compare them to the sample's thermal history constrained by apatite U-Pb, zircon and apatite (U-Th)/He, and apatite fission-track data. After the emplacement of the Duluth Complex at 1099 Ma till ,1040 Ma, FC1 cooled rapidly to ,200 °C, followed by a long residence at lower temperatures. We predict that the zircon Raman system closed during rapid cooling between ,1070 and 1040 Ma. We discuss the annealing of radiation damage in zircon on a geological time scale with respect to (1) our FC1 data, (2) laboratory-based annealing models, (3) zircon Raman data from other geological settings, and (4) other thermochronometric systems.

Improvements in handling and modeling low temperature thermochronological data

SPURIOUS AGE-EU ASSOCIATIONS IN THERMOCHRONOLOGICAL DATA

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Associations between the effective uranium content (eU) and single-grain ages often occur in (U-Th)/He, fission-track and zircon Raman datasets. The meaning of these associations has been discussed for several decades. The dominant explanation is a change in He-diffusion, fission-track annealing, and α-radiation-damage annealing kinetics with increasing radiation damage, for which eU is a proxy. However, several thermochronologists have called into question that an observed age-eU association always results from a radiation-damage effect. In this contribution, we discuss spurious age-eU associations that are not due to radiation-damage. We show age-eU-correlated apatite fission-track, zircon (U-Th)/He and zircon Raman data that cannot be explained by radiation-damage. We show that scatter and systematic offset in the relationship between radioactive parents and radiogenic daughters create spurious associations in an age-eU plot. These are are difficult to distinguish from those caused by radiation damage. The daughter-parent plot is an alternative tool to qualitatively separate different causes of age-eU association. We present examples from fission-track, (U-Th)/He and zircon Raman dating that highlight the usefulness of analyzing the daughter-parent relationship for thermochronological data interpretation.

Celebration of the research achievements of Rod Brown

RECONSIDERING THE ALPHA EJECTION CORRECTION FOR APATITE FRAGMENTS: A LARGE-N EXAMPLE FROM A SIERRA NEVADA GRANITOID

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The problem of crystal fragments presents challenges as well as opportunities for apatite U-Th/He dating. A key observation made by Brown et al. (2013) was that the large dispersion of raw uncorrected fragment dates is due to the fact that these dates can be both younger and older than the whole crystal, and that fragments of the same length can yield different dates, while, conversely, fragments of different lengths can yield the same date. In some circumstances, Brown and colleagues argued using a synthetic dataset that it may be better to derive thermal history constraints using raw, uncorrected ages. Here, a new large-n dataset of fragment dates from a well-characterized granitoid sample (with >200 previously published dates) is exploited to explore the assumptions underlying the use of the alpha-ejection correction for fragmented grains in igneous samples.

Rates and timing of Earth system processes

CENOZOIC EXHUMATION HISTORY AND PATTERNS ACROSS THE HENGDUAN MOUNTAINS: INSIGHTS FROM THE COMPARISON OF MULTIPLE METHODS OF ANALYSIS OF A LARGE DATA SET

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The Hengduan Mountains on the southeastern Tibetan Plateau edge, exhibits complex tectonic and geomorphologic patterns. Low-relief high plateaus are juxtaposed with high-relief regions where the Mekong, Salween and Yangtze rivers flow in parallel and incise into steep gorges. It is important to understand the deformational response to continental collision and different models have been proposed to explain the complex geomorphology. Tectonic models can be resolved by spatio-temporal patterns of erosion rates through the analysis of compiled thermochronological data. Two analysis methods were utilized: (1) locally-clustered pseudo age-elevation profiles, converted into erosion rates with local crustal geothermal gradient estimates, and (2) a linear inversion method parameterized by a spatial correlation structure to spatially variable erosion rates and a 1-D thermal model (GLIDE: Gaussian Linear Inversion of Data to Exhumation rate). Both methods assume a 1-D, vertical heat transport, but with spatial variation in vertical motion rate. These two methods mainly differ in the dependence of spatial resolution structure on expert knowledge and correlation model, respectively. Calibrated with the modern geothermal gradient from geothermal results and evaluated in terms of temporal resolution, the erosion histories of 95 subareas were derived. Although GLIDE smooths and the pseudo profiles simplify the erosion history with low-resolution regressions, the results with these two methods show similar patterns of regional and local signals. Based on the results, we proposed a model with two Cenozoic active phases of extrusion and thrusting with transferred boundaries, likely controlled by the continuous northward indentation of the Indian plate corner.

Developments and challenges in (U-Th-Sm)/He thermochronology

DECIPHERING THE 4-D EVOLUTION ALONG AND ACROSS THE INSUBRIC LINE BY THERMOCHRONOLOGY

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The Lepontine dome, the Insubric Line and the adjacent Southern European Alps are an archetypal example of indentation tectonics. Late-stage collision led to a highly asymmetric exhumation pattern with vertical displacement across the fault line in the range of 15 (±5) km. Exploring the faulting and exhumation history of the suture between European and Adriatic plate by applying multiple thermochronometers on both sides of the fault is the main goal of this project. Thermochronological results are embedded into paleostress analyses as well as the attempt to date brittle fault structures by U-Pb means.
(U-Th)/He dating on 44 apatite and 28 zircon samples was applied to densely-spaced horizontal as well as vertical transects across and adjacent to the Insubric Line. AHe ages N of the fault line prominently cluster around 8-12 Ma, pointing towards more recent tectonic activity than previously assumed. The ZHe age pattern is more dispersed with unexpectedly old ages of around 50 Ma from 10 samples along a vertical profile spanning 2000 m just N of the Insubric Line. As these ages from highly-sheared samples are older than prominent ductile backthrusting and backfolding between ca. 35 and 30 Ma, we tentatively suggest a slow-down of He mobility due to crystal imperfections acting as He traps. In order to verify this pattern we currently (1) carry out U-Pb apatite dating on the same samples, (2) complement this profile by apatite and zircon fission track dating and (3) add data from a second parallel profile for comparison.

Rates and timing of Earth system processes

TRACKING THE IMPACT OF THE SOUTH BOHEMIAN BASEMENT SPUR ON ALPINE WEDGE EXHUMATION BY THERMOCHRONOLOGY

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Thermochronology in the Eastern Alps was mainly focused on the core of the collisional orogen, where exhumation has been most prominent. Further to the east, some FT work is concentrated along fault zones but thermochronometers with lower closure temperatures have hardly been applied to higher elements of the nappe pile. Due to the scarcity of the dataset and preferential application of FT dating uppermost crustal cooling below ca. 80 °C remains undetected.
We present new low-T thermochronological ages from the easternmost Eastern Alps. We carried out AHe dating on clastic units, i.e. Gosau Group, Rhenodanubian Flysch and Lunz Formation. Additional AFT analysis was performed on a smaller subset of these samples.
We find reset AHe and subordinately reset AFT ages, that monitor a so far un(der)appreciated phase of prominent cooling between ca. 18 to 25 Ma. For flysch sandstones both thermochronometers yield similar ages, implying an exhumation phase, which removed up to 5 km of overburden. Similar results were found for Lunz sandstone samples from the Northern Calcareous Alps.
Our new results are difficult to reconcile with large-scale geodynamic models that imply tectonic quiescence during large-scale subsidence and widespread deposition of Augenstein clastics. We discuss our findings in the light of postcollisional thrust wedge evolution and the impact of margin architecture, particularly the role of the South Bohemian basement spur. This promontory acted as a buttress for foreland-propagating thrusting, pinning deformation and intensifying antiformal stacking and thus exhumation above it.

Developments and challenges in (U-Th-Sm)/He thermochronology

(U-TH)/HE GEOCHRONOLOGY OF IRON OXIDES: A NEW METHOD TO DECIPHER PAST WEATHERING EPISODES

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Due to their long-term stability throughout the intertropical zone, laterites are archives of past climates. Hematite and goethite, which are the main components of the ferruginous duricrust that is present in most lateritic profiles, can be dated using the (U-Th)/He method and thereby allow to explore the duration, frequency and spatial extent of past weathering events.
This contribution presents an approach which couples (U-Th)/He geochronology of supergene hematite and goethite with high resolution mineralogical and geochemical methods. Our data derives from the South American Guiana shield which has been tectonically stable and in tropical latitudes since the Cretaceous- conditions favorable for the development of thick lateritic profile. Two coupled data sets from lateritic duricrusts from the northeastern and eastern Guiana shield reveal the existence of several important weathering events during the Cenozoic. Placing mineralogical and geochemical processes into a temporal framework enables us to extract paleoclimatic information from lateritic iron duricrusts. The results from the eastern part of the shield indicate the existence of three discrete weathering events during the Late Cretaceous / Early Paleocene, the Oligocene and the Middle Miocene that can be related to seasonally contrasted tropical climate. By contrast, the results from the northeastern Guiana shield are dominated by a Late Neogene weathering event which shows characteristics of more humid climatic conditions.

Rates and timing of Earth system processes

THE GROWTH OF THE MONGOL-OKHOTSK BELT IN CENTRAL MONGOLIA: INSIGHTS FROM LOW-TEMPERATURE THERMOCHRONOLOGY

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The Mongol Okhotsk Belt (MOB), formed during the closure of the Mongol-Okhotsk Ocean (MOO), extends for over 3000 km and marks the final assembly of the Permo-Triassic Central Asian Orogenic Belt. The closure of the MOO is generally accepted to have happened from west to east as the Mongolian orocline progressively formed. The styles and kinematics of deformation leading to and during the collision, however, remain largely unconstrained and obscured by the later collapse of the belt. The Buregkhangai Basin (BB) is a Triassic to early Jurassic continental basin several kilometers thick and located in the northern side of the MOB near the oroclinal hinge. It provides the most complete stratigraphic record during the closure of the MOO. Moreover, the BB is affected by a NW-verging shortening event and by a prominent NE-SW strike-slip event formed during the closure of the MOO. Eight samples from Carboniferous to Early Jurassic units including samples from the BB were collected along a ca. 140km transect within the MOB and analyzed using apatite fission track thermochronology. Cooling histories from these samples provide constraints on the timing and amount of exhumation driven by erosion and deformation during the growth of the MOB.

Developments and challenges in fission-track thermochronology

PATTERNS OF ANDEAN GROWTH IN THE ECUADORIAN ANDES

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Reconstructing the exhumation history of accretionary orogens is essential for understanding the mechanisms and rates of tectonic deformation that shape complex structures. In the frontal Andean margin of northeastern Ecuador, the Napo Uplift (NU) is associated with slip along a deep mega-thrust system. Despite evidence of exhumation since the Late Cretaceous has been found west of the NU, particularly in the Cordillera Real in Ecuador, exhumation patterns in the region remain poorly constrained.

Our study aims to evaluate spatiotemporal trends of rock uplift by employing two approaches. First, we report 8 new apatite fission track (AFT) Ages (12-173 Ma), 4 new apatite U-Pb Ages (70–185 Ma), and 9 (U-Th)/He ages from Jurassic magmatic rocks and Lower Cretaceous-Paleogene sedimentary rocks within the NU. New vitrinite reflectance data in interlayered Cretaceous mudstones document maximum temperatures lower than 80°C (Ro<0.55%), which agrees with partial thermal resetting of the AFT system.

Overlapping apatite and zircon U-Pb ages in Jurassic plutons document post-magmatic cooling and place constraints on maximum exhumation. Multi-elemental apatite geochemical data reveal that Upper Cretaceous sandstones were at least partially sourced from a coeval magmatic arc in the west. Young AFT ages along the hanging-wall block of the Abitagua block indicate out-of-sequence slip along the Ecuadorian orogenic wedge, most likely favored by the inherited structural grain. Thermo-kinematic modeling of a balanced structural cross-section that integrates the new and published thermochronological data allows estimating shortening rates.

Developments and challenges in (U-Th-Sm)/He thermochronology

A SURVEY OF INCLUSIONS AND LI CONCENTRATIONS IN MAGNETITE FOR (U-TH)/HE AND COSMOGENIC 3HE DATING

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Magnetite is highly retentive to helium and a target phase for (U-Th)/He and cosmogenic 3He exposure dating. It occurs in many geologic environments, and could, therefore, be a versatile tool for geochronology, thermochronology, and detrital studies. However, magnetite grains frequently contain mineral and fluid inclusions, which can increase 4He and 3He concentrations and lead to erroneous ages. Previous studies have shown that using microCT pre-screening to select only grains without inclusions can significantly improve the resulting data. This study evaluates the influence of lithology and geologic environments on the number of inclusions and U, Th, and Li concentrations to inform sampling strategies. >3000 magnetite grains were surveyed from a range of lithologies, including felsic to ultramafic volcanic and intrusive igneous rocks, as well as hydrothermal and detrital magnetite. Grains were characterized by type, number, and volume fraction of inclusions using microCT and this data was compared to SEM pre-screening. 3D microCT pre-screening was able to detect more inclusions than using 2D SEM, and is thus a more reliable method. Magnetite grains from (ultra-)mafic rocks contain fewer inclusions but have significantly lower U and Th concentrations than those from felsic lithologies. These data suggest that while magnetite grains in felsic rocks contain more inclusions, they also have the potential to produce more precise (U-Th)/He ages. Felsic rocks also have higher Li concentrations, making them potentially more problematic for cosmogenic 3He applications. We discuss study design and sampling strategies to optimize the selection of magnetite grains for geochronology.

Rates and timing of Earth system processes

THE LONG-LASTING EXHUMATION HISTORY OF THE ÖTZTAL-STUBAI-COMPLEX (EASTERN EUROPEAN ALPS): NEW CONSTRAINTS FROM ZIRCON (U-TH)/HE AGE-ELEVATION PROFILES AND THERMO-KINEMATIC MODELING

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The Eastern European Alps formed during two orogenic cycles, which took place in the Cretaceous and Cenozoic. In the Ötztal-Stubai-Complex, the record of the first orogeny is well preserved, because during the second orogeny the complex remained largely undeformed. We present new zircon (U-Th)/He (ZHe) ages and employ thermo-kinematic modeling to decipher the cooling and exhumation history of the central Ötztal-Stubai-Complex since the Late Cretaceous. Our ZHe ages from two elevation profiles increase over a vertical distance of 1500 m from 56±3 to 69±3 Ma (Stubaital) and from 50±2 to 71±4 Ma (Kaunertal). We use these ages and few published zircon and apatite fission track ages from our study area for inverse thermo-kinematic modeling. The age data are well reproduced with a three-phase exhumation history. A first phase with relatively fast exhumation (~250 m/Myr) during the Late Cretaceous ended at ,70 Ma. We interpret this phase to reflect the erosion of the Eoalpine mountain belt. As Late Cretaceous normal faults occur at the margins of the Ötztal-Stubai-Complex, normal faulting may have also contributed to its exhumation. Subsequently, a long period with slow exhumation (<10 m/Myr) prevailed until ,16 Ma. This slow exhumation suggests a rather low topography with little relief until the mid-Miocene, even though the second Alpine orogeny had already begun in the Eocene. Accelerated exhumation since the mid-Miocene (~230 m/Myr) is interpreted to reflect erosion of the mountain belt, due to the development of high topography in front of the Adriatic indenter and repeated glaciations during the Quaternary.

Rates and timing of Earth system processes

SPATIALLY FOCUSED EROSION IN THE HIGH HIMALAYA AND THE GEOMETRY OF THE MAIN HIMALAYAN THRUST FROM THERMOKINEMATIC MODELING OF THERMOCHRONOLOGICAL DATA

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The Himalayan mountain range is the result of the long-lasting collision between India and Eurasia. At the current stage of collision, rock exhumation in the Himalaya is largely controlled by slip along the seismically active Main Himalayan Thrust and coeval erosion. Owing to the flat-ramp geometry of the Main Himalayan Thrust, cooling and exhumation above the mid-crustal ramp are faster than above the adjacent upper-crustal flat, but the dip angle and the northward extent of the crustal ramp remain poorly known. To better constrain the geometry of the Main Himalayan Thrust, we applied low-temperature thermochronology dating in the northern High Himalaya (Gyirong region, China). The Pliocene-Quaternary cooling of the study area is constrained by apatite fission track ages and apatite and zircon (U-Th)/He ages between ~5 Ma and ~0.5 Ma, which show a marked trend of southward-younging ages. Together with published cooling ages from Nepal, the age data define a well-developed U-shaped pattern across the Main Himalayan Thrust, with ages increasing to the north and south from a minimum in the High Himalaya. A thermokinematic model, which contains a thrust fault with a flat-ramp-flat geometry, is able to explain the observed cooling pattern and indicates that the Main Himalayan Thrust ramp has a dip of 20°N, a width of 55 km, and a depth of 31 km. Farther north, at depths of about 30 to 40 km, the Main Himalayan Thrust is developed as a gently north-dipping ductile shear zone and forms a prominent reflector visible in seismic reflection data.

Rates and timing of Earth system processes

AGE-ELEVATION RELATIONSHIPS FROM CERRO MERCEDARIO (6720M) RECORD EXHUMATION OF THE LA RAMADA MASSIF, HIGH ANDES OF WESTERN ARGENTINA

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The Frontal Cordillera (FC) basement culmination is a first-order geologic feature of the southern central Andes, hosting the highest hinterland topography above the modern Pampean flat-slab segment. Yet, the timing of uplift and exhumation of the FC remains uncertain, and few efforts have been made to map range-bounding structures in detail. We conducted a multi-thermochronometric (apatite and zircon U-Th/He) study of seven samples collected along an ~4.3 km age-elevation transect from the northeast ridge of Cerro Mercedario, the eighth-highest peak in the Andes and the tallest peak in the La Ramada Massif at ~31°S. ZHe dates between 2 and 3 km asl are dispersed but approach the crystallization age of host rocks with increasing elevation. These dates are interpreted to represent partial resetting of the ZHe system either by 1) residence of the lowest samples near the zircon partial retention zone at the onset of Andean exhumation, or 2) reheating by sediment and/or thrust sheet burial from the impinging thrust belt to the west. Single grain AHe dates range from 8.53 ± 0.23 to 35.81 ± 0.37 Ma, with median dates of ~10.47 to ~17.34 Ma with increasing elevation. When integrated with geologic mapping these data are consistent with thrust driven exhumation along the Santa Cruz and Espanacito faults, two regional scale reverse faults responsible for uplift of the La Ramada massif. The latter stage of middle to late Miocene cooling and exhumation of the FC at this latitude records out-of-sequence deformation coeval with contraction in the eastward adjacent Precordillera.

Developments and challenges in (U-Th-Sm)/He thermochronology

A NEW IN-SITU (U-TH)/(HE-PB) DOUBLE DATING METHOD OF APATITE

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The in-situ double dating method of (U-Th)/(He-Pb) enables the simultaneous determination of two ages on a single apatite grain, namely U-Pb and (U-Th)/He ages. U-Pb dating is particularly useful in studying tectonic magmatism, high-grade metamorphism, and tracing provenance. (U-Th)/He thermochronology covers the temperature range of 60-90℃, and thus provides information on tectonic activity related to the middle and upper crust. Currently, popular double dating methods measure Helium first and then obtain U and Th concentrations and U-Pb ages of the matrix through LA-ICP-MS single-point analysis. However, this method has two drawbacks for detrital geochronology: 1) it cannot overcome age bias caused by uneven U content, and 2) it cannot obtain isochron ages for single-grain U-Pb systems. To address these issues, this study presents a reverse method: first determining U and Th concentrations and U-Pb age, and then measuring Helium. The workflow involves: 1) using a FEP film to prepare a mount and filtering out undesired particles under an optical microscope; 2) obtaining U and Th content and U-Pb age through LA- ICP-MS scan analysis; 3) polishing to remove laser ablation pits (~3-5μm); 4) selecting a region with even U content and analyzing Helium using ResoChron; 5) measuring the volume of the Helium ablation pit using a confocal microscope; and 6) reducing data and calculating ages. This method performed well on Durango, MRC, and MAD apatites.

Advances in noble gas and solid state thermochronology

SIMULTANEOUS U-PB AND U-TH ZIRCON DATING APPROACH BY LA-ICP-MS FOR QUATERNARY GEOCHRONOLOGY

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U-Pb and U-Th dating methods using zircon have contributed greatly to reveal Earth's history. Zircon U-Pb dating has a wide datable range of 4.5 Ga to 0.1 Ma, whereas zircon U-Th dating has a narrow datable range of < 0.4 Ma because it relies on disequilibrium of 230Th with ~75 ka decay constant. In terms of Quaternary dating, it should be a great advantage if both U-Pb and U-Th dating results are acquired simultaneously, because they can be cross-checked internally similar with the U-Pb method which can be cross-checked internally by 238U-206Pb and 235U-207Pb dates.

To this end, Ito (2014) analyzed the ,0.1 Ma Toya Tephra, Hokkaido, Japan, and demonstrated that simultaneous U-Pb and U-Th dating is possible using LA-ICP-MS, which seemed to have paved a way to date Quaternary igneous rocks whereby ages can be cross-checked in a quick and cost-effective manner. However, Guillong et al. (2015) showed that Ito's (2014) approach lacks rigourous treatments on U-Th data, namely, lack of evaluation of 1) abundance sensitivity on 230Th and 2) molecular interferences on 230Th.

In this study, 1) and 2) were evaluated using monazite from Toya and synthetic zircon free of U and Th, respectively. As a result, the effect of 2) was found negligible. The effect of 1) was evaluated using various correction factors. After the correction, zircons from Toya Tephra showed ~0.1 Ma by both U-Pb and U-Th methods. Concludingly, it was reassured that simultaneous U-Pb and U-Th dating is possible and viable.

Developments and challenges in (U-Th-Sm)/He thermochronology

INVESTIGATION OF LIGHTNING EFFECT ON (U-TH)/HE SYSTEMTICS BY ARTIFICIAL LIGHTNING STRIKE EXPERIMENT

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Lightning can cause extreme pressure-temperature metamorphism of rocks, resulting in formation of fulgurite. We hypothesise that low-temperature thermochronology methods, such as apatite or zircon (U-Th)/He, can be potentially useful in constraining the age of fulgurites with implications for past lightning activity and other weather phenomena. However, to our knowledge no assessments have been performed as to whether lightning may affect (U-Th)/He thermochronometry or not. Here we report on the results of artificial lightning experiments employing Fish Canyon Tuff (FCT). A FCT rock slab was directly hit by lightning induced by a high voltage lod (impulse generator) from ~4 m distance. Although the power (or energy) of the released artificial lightning was not measured, we assume that it was approximately one tenth of natural lightning or less. The FCT slab was hit 10 times in the same condition during one hour experiment. Apatite grains from the lightning-hit FCT revealed a weighted mean (U-Th)/He age of ~18.5 Ma, which was apparently younger than apatite (U-Th)/He ages from the intact FCT. The lightning-hit FCT zircon yielded (U- Th)/He ages that are indistinguishable from (U-Th)/He ages of the intact FCT zircon, indicating that no significant Helium diffusion occurred in zircon. From this experiment, we assume that lightning can induce rejuvenation of (U-Th)/He system in apatite, and therefore a certain care for lightning is necessary for apatite (U-Th)/He thermochronometry.

Developments and challenges in fission-track thermochronology

CONFINED FISSION TRACK DETECTION USING FEMTOSECOND LASER ABLATION PITS: A TRIAL AND ERROR

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Confined fission track (CFT) length analysis is the most basic and important tool in fission-track (FT) thermochronology. However, young and/or low-uranium-content samples have very few host pits (or surface-tracks) for CFT detection. As a result, thousands of grains must be prepared to find only ten CFTs. Among FT researchers, they require artificial processes to make host pits on the mineral surfaces using heavy-ion or californium-252 irradiations. This method is useful and practical, but its use has been restricted due to a limited number of facilities. Recently, laser ablation systems coupled to ICP mass spectrometry (LA-ICP-MS) has been increasingly utilized for the evaluation of uranium content in FT analysis. With this widespread laser equipment, we would like to suggest that laser ablation pit (LAP) may be effective in detecting CFTs. Femtosecond laser combined with Galvanometric optics enable to perform high-repetition ablation and high-speed scanning for cm-order wide area. Using femtosecond laser ablation pits (fsLAP), the authors carry out the following three experiments: 1) to establish conditions free from the thermal effects of laser ablation on FT annealing in apatite; 2) to compare CFT detection efficiencies with and without fsLAP using the Durango apatite; 3) to develop new lasers with 2-micrometer diameter or smaller. Experiments on 1) and 2) are ongoing and preliminary tests have shown good results.

Advances in noble gas and solid state thermochronology

SIMULTANEOUS DETERMINATION OF ZIRCON U−TH DISEQUILIBRIUM AND FISSION-TRACK AGES FOR VOLCANIC TEPHRAS YOUNGER THAN 100,000 YEARS USING LASER ABLATION−ICP MASS SPECTROMETRY (LA-ICP-MS)

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The period of 50,000 to 100,000 years ago is a chronological gap due to the limited applicable age range between the upper limit of the carbon-14 and the lower limit of other radiometric dating methods (e.g., zircon U-Pb and sanidine Ar/Ar). This issue is an obstacle to Quaternary research, especially on volcanology. The key to this problem is the 238U−230Th disequilibrium dating (hereafter U-Th) method, which utilizes the intermediate product of the uranium series, thorium-230 (half-life 75,000 years). The method is applicable to uranium bearing minerals such as zircon, apatite, ilmenite, and monazite, and the practical dating range is several thousand to 350,000 years. The authors aim to develop the zircon U−Th disequilibrium and fission-track (FT) double dating method using LA-ICP-MS for simultaneous determinations on a crystallization age in magma and a cooling age close to volcanic eruption. We will show results of the following three experiments: (1) U-concentration measurement under the LA-ICP-MS conditions used for U−Th dating developed by Niki et al. (2022), comparing with the conventional method using thermal neutron induced tracks, (2) FT dating of reference zircons older than 350,000 years ago including Fish Canyon Tuff (28.4 Ma), Baba Tuff (12 Ma), and Bishop Tuff (0.767 Ma) based on the U concentrations determined in (1), and (3) U−Th/FT double dating of zircons from Sambe Kisuki pumice (100 ka) and younger Sambe tephras in Japan (40-60 ka).

[1] Niki S., Kosugi S., Iwano H., Danhara T. and Hirata T. (2022) Geostandards and Geoanalytical Research. doi: 10.1111/ggr.12458

Rates and timing of Earth system processes

LOW TEMPERATURE THERMOCHRONOLOGY OF THE MIDLAND VALLEY OF SCOTLAND: INSIGHTS INTO ITS CENOZOIC THERMAL EVOLUTION

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The Midland Valley (MV) of Scotland is a NE-SW oriented sedimentary basin comprised of Ordovician and Silurian inliers, Devonian sandstones, Carboniferous sandstones, mudstones, limestone, shale coal measures, and igneous rocks. It is delimited by the Highland Boundary Fault in the north and the Southern Boundary Fault in the south and has been an important resource of hydrocarbons and minerals. It remains an area of interest due to its potential for unconventional gas resources, geothermal energy, and potential for subsurface energy storage. However, the post-Carboniferous burial and exhumation history of the MV basin, and the geological processes driving this evolution, are not fully understood.

Here, we present the first (U-Th)/He (AHe) data from the MV alongside apatite fission-track (AFT) data to constrain the thermal history of the basin. AFT ages from five boreholes across the MV, from Leven in the east to Glasgow in the west, are younger than the stratigraphic age, ranging from 186.1 ± 9.3 to 84.9 ± 5.4 Ma. The new AHe ages are typically Late Cretaceous to Neogene, significantly younger than the associated AFT ages. We use QTQt to jointly invert the data, infer the post-depositional thermal history of the basin, and explore the influence of geothermal gradient changes through time.

The new data and models will better constrain when and how much sediment has been deposited and then removed from the MV since the Carboniferous and the extent to which the North Atlantic plume influenced the uplift history and thermal structure of the basin in the early Cenozoic.

Advances in noble gas and solid state thermochronology

ASSESSING MECHANISMS OF ARGON ISOTOPE REDISTRIBUTION IN MUSCOVITE: PRELIMINARY RESULTS FROM THE BLACK HILLS, SOUTH DAKOTA

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Several key assumptions form the basis of extracting continuous thermal history information from the Ar isotopic compositions of minerals. Recent in-situ 40Ar/39Ar and geochemical analyses have shown that argon distributions are frequently a consequence of fluid-associated retrograde reactions, even in gem-quality mica (Naumenko-Dèzes et al., 2021). Mica can retain 40Ar/39Ar crystallisation ages at temperatures above 500°C (Airaghi et al., 2018), despite predicted closure temperatures. However, retrograde re-equilibration often occurs, rendering mica useful for hygrochronometry (Villa, 2016). We test the hypothesis that diffusion profiles in white mica can remain over geological timescales, despite the effects of partial retrograde re-equilibration.
A Mesoproterozoic metasedimentary sequence is intruded by a granitic core in the Black Hills. The metasedimentary rocks yield white mica 40Ar/39Ar total-fusion dates that increase with distance from the granite, span several 100 Ma and have been interpreted to record cooling (Dahl & Foland 2008). However, the role of fluid interaction on the Ar isotopic compositions has not been thoroughly assessed. To test the hypothesis, we have re-sampled the meta-sedimentary units and the Harney Peak Granite. White micas are initially classified using optical light petrology and QEMSCAN, before detailed characterisation using EPMA, EBSD, TEM, SIMS - δ18O and in-situ Rb-Sr dating to add a petrographic and temporal context for the in-situ Ar isotopic data. In-situ Ar isotope analyses will be compared to Ar isotopic data acquired using furnace step-heating to assess the causes of inflexions in Arrhenius trajectories. By studying a range of textures to provide recommendations for interpreting 40Ar/39Ar mica ages.

Developments and challenges in fission-track thermochronology

AN EMPIRICAL CALIBRATION OF THE MONAZITE FISSION-TRACK PARTIAL ANNEALING ZONE FROM THE RAY MINE BOREHOLE, ARIZONA, USA

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Monazite fission-track (MFT) presents itself as a new, ultra-low temperature thermochronometer. Oven-based laboratory studies have constrained the monazite partial annealing zone (MPAZ) to ≤ 25-50 °C, giving MFT the potential to be among the lowest temperature thermochronometers presently available. Recent work standardising the etching protocol and obtaining 238U concentrations via laser ablation inductively coupled plasma mass spectrometry or electron microprobe have enabled relatively routine MFT dating. However, fission-track dating of both monazite U-Th-Pb standards and unknown samples have revealed consistently young central ages (typically < 8 Ma), dispersed single-grain ages (failing the χ2 test), and broad confined-length distributions (means of 10.6 μm). In other FT systems such as apatite and zircon, data with these results are indicative of prolonged residence in the partial annealing zone or the presence of a mixed age. Thus, there remains considerable uncertainty and speculation on the specific controls of fission-track annealing within monazite. Paleo-surface temperature, geochemistry, and exhumation rate are all suggested as exerting an influence on annealing. As a result, we require additional constraints and calibration of the MPAZ in order to reasonably interpret a MFT age. To address this, we present MFT central ages, major and trace element geochemistry, and confined-length distributions from 6 samples collected from a 1.2 km borehole through schist and two-mica granite from the Ray porphyry copper system in southern Arizona, USA. In combination with traditional low-temperature systems such as apatite fission-track, we place empirical constraints on the MPAZ to better calibrate the MFT system.

Rates and timing of Earth system processes

SEDIMENT TRANSPORT DURING GLACIER RETREAT: APATITE DOUBLE-DATING AND CHEMISTRY PROVENANCE

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Analytical advances in the dating of apatite have helped to improve its utility as a provenance tool. The advent of LA-ICP-MS techniques now allows thermochronometric, geochronometric, and chemical data to be collected in a single session. As such, we are able to comprehensively trace sediment across a catchment based on lithology, style of metamorphism, and source elevation. This allows apatite to be used as a provenance tool in complex glacial catchments and may help improve our understanding of changes in erosion and sediment transport regimes during glacier retreat. In this work, we collected samples across the Bugaboo Glacier catchment in western Canada, where ice has retreated>2 km in the last century. Detrital samples were collected from the outwash river and two till samples, coupled with a bedrock elevation profile. These bedrock samples encompass the catchment's two principal lithologies, a Cretaceous granitic intrusion, and Neoproterozoic metasediments, as well as the contact aureole surrounding the intrusion. Central ages from the elevation profile range from 41.4 Ma at the highest point to 23.9 Ma at the lowest, while single grain U-Pb dates range from 68.7-151.3 Ma in granites to 90.5-1952 Ma in metasediments. Supplementary REE data also highlight key differences between the lithologies and apatites sourced from the contact aureole. Detrital mixture models and multi-dimensional scaling suggest the till samples are composed of sediment derived from different elevations within the catchment, while the sediments of the modern outwash river appear to be derived from erosion of these tills, left exposed by retreating ice.

Improvements in handling and modeling low temperature thermochronological data

SOLVING CRUSTAL HEAT TRANSPORT FOR THERMOCHRONOLOGY USING PHYSICS-INFORMED NEURAL NETWORKS

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I present a deep learning approach based on the physics-informed neural networks (PINNs) for solving thermal evolution of the crust during tectonic uplift with a changing landscape. The approach approximates the temperature field of the crust with deep neural networks, which are trained by optimizing the heat advection-diffusion equation under boundary conditions such as initial or final thermal structure, topographic history, and surface and basal temperatures. From the trained neural networks of temperature field and the prescribed velocity field, one can predict the temperature history of a given rock particle that can be used to compute the cooling ages of thermochronology. For the inverse problem, the forward model can be combined with a global optimization algorithm that minimizes the misfits between predicted and observed thermochronological data, in order to constrain unknown parameters in the uplift history or boundary conditions. I demonstrate the approach with solutions of one- and three-dimensional forward and inverse models of the crustal thermal evolution, which are consistent with results of the finite-element method. The 3D model simulates the post-orogenic topographic decay of the Dabie Shan, China, with constraints from fission-track and (U-Th)/He ages.

Developments and challenges in fission-track thermochronology

TOPOGRAPHIC GROWTH OF THE NORTHEASTERN TIBETAN PLATEAU SINCE THE EARLY MIOCENE–LATE MIOCENE CONSTRAINED BY FISSION TRACK/U-PB DOUBLE DATING AND TRACE ELEMENTS ANALYSIS ON DETRITAL APATITE GRAINS

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The proto-Tibetan Plateau formed during the Early Cenozoic as a result of the collision of the India Plate and Eurasian Plate, after which deformation migrated outwards from the central Tibetan Plateau to the southern and northern margins. This paper aims to illustrate the related uplift and exhumation processes through double-dating techniques (fission-track and U-Pb ages) and trace element analysis on detrital apatite grains collected from modern rivers and Late Oligocene–Pliocene sedimentary successions from the northeastern Tibetan Plateau. The rapid exhumation of the northeastern Tibetan Plateau primarily occurred in the Late Miocene. However, our results show that during the Late Oligocene–Early Miocene and Pliocene, a major source for the sedimentary successions was the north and central Qilian Orogenic Belt. In contrast, during the Early Miocene–Late Miocene, sediments were transported from the southwestern Haiyuan Fault zone through the Yellow River drainage. The results demonstrate that the sediments from the Yellow River and the sampled sedimentary sections were derived from a mix of sources including highlands in the northeastern Tibetan Plateau and localized regions, which imply that the progressive eastward migration of the Tibetan Plateau occurred during the Early Miocene–Late Miocene.

Rates and timing of Earth system processes

CENOZOIC TECTONIC DEVELOPMENT IN THE NORTHEASTERN TIBETAN PLATEAU: EVIDENCE FROM THERMOCHRONOLOGICAL AND SEDIMENTOLOGICAL RECORDS

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The northeastern Tibetan Plateau occupies the northernmost portion of the plateau, whose timing and pattern of deformation during its Cenozoic tectonic development provide constraints on the kinematics and dynamics of plateau formation and Asian climate evolution. Our knowledge of the tectonic growth in the northeastern Tibetan Plateau has progressed immensely over the past decades, particularly the last decade, and thus calls for a review on the tectonic history recorded by mountain building and adjacent basin deposition. The Paleogene crustal shortening, if occurred, may have been confined to the Qaidam Shan and West Qinling. We highlight that more investigations are needed to verify the reliability and areal extent of the Paleogene crustal shortening in the northeastern Tibetan Plateau. Furthermore, more recent studies suggest that the middle-Miocene deformation is widely distributed across the Qilian Shan. Based on a synthesis of studies on deformation timing and pattern in the Qilian Shan and its adjacent foreland basins, such as the Hexi Corridor and northern Qaidam Basin, we indicate that the Qilian Shan underwent a phase of approximately synchronous deformation during the middle Miocene. Since then, the crustal deformation has progressively propagated outward, including northward into the Hexi Corridor and Gobi-Alxa Block, southward into the northern Qaidam Basin, and eastward along the left-lateral strike-slip Qilian- Haiyuan fault. The synchronous middle-Miocene deformation across the Qilian Shan could be a consequence of progressive northward growth of the plateau or a far-field effect of mantle lithosphere removal that occurred in the southern or middle portion of the plateau.

Rates and timing of Earth system processes

TIMING, RATES, AND SPATIAL DISTRIBUTION OF EXHUMATION ALONG THE NEWFOUNDLAND MARGIN

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Tectonic models for the magma-poor Newfoundland margin predict discrete phases of lithospheric extension during the Mesozoic breakup of Pangea and opening of the Atlantic Ocean. The stepwise progression of these extensional phases resulted in margin-parallel architectural domains that were generated by lithospheric stretching, hyperextension and mantle exhumation, and breakup. Correspondingly, extensional deformation is predicted to progressively shift oceanward during rift-margin development. This study investigates the timing, rates, and spatial distribution of Mesozoic exhumation across the Newfoundland margin to evaluate magma-poor rift tectonic models. New zircon and apatite fission-track and (U-Th)/He (ZFT, AFT, ZHe, and AHe) analyses on bedrock samples from onshore Newfoundland were integrated with published detrital ZFT and U- Pb results from the offshore Jeanne d'Arc basin (Grand Banks). Inverse thermal modelling results for onshore bedrock samples show accelerated, late Permian to Jurassic cooling that corroborate the timing of lithospheric stretching phases and require Mesozoic brittle deformation in Newfoundland. The highest rates of exhumation are observed along a mid-Paleozoic suture and suggests that inherited structures accommodated some Mesozoic extension. Onshore rocks yield slow cooling rates during the Early Cretaceous and indicate that deformation propagated oceanward during the onset of hyperextension and mantle exhumation. Early Cretaceous ZFT cooling populations from offshore Lower Cretaceous syn-rift strata confirm that rift-related exhumation continued in the Grand Banks region. Extensional deformation generally propagated oceanward as predicted by rift margin development models, but the distribution was complicated by inherited structures and more widespread than anticipated.

Developments and challenges in fission-track thermochronology

A VIRTUAL KTB (KONTINENTALE TIEFBOHRUNG): PROGRESS REPORT

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The deep continental borehole on the western margin of the Bohemian Massif is one of the foremost natural laboratories for investigating geochronological techniques. We contended that the geological evidence and low-temperature chronometers are consistent with exhumation at the end of the Cretaceous and near-isothermal holding since. Our apatite fission-track age and confined-track length profiles are however not in good agreement with model predictions. This is in part due to a non-standard etching protocol, which underestimated the mean track lengths. In addition, although different models make different predictions, there appears to exist a desperate opposition to isothermal holding. A string of crypto-tectonic, crypto-volcanic and crypto-palaeotemperature factors have been fielded against isothermal holding, without evidence (references withheld). We aim to resolve this confusion by improving statistics and reducing experimental factors and operator biases. Using deep ion irradiation and longer etch times multiplies the number of confined tracks. We take microscope images of each grain and each track, and measure its orientation, length, width and cone angle. We aim to put these images and measurements on a server so as to create a virtual borehole, which can be investigated by other scientists using their own selection criteria and techniques. We expect that this will contribute to a congruent understanding of selection and measurements biases, and perhaps lead to methods for mitigating or avoiding errors. We aim so to establish a benchmark for isothermal (?) geological annealing of fossil tracks in apatite.

Developments and challenges in fission-track thermochronology

A NUMERICAL SIMULATION OF CONFINED-TRACK ETCHING IN APATITE

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We report initial results of a computer simulation of fission-track etching in apatite. It traces the etchant from the surface down along a host track, across to a confined track and along the confined track to both ends (Rebetez et al., 1988). Our model tries to be faithful to the empirical evidence about track etching in apatite (Jonckheere et al., 2022), but it does not claim to give accurate numerical results at present. Instead, it aims at a qualitative understanding of the interactions between different variables, and to suggest some courses of further investigation. The input parameters are the track densities, length distributions, immersion times, apatite and track etch rates, and the use or otherwise of ion irradiation. The model calculates the times required for etching the host and confined tracks and the distance between them using the empirical track and apatite etch rates of Aslanian et al. (2021; 5.5 M HNO3; 21 °C). The output includes statistics for the host and confined tracks, in particular their lengths, widths and orientations. The program also calculates the effective etch times of the confined tracks, and the extent of overetching. In general, the results establish the tautological fact that those confined tracks are measured that possess the right combination of properties to be measurable. The results also show, however, that there are different and unsuspected ways of meeting this condition. Their investigation suggests practical experiments, e.g. for calculating track etch rates from confined track widths. Selected results will be presented for discussion.

Developments and challenges in fission-track thermochronology

AMBIENT TEMPERATURE ANNEALING OF IMPLANTED 252CF FISSION-TRACKS IN MONAZITE

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The experiments of Jones et al.1 constrained the thermal annealing properties of fission tracks in the rare earth element phosphate mineral, monazite. Results showed that it has the potential to be a new ultra-low temperature thermochronometer, sensitive to temperatures <50 degrees C. An intriguing observation across the experiments was the large variation (1.11 um) in mean track lengths of “unannealed” control samples, significantly greater than the measurement uncertainty. It was hypothesised that these considerable differences were the product of ambient temperature fission-track annealing, a process that has been documented in apatites2,3, affecting the various control samples to differing degrees.

To test this, a series of isothermal annealing experiments were performed on monazite crystals from the Devonian Harcourt Granodiorite (Victoria, Australia). Following the methods of Jones et al.1, 252Cf fission-tracks were implanted into polished mineral surfaces cut parallel to {100} for 15 minutes and left at ambient temperatures (,21 degrees C) for a maximum of 126 days. The implanted tracks were then etched, measured on captured digital image stacks and converted to calculated mean lengths of equivalent confined fission-tracks. Results show that mean lengths shortened by ,1.5 um within seven days, with annealing plateauing after 28 days. Here, we explore the implications of using a revised, longer initial fission-track length on previously established monazite empirical annealing models.

1Jones S, Gleadow A, Kohn B (2021). Geochronology, 3, 89-102
2Belton D (2006). PhD thesis, The University of Melbourne
3Tamer M, Ketcham R (2020). Geochemistry, Geophysics, Geosystems, 21, 110

Developments and challenges in (U-Th-Sm)/He thermochronology

EVALUATING THE ROLE OF RADIATION DAMAGE ZONATION ON ZIRCON (U-TH)/HE DATE-EU PATTERNS

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Natural zircon crystals commonly exhibit internal U and Th zonation resulting in heterogeneous effective radiation damage, variable He diffusion behavior, and intrasample zircon (U-Th)/He (ZHe) data scatter. To understand how zonation impacts the ZHe system and dates predicted using a damage-diffusivity model, we characterized suites of zircon crystals from three previously studied samples with distinct ZHe date-eU patterns from the northern Madison Range, MT, Mecca Hills, CA, and Punchbowl Formation in CA using scanning electron microscopy, Raman spectral mapping, and LA-ICP-MS. Analyses reveal a range of zonation styles in each sample, with 45% of all grains exhibiting core-rim or irregular zonation, indicating that many zircon grains that could be used for (U-Th)/He dating have spatially heterogeneous accumulated radiation damage. We evaluated 30 hypothetical grains with endmember core-rim zonation profiles and 12 profiles derived from LA-ICP-MS data using published thermal histories for each sample. These zonation profiles produced predicted ZHe dates that varied by 4-31% of the modeled dates of unzoned grains for thermal histories that yielded uniform and positive ZHe date-eU patterns. This difference increased to 15-85% for samples with a thermal history that yielded a negative ZHe date-eU trend. Models reveal that the effect of zoned actinides and associated radiation damage is magnified for samples characterized by negative ZHe date-eU trends produced by protracted thermal histories including extended residence in the partial retention zone. Considering zircon damage zonation may be helpful when interrogating samples with complex ZHe date-eU patterns that are otherwise difficult to interpret.

Improvements in handling and modeling low temperature thermochronological data

WHAT'S NEW IN HEFTY 2

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The latest version of HeFTy incorporates several new capabilities to help derive thermal history information from thermochronometric data more quickly, flexibly, and robustly. The statistical schema now uses Fisher's method to combine goodness-of-fit results from multiple tests into a single composite value, allowing it to more accurately incorporate more information. Calculations for multiple thermochronometers in a single sample have been parallelized to better take advantage of multi-core processors. An enhanced version of the Controlled Random Search algorithm that allows time-varying nodal points and honors constraints such as maximum heating and cooling rates can achieve solutions orders of magnitude more quickly than a Monte Carlo approach. This comes at a cost in thoroughly searching and documenting the solution space, and further steps have been added to mitigate this effect. A 1-d thermal model can be used to model time-depth (t-z) rather than time-temperature (t-T) histories. This functionality allows the thermal buffering and lag effects of the crust to be included in the thermal history. In particular, it paves the way for utilizing sets of samples along elevation transects by providing a self-consistent mechanism for changing the temperature relationships of samples at different paleodepths due to isotherm compression and expansion during exhumation and burial, respectively. Combined, these enhancements create many new avenues for analysis, but it remains incumbent upon the user to set up hypotheses that are well matched to the geological problem being studied, and that respect geological realities. The simplest path that fits the data may not be geologically realistic.

Developments and challenges in fission-track thermochronology

ETCHING TOWARD THE FUTURE OF APATITE FISSION-TRACK ANALYSIS

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A model describing the along-track etching structure of fission tracks, and in particular the diminishment of etching velocity toward track tips, explains otherwise inexplicable step-etch observations. It also encapsulates the variable etching time of individual tracks, an inevitable circumstance in fission-track analysis resulting in varying degrees of etching completeness and likely responsible for suboptimal reproducibility among analysts.

Variable along-track etching also explains semi-track length distributions, which for unannealed to lightly annealed tracks feature shorter maximum lengths than expected based on confined track measurements: 20 seconds is insufficient to fully etch a long track starting from one tip to the other. A slightly longer etch may reduce this discrepancy, possibly paving the way to use semi-track lengths as an additional source of thermal history information.

Though a significant step forward from ignoring etching structure, the current model is oversimplified, owing to the limited data that went into it. Etching structure is certainly more complex, with anisotropy effects, and non-linear reduction in etching velocity away from an origin point that is not centered and may even feature a slow-etching zone based on recent TEM observations by Li and others.

The etching structure of both the track and surrounding undamaged mineral ultimately control the geometry of an etched fission track. It may be possible to use the full shape of etched tracks discerned by image analysis to infer both etching structure and extent of etching, eliminating an important component of analyst bias and making confined length measurements more plentiful and robust.

Rates and timing of Earth system processes

BOREHOLE CALIBRATION OF ESR THERMOCHRONOMETRY

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Electron spin resonance (ESR) thermochronometry applied to quartz minerals has the potential to resolve rock cooling <60 °C over the past few Myr. Although initial applications of the tech-nique appear promising, the method requires further validation. We have collected a range of borehole samples with known isothermal histories from the MIZ1 borehole (Japan) and the KTB borehole (Germany) to investigate the potential of this technique, as well as to validate our la-boratory measurements and numerical models.

Preliminary data reveal that the ESR dose response and thermal decay of different quartz sam-ples is highly variable. Whereas the Al-centre of some samples exhibits linear signal growth in response to radiation exposure up to 15 kGy, other samples exhibit exponential, or double-exponential growth and saturate at doses of 3-4 kGy. The Ti-centre of most samples is well described by a single saturating exponential function, however samples from the MIZ1 borehole exhibit pronounced sub-linearity in the low-dose response region. Furthermore, whereas for some samples the Al-centre is less thermally stable than the Ti-centre, for other samples the inverse is observed. These observations suggest that a uniform measurement protocol and data-fitting approach may not be appropriate for quartz ESR data.

Inversion of two KTB samples yielded temperatures within uncertainty of borehole temperature, however results for the MIZ1 borehole are more variable and can only recover temperature at best within ,10%. Investigations into the cause of the poor results for the MIZ1 borehole are ongoing (i.e. measurement protocol, data-fitting/numerical model) and will be discussed.

Rates and timing of Earth system processes

FROM DEEP SUBDUCTION TO THE EARTH'S SURFACE: THERMOCHRONOLOGY OF THE SEVE NAPPE COMPLEX, CENTRAL SCANDINAVIAN CALEDONIDES

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The Seve Nappe Complex (SNC) in the Scandinavian Caledonides has undergone high- to ultra-high pressure (HP-UHP) metamorphism along its >1000 km length. Detailed P-T-t studies constrain initial deep subduction in the late Cambrian-early Ordovician followed by exhumation in the Silurian to mid-crustal levels. We present thermochronologic data that links P-T-t paths with the shallow crustal history of the SNC to understand the timing and mechanisms responsible for the exhumation of these UHP rocks to the Earth's surface.

Apatite fission track (AFT) thermochronology was conducted on a ,3 km vertical profile collected from Åreskutan Mt (UHP Middle Seve Nappe) connecting with the adjacent COSC-1 drillhole (,2.4 km deep in the amphibolite-facies Lower Seve Nappe). At Åreskutan Mt AFT ages range from ca. 240–190 Ma, while in the drillhole AFT ages, including previously published data, range from ca. 190–70 Ma. Preliminary inverse thermal models (HeFTy) indicate rapid cooling during the Late Triassic (ca. 250 Ma) and Late Jurassic (ca. 150 Ma), with the Late Jurassic rapid cooling also shown in the AFT age-elevation plot. The youngest 40Ar/39Ar white mica and biotite age spectra obtained on the Middle and Lower Seve nappes are c. 405 Ma. The long hiatus (ca. 160 Myr) between the 40Ar/39Ar and AFT data indicates that final exhumation of the SNC to near-surface levels is unrelated to the Caledonian subduction cycle which formed the UHP unit, but has instead occurred in a number of episodes subsequent to that.

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Rates and timing of Earth system processes

THE EVOLUTION OF THE VALSUGANA FAULT SYSTEM CONSTRAINED BY CLOSE-MESHED LOW TEMPERATURE THERMOCHRONOLOGY: NEW FINDINGS ON THE MOST PROMINENT THRUST BELT WITHIN THE SOUTHERN ALPINE CONTINENTAL INDENTER

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The tectonic history of the European Alps has been characterized by the indentation of the Adriatic microplate into the European realm since the late Eocene. A Fragmentation of this continental Indenter along the Giudicarie fault system (GFS) from the Oligocene onwards causes a pronounced decoupling of the Western and the Eastern Alps tectonic evolution. N(W)-directed movement of the Dolomites Indenter, located east of the GFS, causes severe Neoalpine N-S shortening within the Eastern Alps. At the same time, the Dolomites Indenter accommodates a significant amount of deformation itself, as field data and analyses of shear zones show.

Here we present a new low-temperature thermochronological dataset (apatite U-Th/He and apatite fission track) across the Valsugana fault system, a ,100 km long WSW – ENE striking thrust belt along the southern front of the Western Dolomites, including cooling paths, cooling versus elevation profiles and retrodeformed cross sections. The results argue against a strict in-sequence fault activity within the thrust belt but indicate a more complex fault system development, including backstepping fault activity. Cooling paths derived from samples of the central Valsugana fault zone (Cima d'Asta) allow a reconstruction of the dominantly Miocene tectonic history.

The presented study is an excerpt of a larger research project which focuses on the internal deformation of the Dolomites Indenter: (1) close-meshed thermochronological data which cover the entire Dolomites Indenter, (2) focused mapping along shear zones and (3) analogue modelling with varying boundary conditions are combined to display the complex tectonic evolution of this highly stressed crustal fragment.

Rates and timing of Earth system processes

THE EVOLUTION OF A THRUST BELT WITHIN A CONTINENTAL INDENTER: INVESTIGATING THE INTERNAL DEFORMATION OF THE DOLOMITES INDENTER (SOUTHERN ALPS) IN A COMBINED LOW-TEMPERATURE THERMOCHRONOLOGY, FIELD AND ANALOGUE MODELLING STUDY

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The Dolomites Indenter represents the front of the Neogene to ongoing N(W)-directed continental indentation of the Adriatic microplate into Europe. Concomitant shortening is accommodated within a dominantly WSW – ENE striking and S-vergent thrust belt.
In this contribution, we present a new low-temperature thermochronological dataset over the Indenter from the Periadriatic fault system (N) to the footwall of the Bassano thrust (S) and from Lake Garda (W) to Bled (E). The extensive dataset covers the Dolomites' major fault systems (see separate contribution for a detailed study of the Valsugana fault system), includes elevation profiles and aims to capture the cooling and exhumation history of the Indenter. First results argue against strict in-sequence fault activity within the thrust belt but suggest a more complex evolution. Moreover, the results point to a significant younging trend towards E at least for the apatite U-Th/He data (Miocene in the W – latest Miocene to Pliocene in the E).
This study combines (1) the thermochronological dataset with (2) analogue modelling of the Dolomites Indenter's internal deformation and (3) structural fieldwork along major faults systems. Our analogue models show that the presence of an inherited platform-basin configuration rules the overall style of compressional deformation, the spacing of the evolving fault systems and the topography evolution. The latter two observations are of special interest when combining analogue models and low-temperature thermochronological data. The plausibility of the results of the analogue models is checked by comparing them with the structural data collected in the field along the faults.

Developments and challenges in fission-track thermochronology

REPORTING OF FISSION-TRACK CHRONOLOGY DATA: AN UPDATE

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Since early attempts to standardize the treatment of fission-track (FT) data and system calibration more than 30 years ago, the methodology has undergone major advances, which necessitate the development of new, updated data reporting schemas. These advances include, but are not limited to, the measurement of mineral compositional data and kinetic indicators, LA-ICP-MS for 238U content determinations and elemental mapping, thermal history modelling, double or triple single-grain dating, deconvolution of detrital grain populations, data visualization based on large data sets, digital FT analysis and AI protocols. Consequently, large discrepancies remain in the detail and way FT data and their associated analytical procedures, calibration methods, geo-sample metadata, geochemical analyses and thermal history modelling protocols and results are reported. These inconsistencies hinder public data transparency, accessibility and reuse, and often impede Big Data regional syntheses and inter-laboratory analytical comparisons.

It is now timely to revisit and reset guidelines for reporting FT data in structured formats. Here, we summarize recommendations included in a manuscript submitted for a Geological Society of America Bulletin special volume on 'The Reporting and Interpretation of Geochronologic Data' that addresses these issues. The FT reporting guidelines are recommended for adoption across the thermochronology community, so that they increasingly conform with FAIR Data Principles. Adopting such practices will enable regional age recalculations and thermal history (re-)modelling to be performed using the same parameters and allow future integration with other numerical geoscience techniques. FT data reporting recommendations should remain an ongoing topic of community discussion as new practices develop.

Rates and timing of Earth system processes

LATE ALPINE MULTISTAGE EXHUMATION OF THE NORTHWESTERN RHODOPE METAMORPHIC COMPLEX (NORTHERN RILA MOUNTAINS, BULGARIA)

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The Rhodope Metamorphic Complex is exposed in several mountain ranges in southern Bulgaria and northern Greece, including the Rhodope, Rila, Pirin, Vrontous and Pangaion mountains. Numerous studies of the massif during the previous thirty years have revealed complex Alpine evolution that includes continental collision, partial subduction and syn-metamorphic nappe stacking followed by syn- to post-compressional extension. Generally, the geology of the Rhodope Mountains has attracted far more attention than some other parts of the complex, e.g. the Pirin and Rila mountains in southern Bulgaria. One of the probable reasons is that the Pirin and Rila mountains are the highest and least accessible parts of the Rhodope Metamorphic Complex, culminating at 2925 m in the Rila Mountains.

We present new 40Ar/39Ar and fission-track data that have been combined with detailed structural studies to investigate the tectonothermal evolution of the northern Rila Mountains. Late Early Cretaceous (~101 ± 0.1 Ma) cooling of the Variscan high-grade metamorphic basement through 440–400°C was caused by either erosion of the emplacing thrust sheet, or post-compressional denudation. A pulse of increased extensional cooling during the Eocene (39–35Ma) was related to exhumation along the North Rhodopean Extensional System. The extensional system became inactive in the early Oligocene and was sealed by transgressive terrigenous deposits. Exhumation of the rocks in the northern part of the Rila Mountains below 110 ± 10 °C during the Middle–Late Miocene was associated with displacement along a system of high-angle normal faults and the formation of extensional sedimentary basins.

Rates and timing of Earth system processes

UNDERSTANDING RATES AND TIMING OF COOLING IN FOLD-THRUST BELTS: INSIGHTS FROM LOW-TEMPERATURE THERMOCHRONOLOGY FROM EASTERN NEPAL HIMALAYA.

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Low temperature thermochronometric ages of orogenic systems can provide information about rates and timing of cooling due to crustal deformation. The Himalayan fold-thrust belt is a perfect natural laboratory to test patterns of cooling related to fold-thrust belt kinematics. We combine new zircon [U-Th]/He (ZHe) and apatite fission track (AFT) ages with published white mica 40Ar-39Ar ages (Larson et al., 2019) and zircon fission track (ZFT) ages (Nakajima et al., 2020) and new balanced cross-sections from eastern Nepal to assess how fold-thrust belt geometry and kinematics affect exhumation and cooling pathways. Preliminary ZHe and AFT results show rapid cooling and exhumation during the mid-late Miocene. ZHe, ZFT and AFT ages all show a regional northward younging in cooling patterns which may highlight the position and geometry of the active ramp in the main basal décollement. Preliminary inverse thermal history models for the southernmost sample show slow cooling (0.6-0.8 mm/yr) between ca.18-13 Ma, rapid cooling (,1.25-1.5 mm/yr) between ca. 13-9 Ma and slow cooling (0.4 mm/yr) ca. 9-1 Ma. The northernmost sample shows slow cooling (,0.2-0.3 mm/yr) between 18-4 Ma and rapid cooling (3.3-2.8 mm/yr) between ca. 4-1 Ma. We interpret periods of fast cooling to indicate timing of thrusting (13-9 Ma: Ramgarh thrust; 4-1 Ma: Lesser Himalayan Duplex growth or Main Boundary Thrust). This study adds to the growing body of evidence that fold-thrust belt kinematics as well as fault geometry influence the spatial distribution of cooling ages in the Himalaya

Rates and timing of Earth system processes

COMBINED THERMOCHRONOLOGICAL AND PROVENANCE DATA TO ASSESS THE UPLIFT HISTORY OF SLOWLY EXHUMING OROGENS: THE CASE OF THE NORTHWESTERN COLOMBIAN ANDES

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The ability of low-temperature thermochronometers to constrain the most recent episodes of rock uplift in mountain ranges from bedrock analysis requires >2 km of erosion/exhumation. This requires the implementation of complementary stratigraphic and provenance analyses of adjacent sedimentary basins, which enable tracking changes in the configuration of sediment routing systems as mountain ranges uplift. The northern-Central Cordillera of Colombia has been slowly exhuming since the Oligocene-early Miocene, as indicated by most of the available thermochronological data. Scarce <8 Ma apatite helium cooling ages, obtained from basement rocks exposed in the deepest part of the adjacent Cauca canyon, suggest a recent pulse of rapid exhumation that has yet to be constrained. Thus, most of the Neogene history of rock uplift of the Cordillera is poorly known, as is its relationship with the late Miocene transition from “normal” to flat-slab subduction of the Nazca plate beneath northwestern South America. Here, we combine previous thermochronological constraints from the Colombian Central and Western Cordilleras with new and published stratigraphic and provenance data of the Neogene infill of the intra-montane Cauca and Amagá basins. We hypothesize that these basins evolved as isolated depocenters dominated by fluvial-deltaic settings, which were locally sourced by discontinuous uplifts of the surrounding proto-Cordilleras. Progressive mountain uplift led to the installation of a longitudinal river system connecting formerly isolated basins accompanied by regional paleogeographic reorganizations. We expect to provide fundamental constraints on the uplift and drainage evolution of the cordillera in response to a subduction-related transpressional tectonic regime.

Celebration of the research achievements of Rod Brown

DID SUDDEN UPLIFT OF THE TRANSANTARCTIC MOUNTAINS INITIATE ANTARCTICA'S PERMANENT GLACIATION? – NEW THERMOCHRONOLOGICAL CONSTRAINTS FROM THE MOUNTAINEER RANGE

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The Transantarctic Mountains constitute an extensive high-standing plateau on early Paleozoic basement rocks covered in places by Permian – Jurassic sedimentary strata and volcanic rocks. This pattern differs only in northern Victoria Land at the Pacific termination of the mountain chain where the plateau landscape changes to cone mountains and eventually to Alpine topography.
Here, the Mountaineer Range exposes basement rocks and Cenozoic intrusives in a dissected high-relief topography up to 3500 m in elevation, which is substantially higher than the surrounding mesas. AFT and AHe analyses of 41 samples from five vertical profiles range between 25 and 45 Ma and correlate with elevation. The ages coincide with the time of igneous activity between ~50 and ~25 Ma. Thermal history modelling of age data and proxies suggest common cooling commencing at ~ 35 Ma followed by differential cooling during Oligocene – Pliocene times.
This history refers to rapid inversion and downwearing of a shallow Mesozoic basin in the context of mid-Cenozoic granite emplacement and uplift, followed by incision and differential erosion. Tectonic activity and uplift of the Mountaineer Range began earlier than in the main Transantarctic Mountains and amounts of both uplift and exhumation exceed those of the tableland areas further south. New Earth System climate models suggest that the evolving topography in northern Victoria Land at the Eocene-Oligocene boundary may have served as nucleation centre of an early ice cap, qualifying the region as a potential key area for initial ice sheet formation and glaciation of the Antarctic continent.

Rates and timing of Earth system processes

LOW-TEMPERATURE THERMOCHRONOLOGY AND BRITTLE REACTIVATIONS OF THE PERNAMBUCO SHEAR ZONE, BORBOREMA PROVINCE, BRAZIL

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The basement of Borborema Province (NE Brazil) was affected by deformation during the Phanerozoic, in response to tectonic pulses as well as magmatic events, leading to uplift and culminating with the West Gondwana break-up however the timing, duration and driving forces of the reactivations are still an ongoing debate. In this study we use low-temperature thermochronology to constrain the timing of cooling and possible reactivations of the Pernambuco shear zone. We report on new AFT, ZFT and AHe results from the crystalline basement of the Pernambuco shear zone. AFT results yield central ages ranging from 80 to 199 Ma. ZFT results yield central ages spanning from 420 to 752 Ma. AHe results show a wide single grain ages variation within samples, and mean ages vary from 38 to 103 Ma. Inverse thermal modeling suggests that during the Paleozoic the study area experienced accelerated cooling after the orogenic cycle until the Silurian–Devonian, with cooling rates from 1.5 to 8.0 °C/m.y. Conversely, monotonic cooling has been registered since 250–200 Ma for almost all samples whereas samples closer to the Ibimirim fault, the border fault of the Jatobá basin, experienced a cooling event at 140–115 Ma. Such a cooling event is interpreted as a denudation event associated with syn-rift erosion of preexisting topography. Modeling of a syn-rift sediment from Jatobá basin revealed maximum burial temperatures of 70–105 °C until 100–85 Ma. Using average paleogeothermal gradients estimates, we infer that the Jatobá basin experienced a post-rift denudation of 1.4 to 2.8 km.

Rates and timing of Earth system processes

CAN IN SITU PRODUCED COSMOGENIC 21NE IN COEXISTING QUARTZ AND SANIDINE MINERALS BE USED AS MULTI-MINERAL SYSTEM TO DATE PRECISELY LANDSCAPE SURFACE AGES

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The thermally activated diffusion of neon in feldspar has been reported faster than that is in the quartz (Gourbet et al., 2012), and therefore, it is an open-system for neon in some kind types of feldspar under the Earth surface temperature (Tremblay et al., 2014). The low closed temperature of the neon in specific feldspar hinders the application of cosmogenic 21Ne–feldspar mineral pair in the cosmogenic exposure dating of landscape surfaces, while it endows the cosmogenic 21Ne–feldspar pair with potential ability to be acted as ultra-low temperature thermochronometer to restrict the exhumation rate in the shallow surface. Although the diffusion kinetics vary widely across the different feldspars studies (Tremblay et al., 2017) and it would result that the obtained values may not reflect precise erosion rates, the cosmogenic 21Ne–feldspar system should provide a best approximation, i.e., an order of magnitude estimate of the prevailing exhumation rate, and this value could provide a boundary condition for the calculation of surface cosmogenic 21Ne exposure ages by using cosmogenic 21Ne–quartz pair. As a result, based on the in situ produced cosmogenic 21Ne concentrations measured in feldspar that coexisted with quartz in the exposed rocks, the exposure histories of landscape surface could be precisely restricted. A proof- of-concept study for this multi-mineral system is ongoing by using granite samples from the landscape surfaces in the southeastern margin of the Tibetan Plateau.

Rates and timing of Earth system processes

THE MØRE-TRØNDELAG FAULT COMPLEX LONGSTANDING INFLUENCE ON LANDSCAPE EVOLUTION IN MID-NORWAY

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The variable topography of southern mid-Norway is controlled by the Møre-Trøndelag Fault Complex (MTFC), a NE-SW trending, ca. 300 long by 60 km wide strike-slip megastructure whose influence extends offshore. The MTFC comprises a wide range of ductile and brittle fault rocks, juxtaposing lower crustal units, Caledonian nappes, and Devonian/Jurassic basin relicts. Such intricate structural arrangement indicates multiple reactivations of the MTFC. The existing K-Ar and fission track data suggest km-scale normal sense block displacement on the southern MTFC during the Mesozoic and potentially the Cenozoic. However, no clear patterns have emerged further north, where the escarpment is topographically subdued. We present the first Laser Ablation Apatite Fission Track (LAFT) and Apatite U-Pb (AUPb) ages acquired by double-dating analysis at the Geological Survey of Norway, obtained from a NW-SE transect across the northern MTFC. AUPb ages ranging from ca. 450 Ma on the east of the MTFC to 400 Ma on the west match published 40Ar/39Ar data that document post-orogenic cooling and crustal extension. The LAFT central ages range between late Carboniferous and Middle-Jurassic, and their geographical distribution suggests distinct cooling patterns along the transect. These preliminary LAFT results support the previous interpretation of a thermochronologically-resolvable footwall displacement along the MTFC during a multi-phase rifting, with an apparent decrease of the vertical slip from SW to NE concurrently with the topography. Future LAFT dating, track length measurements, and other isotopic analyses should allow to better constrain the thermotectonic evolution of the MTFC after the Caledonian orogeny.

Rates and timing of Earth system processes

THERMOCHRONOLOGY OF SOUTH AMERICA PASSIVE MARGIN BETWEEN URUGUAY AND SOUTHERNMOST BRAZIL: INSIGHTS FROM LOW-TEMPERATURE THERMOCHRONOLOGY AND SEISMIC ANALYSIS

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Thermochronology studies carried out in crystalline rocks on the South America passive margin reveal distinct cooling patterns along the coast. While the onshore basement geology of most of the Atlantic margin records syn- to post-rift exhumation, the region between Uruguay and southernmost Brazil primarily presents pre-rift cooling. This area encompasses the Rio de La Plata craton, the Dom Feliciano belt, and the marginal Pelotas Basin. Apatite and zircon fission track and (U-Th)/He ages imply early Paleozoic basement cooling, likely related to regional exhumation after the Brasiliano/Pan-African tectonic cycle (Neoproterozoic-Cambrian), West Gondwana formation. The region then had protracted and continuous cooling during the Paleozoic-Mesozoic, until South Atlantic Ocean opening. The presently exposed basement was near surface (T ≤ 60 °C) in the Jurassic-Cretaceous transition, immediately before the extrusive magmatism in the Paraná-Etendeka Large Igneous Province and rift propagation northwards. Seismic analysis in the offshore Pelotas Basin indicates limited siliciclastic deposition during rifting accompanied by magmatism along the developing coastline (ca. 133-113 Ma). Inverse thermal models suggest a subtle post-rift reheating, raising rock temperatures up to 75 °C in the late Cretaceous/Palaeogene. This geothermal disturbance may be responsible for notable dispersion of apatite (U–Th)/He ages. The final cooling phase is poorly constrained but appears to start by the Eocene. The Pelotas Basin seismic suggests an increase in sedimentation rate from the Oligocene, which might be linked to final exhumation onshore and consequent increase of sediment supply offshore.

Developments and challenges in (U-Th-Sm)/He thermochronology

GETTING THE MOST OUT OF A SINGLE-GRAIN: LA-ICP-MS IN-SITU (U-TH-SM)/HE ANALYSIS

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The in-situ (U-Th-Sm)/He approach does have the potential to reliably reconstruct the cooling history of single apatite/zircon grains, similar to the 4He/3He approach. Although enough knowledge has been gained over the last decades on the theoretical background of He production, emission, and diffusion, there is still a lack of observational in-situ studies. The latter is required to verify that the in-situ (U-Th-Sm)/He method reliably predicts cooling histories from age standards, but, more importantly, from everyday samples.
In this study, we will analyze apatite and zircon age standards (Fish Canyon Tuff, Mt McClure) and samples from SW Germany with the LA-ICP-MS in-situ (U-Th-Sm)/He method to reconstruct/verify their cooling histories using multiple measurements in single grains. Inner grain variations in U, Th, and Sm will be measured and used together with grain morphology to model He distributions as a function of cooling history. Predictions will be compared to independently determined cooling histories. In addition, we will study the uncertainties associated with this approach and the minimum requirements for reliable cooling history reconstructions, such as the quantity, size and location of ablation spots.

Improvements in handling and modeling low temperature thermochronological data

(MIS)IDENTIFICATION OF MAGMATIC AND EXHUMATION AGES BY DOUBLE DATING AND ITS IMPACT ON LAG-TIME ANALYSIS

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The geologic interpretation of detrital thermochronometric datasets requires correct identification of ages as either the record of exhumational cooling or the record of magmatism and subsequent post-magmatic cooling independent of exhumation. A classic approach for identifying magmatic cooling ages is through double dating leveraging paired high- and low-temperature geo/thermochronologic systems, which should yield, within error, indistinguishable ages from the same grain. Low-temperature thermochronometric ages that are younger than their corresponding crystallization ages are mostly invariably interpreted to record exhumation. To test this last assumption, we applied a detrital zircon U-Pb and (U-Th)/He double-dating approach to an extremely well-constrained source-to-sink system in the southern European Alps, archiving the progressive unroofing of the Bergell-Novate volcanic-plutonic complex and associated country rocks. We depth-profiled U-Pb dated unpolished detrital zircon grains from selected strata and performed (U-Th)/He analysis on non-magmatic grains. We found that 40% of the double-dated non-magmatic grains yielded (U-Th)/He ages overlapping in age with the Bergell and Novate magmatism. Our results demonstrates that only a fraction of the grains yielding magmatic He (or FT) ages can be identified by a double-dating approach. Therefore, the assumption that all the remaining grains constrain exhumation can be potentially misleading. Our findings have major implications for detrital thermochronometric studies that emphasize the importance of the youngest thermochronologic age peaks for lag time analysis, as zircon grains from a contact aureole always form the youngest thermochronologic age peak in polymodal grain-age distributions derived from erosion of the uppermost levels of a single volcanic-plutonic source.

Rates and timing of Earth system processes

INCISION HISTORY OF ZION CANYON, NEW CONSTRAINTS FROM LOW TEMPERATURE THERMOCHRONOLOGY (WESTERN MARGIN OF THE COLORADO PLATEAU, USA)

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The Colorado Plateau is characterized by a low-relief, high-altitude surface that is dissected by outstanding canyons. The chronology of plateau uplift and of subsequent canyon incision is still debated. The timing of canyon incision has major implications for the timing of plateau uplift, uplift processes, and for feedbacks on regional climate. Previous studies constraining the rates of landscape evolution and the timing of canyon incision have mostly focused on the Grand Canyon and constraints on the timing of canyon incision are still needed in other areas of the plateau. We provide new apatite fission-track and (U-Th-Sm)/He data to decipher the incision history of Zion Canyon on the Western margin of the plateau. The high geothermal gradient (>50°C/km) in this region enables these thermochronometers to record the timing of incision, despite limited exhumation. Inverse thermal modelling of our thermochronological data indicate reheating to temperatures of ~70°C during the Cenozoic and a cooling phase starting at ~7 Ma. We relate this cooling phase to the onset of exhumation along the western Colorado Plateau and initial canyon incision. Our results are consistent with local uplift and incision by the Virgin River since 4-3 Ma in the Zion area. Together with existing structural cross-sections, our results suggest Zion Canyon incision began after uplift of the western Colorado Plateau and before tectonic activity on the Hurricane fault. Our results suggest that the onset of exhumation in Zion area occurred before capture of the upper Virgin River by the Colorado River across the Grand Wash Cliffs.

Rates and timing of Earth system processes

POTENTIAL IMPACT OF GLACIATIONS ON THE EXHUMATION HISTORY OF THE KYRGYZ RANGE – WESTERN TIEN SHAN (KYRGYZSTAN).

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Constraining the effect of global climatic changes on Earth-surface processes is crucial to our understanding of landscape evolution. One debated question is the impact of Cenozoic cooling and subsequent glaciations on the erosion of mountain ranges. The (U-Th-Sm)/He system measured in apatites can record low-temperature (<100 ◦C) cooling histories and thus has the sensitivity to detect million-year timescale changes in exhumation rates in glaciated regions.

Previous thermochronology studies in the Kyrgyz Range identified an increase of exhumation rates over the last 3 Ma, which could be the result of enhanced glacial erosion (Bullen et al., 2003; Sobel et al., 2006). Furthermore, an analysis of published thermochronology data found the Kyrgyz Range to be one of the few locations with the potential to record the effects of Pleistocene glaciations (Schildgen et al., 2018).

In this study, we present new AHe ages for 6 samples collected along an elevation profile in the glacial Ala Archa Valley. Samples span 1850 m in elevation and were collected from granite outcrops. These results expand the previous dataset by Bullen et al. (2003) by adding both lower- and higher-elevation samples. The resulting age-elevation relationship exhibits 1) a break-in slope at low elevation, showing an increase of exhumation rates at 3.4 (± 1.0) Ma and 2) a crescent shape with older ages located at mid-elevation. We interpret these features as the result of the dual effect of glacial erosion, which increased local valley relief and limited mountain heights.

Rates and timing of Earth system processes

ENHANCED EXHUMATION IN THE EAST KARAKORAM DURING THE MID-PLEISTOCENE CLIMATE TRANSITION: A DETRITAL PROVENANCE ASSESSMENT

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Around the Nanga Parbat massif in the west and the Namche Barwa massif in the east, the Himalayan orogen exhibits an abrupt strike change from roughly E-W to N-S, forming two structural syntaxes. Each syntaxis is drained by a major trans-orogenic river system: the Indus and Ganges-Brahmaputra, respectively. The syntaxes record rapid exhumation rates (up to c. 10 mm/a), together with Plio-Pleistocene mineral (re)crystallisation and cooling ages [1,2,3]. The Namche Barwa massif supplies c. 65% of Brahmaputra bedload [4]. In contrast, the Nanga Parbat massif supplies c. 10% of modern Indus bedload, which instead is dominantly sourced from the East Karakoram [5].

We present detrital rutile and zircon U-Pb data from the Indus fan, sampled by IODP expedition 355 and ODP leg 117. These data record abrupt increases in the proportion of sediment sourced from the Nanga Parbat massif between c. 8-6 Ma and again at c. 2 Ma, coherent with bedrock studies [2,3]. The Nanga Parbat massif then dominates sediment supply until c. 1.5-0.6 Ma, followed by an abrupt switch to East Karakoram sourcing.

The East Karakoram includes some of Earth's highest peaks, and largest extra-polar glaciers. Therefore, a provocative possibility is that the jump in erosion focus was driven by the well-documented switch from c. 41 ka, obliquity-dominated, to 100 kyr, eccentricity-dominated orbital forcing (the Mid-Pleistocene Transition). This transition occurred at c. 1 Ma [6], and could have driven enhanced glacially-mediated erosion in the east Karakoram, outpacing Nanga Parbat exhumation.

[1] www.doi.org/10.1016/j.earscirev.2016.07.010
[2] www.doi.org/10.1016/j.epsl.2009.09.044
[3] www.doi.org/10.1130/0091-7613(1993)021<0347:SAMARD>2.3.CO;2
[4] www.doi.org/10.1016/j.epsl.2011.05.004
[5] www.doi.org/10.1016/j.epsl.2022.117873
[6] www.doi.org/10.1016/j.quascirev.2006.07.008

Developments and challenges in (U-Th-Sm)/He thermochronology

ZMAP2FT: A TOOL FOR CONVERTING 2D U-TH MAPS INTO 1D COORDINATES FOR IMPROVED (U-TH)/HE APPLICATIONS

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The zonation of parent isotopes within minerals dated by (U-Th)/He can have a significant effect on the Ft correction factor and thus the accuracy of the results [1]. Characterizing and quantifying the zonation of U and Th and, from that, calculating an Ft correction factor is an important step in further improving the quality of (U-Th)/He dates. With the advance of new analytical techniques allowing rapid generation of U-Th maps in dated minerals, there is a need for tools for rapid reduction of the U-Th zonation data for interpretation purposes. Zmap2Ft is a new piece of software written in Python developed to serve this purpose. In brief, it takes a 2D map of pixels, their associated values (in this case U and Th concentrations) and user input crystal vertices and creates a 1D contour. This contour represents a spherical construct with a radial concentration profile as in the 1D contour, which can be readily imported into HeFTy software and used to calculate the Ft correction factor of the equivalent sphere [2]. The software can also reduce the number of data points in order to reduce running time of HeFty. This process streamlines the process of generating 2D maps of zonation of parent isotopes and calculating more accurate Ft correction factors, which improves our ability to generate more accurate (U-Th)/He data.

1. Meesters & Dunai 2002. Chem Geol, 186(3-4)
2. Ketcham 2005. RiMG, 58(1)

Rates and timing of Earth system processes

COMBINED U-TH-PB AND (U-TH)/HE DATING OF QUATERNARY VOLCANIC ROCKS, A CASE STUDY FROM JEJU ISLAND, SOUTH KOREA

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Zircon double-dating (ZDD) is used to measure eruption ages for volcanic samples <1 Ma and requires both crystallisation ages, measured by either U-Pb or U-Th disequilibrium dating, and cooling ages, measured by (U-Th)/He dating, for a set of individual zircon crystals separated from a single volcanic sample. The individual (U-Th)/He dates corrected by their crystallisation ages are then combined to calculate a sample eruption age (Schmitt et al., 2006).
Intraplate magmatism is typically dominated by mafic magmas that are undersaturated in zircon. However, in certain cases zircon is found in intraplate volcanic areas, including zircon autocrysts from evolved magmas present in these systems, as well as exotic crystals putatively inherited from crustal or mantle sources. A case study for such an environment was carried out for Jeju Island, South Korea, where ZDD and (U-Th)/He dating was used to explore the periodicity of trachyte eruptions on the island. The resultant eruption ages group into four age populations ca. 750–477 ka, ca. 97–53 ka, ca. 31–23 ka and ca. 2 ka. Additionally, the crystallisation age spectra show evidence for three stages of zircon crystallisation each preceding an episode of trachyte volcanism except for the 2 ka eruption. The strong temporal link between crystallisation and eruption supports the model of a previously proposed simple magmatic plumbing system for Jeju and other trachyte eruptions (Brenna et al., 2012).

Brenna et al. 2012. Lithos 148, 337–352
Schmitt et al. 2006. JVGR 158(3-4), 281-295.

Rates and timing of Earth system processes

INVESTIGATING THE EFFECTS OF FLAT-SLAB SUBDUCTION ON THE EXHUMATION AND UPLIFT OF THE NORTHERNMOST PERUVIAN ANDES

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Episodes of flat-slab subduction have been widely associated with large-scale intraplate deformation, exhumation, and surface uplift in Cordilleran orogenic systems. Nonetheless, the exact geodynamic mechanisms responsible for the development of this type of subduction and the magnitude of its effects on the overriding plate are still a matter of ongoing debate. Several analog and numerical models have shown that flat-slab subduction and its associated upper plate deformation are likely controlled by the presence on the subducting oceanic plate of overthickened, buoyant portions of oceanic crust, such as oceanic ridges or plateaus. These would not only prevent steep subduction but also mark the locus of maximum exhumation on the continent.

In the Peruvian margin, the existence of a ~1500km long flat-slab section has been explained as the result of the synchronous subduction of the Inca Plateau and the Nazca Ridge. Recent works have shown thermochronological evidence of exhumation tracking the southeastward migration of the Nazca Ridge beneath the continent from ~10°S to ~15°S in the past ~11 My. However, the effects of the passage of the fully subducted Inca Plateau beneath the northernmost Peruvian Andes (~5°S) remain poorly constrained, mainly due to the lack of thermochronological data. To address this problem, we present here new AFT, AHe and bedrock U-Pb data from a transect across the Northernmost Peruvian Andes and compare the observed spatial trends of continental-arc magmatism and late Miocene-Pliocene exhumation with the timing of onset of flat-slab subduction in Peru and with the reconstructed eastward migration of the Inca Plateau.

Rates and timing of Earth system processes

THERMAL HISTORY OF THE EAST ANTARCTIC MARGIN: CAMPAIGN-STYLE APATITE U-PB AND FISSION TRACK STUDY

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East Antarctica records a complex thermal history in response to (1) tectonic events associated with supercontinent assembly and break-up; and (2) climatic processes such as Cenozoic glaciation. However, due to the current extensive ice-cover and poor accessibility of outcrops, large gaps remain in our understanding of the thermo-tectonic evolution of the East Antarctic margin. In particular, a cohesive picture of the magnitude and timing of upper crustal exhumation is yet to be deciphered.

With the aim to reveal new insights into the thermo-tectonic history of East Antarctic margin, we present a large new dataset of apatite fission track and U-Pb data, covering more than 90° of longitude along the East Antarctic margin. Preliminary Apatite U-Pb dates reveal an image of the tectonic terrane configuration, showing conformity with established terrane boundaries that developed during Gondwana assembly. Samples west of the Bunger Hills predominately show Cambrian Apatite U-Pb ages, whilst to the East mostly 1.1-1.5 Ga U-Pb ages are recorded.

First results from apatite fission track analysis indicate Early Carboniferous cooling ages in George V Land in contrast to Permian and Jurassic cooling ages to the west of the Bunger Hills. Few additional samples from the Bunger Hills and Windmill Islands yield cooling ages of ,32-40 Ma, which may be related to the onset of Cenozoic glaciation.

The multi-method `campaign-style` approach highlights regional differences in the thermal response of the Indo- and Australo-Antarctic domains to the tectonic and climatic conditions experienced along the passive margin.

Rates and timing of Earth system processes

EROSIONAL FRAGMENTATION OF A PALEOPROTEROZOIC LAURENTIAN SUPERBASIN DURING SNOWBALL EARTH

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The Paleoproterozoic Athabasca, Thelon, Hornby Bay, and Elu intracratonic basins of Laurentian North America have long been regarded as broadly correlative and once contiguous due to similarities in stratigraphy, paleocurrent indicators, and geochronological data, however supporting evidence for this hypothesis beyond the remnant basins has been lacking. We present geochronology, thermochronological inversions, geochemical data, and detrital zircon age spectra that jointly imply continuity between preserved basin strata and now-exposed shield locations over a large area of northern Canada. Zircon and apatite (U-Th)/He and fission-track thermochronology also reveal a relatively synchronous, rapid late Neoproterozoic cooling event that is interpreted as erosional exhumation during Snowball Earth glaciations that contributed to the formation of the Great Unconformity. Thermochronology is corroborated by a pairwise anomaly in the global zircon Hf and O records, a prominent nadir in global detrital zircon compilations, and immediately precedes a five-fold step increase in worldwide sedimentary rock abundance in the Phanerozoic—all supporting the notion that the late Neoproterozoic was a time of significant erosion. These are the first comprehensive data from exposed Laurentian basement that indicate more extensive mid-Proterozoic sediment cover than is preserved in central Canada and provide evidence of later disruption and erosional fragmentation during the Cryogenian.

Developments and challenges in fission-track thermochronology

EFFECTS OF THE 2019—2020 AUSTRALIAN 'BLACK SUMMER' BUSHFIRES ON LOW-TEMPERATURE THERMOCHRONOLOGY SYSTEMS IN EXPOSED GRANITOIDS

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Thermochronology studies commonly sample from bushfire regions that experience high temperature (>600°C) thermal pulses, surpassing the sensitivity zones of low-temperature systems. This is known to influence ages and track lengths of near-surface minerals in apatite fission-track (AFT) and apatite, zircon (U-Th-Sm)/He (AHe, ZHe) systems. However, the extent of thermal penetration at depth in exposed bedrock immediately following a fire is not well constrained. Moreover, with advancements to the ultra-low-temperature monazite fission-track (MFT) system, it is timely to quantify potential bushfire-induced annealing to assess applicability of MFT in fire-prone environments. We report results combining MFT, AFT, AHe and ZHe thermochronology on bushfire charred exposed bedrock.

S-type Devonian granitoid samples were collected immediately following the largest bushfires on record in SE Australia. Selection was based on burn severity of the overlying canopy. Cores were taken at depth perpendicular to the exposed surface and sliced at 1cm intervals.

Results show younger AFT and MFT ages occur at the 0-1cm slice with some single-grain ages near 0Ma. AFT ages plateau <1cm whereas MFT ages plateau <2cm. Mean track lengths (MTL) for both AFT and MFT plateau at core depths >3cm with near-surface slice reduced by ,1µm from deeper sections in both systems. AHe and ZHe ages show no noticeable reduction in single grain ages along depth indicating thermal pulses tend to effect fission-track annealing more than He diffusion.

This study has major implications for sampling in fire-prone areas particularly for AFT and MFT systems, indicating some removal of the exposed rock may be necessary.

Rates and timing of Earth system processes

THERMAL IMPRINTS OF BREAKUP? A CASE STUDY ON THE CONJUGATED MARGINS OF NORTH GREENLAND AND WEST SVALBARD

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North Greenland und West Svalbard are key areas to understand how the connection between the Northern Atlantic and the Arctic Ocean evolved from Cretaceous to final breakup in the Miocene. Vitrinite reflectance values > 7% from Upper Cretaceous rocks in North Greenland indicate an unusually high thermal maturity. Thermal maturity values are highest near the coast and decrease further inland. High thermal maturation is also observed in Paleogene sediments nearby and along the conjugated Svalbard margin. Here, the deposits yield vitrinite reflectance values up to 4% with values also decreasing towards the inland. The processes associated with heating and the timing of the heating event(s) are still a matter of debate.

We applied apatite fission track and (U-Th-Sm)/He thermochronology to address the hypotheses that (i) both margins, the Greenland and the Svalbard side experienced heating contemporaneously, and (ii) that heating was connected to the final continental breakup in the Miocene.

Our data indicates that the high thermal maturity along the conjugated margins actually reflect several thermal events. The oldest occurred in the late Cretaceous and we propose a connection to volcanic activity in due course of incipient spreading. The two younger events occurred around the Paleocene-Eocene transition and during the late Eocene, coeval with the lateral displacement of Greenland and Svalbard. We associate the thermal events with heat transfer along the involved transform faults, connecting active spreading centres in the north and the south. Overall, we conclude that the thermal anomalies thermally weaken the continental crust prior to final breakup.

Developments and challenges in (U-Th-Sm)/He thermochronology

LOW-TEMPERATURE THERMOCHRONOLOGY IN FAULT ZONES: A TOOL FOR GEOTHERMAL EXPLORATION

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Fault zones constitute a largely underestimated potential for the worldwide expansion of geothermal power generation. Hydrothermal circulations and convection cells along faults can be complex and localized at the scale of the fault system. Furthermore, thermal anomalies can be hidden without surface expression: hot spring, gas leak, massive alteration… Low-temperature thermochronology, sensitive for the temperatures targeted for the geothermal exploration (,60-200°C), appears as a powerful tool to track geothermal anomalies associated to past or long-term or hidden hydrothermal circulations. Recent studies along fault zones in the Eastern Pyrenees reveal that the (U-Th)/He apatite chronometer is sensitive to hydrothermal activity, supported by REE mobility in apatite during fluid-rock interactions. The results demonstrate that apatite can be no longer considered as a closed system and that the effect on AHe dates depends on the intensity of the fluid circulation along the fault. Inside the fault damage zone (DZ) two domains can be distinguished: i) an inner DZ subjected to intense hydrothermal circulations, resulting in AHe rejuvenation or ageing associated to intense mobility in He and REE, and ii) an outer DZ, in which apatites are affected by variable He loss triggering their partial age rejuvenation and associated with REE depletion. Pairing AHe dates with AFT and ZHe dates provides additional constraints for the intensity and extent of the thermal disturbance associated with hydrothermal circulations. This case study opens up new perspectives for the combined use of low-temperature thermochronology and REE analyses for geothermal exploration.

Rates and timing of Earth system processes

40AR/39AR RECORD OF DUCTILE-BRITTLE FAULTING IN THE AXIAL ZONE OF THE EASTERN PYRENEES

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In orogens, most fault zones have polyphase tectonic activity under ductile and/or brittle conditions, which renders challenging their analysis in terms of kinematics, metamorphism, fluid flow and time evolution and may lead to different interpretations of their role during the orogenic evolution. Therefore, 40Ar/39Ar dating of the deformation is an efficient tool to decipher tectonic events in fault zones. This is particularly true in the Axial Zone of the Eastern Pyrenees where few geochronological studies have focused on these fault zones. The Têt and Py faults are major NE-SW trending crustal faults that have accommodated the complex exhumation/cooling history of adjacent crustal blocks, Mont-Louis, Canigou and Carança massifs, as highlighted by thermochronological data (Milesi et al., 2022). These faults record deformation from slightly above the ductile-brittle transition to brittle conditions as witnessed by the presence of thick fault gouges that partially rework low temperature mylonites. In this work, we report 40Ar/39Ar illite/muscovite dating on fault zones showing different activity phases at the brittle-ductile transition characterized by the presence of gouges with variable mixture of polytypes and with different phyllosilicate generations. For these fine-grained materials, we used a sample encapsulation technique to evaluate the amount of 39Ar lost by recoil during irradiation before dating the phyllosilicates. The new dates provide a scenario of fault motion between the early Eocene to the early Miocene that allows a comparison with those predicted by low-temperature thermochronological data and thermal modeling and shows a close link between fault activity and exhumation of adjacent crustal blocks.

Improvements in handling and modeling low temperature thermochronological data

COUPLING QTQT AND PECUBE THERMAL(-KINEMATIC) MODELLING FOR INTERPRETING LOW TEMPERATURE THERMOCHRONOLOGY DATA: APPLICATION TO THE TÊT FAULT ZONE (EASTERN PYRENEES)

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The Earth's surface long-term evolution is controlled by the combination of tectonic, erosion and climate processes. Thermal (-kinematic) modelling approaches based on low-temperature thermochronology are efficient tools to reconstruct the thermal evolution of the crust and tectono-geomorphic histories. The isotherm shape and wavelength are especially controlled by the overlying topography and its evolution; therefore, the upper-crust thermal evolution is influenced by both rock exhumation and topographic changes or fault motion. In this context, constraining the tectono-geomorphological evolution of mountain ranges appears as a major challenge, especially in areas where the exhumation history and topographic evolution are contrasted and difficult to disentangle. We performed 1D thermal (QTQt) and 3D thermo-kinematic (Pecube) modelling along the Têt fault (Eastern Pyrenees) using a dense spatial low-temperature thermochronological dataset. In this area, spatio-temporal variations in Neogene faulting are still unclear and the topographic evolution models are debated. 1D thermal modelling reveals a cooling event (~10°C/Ma) during the Serravallian-Tortonian (12–9 Ma), related to major topographic changes. The different topographic evolution models proposed for the Eastern Pyrenees have been tested in a 3D thermo-kinematic model, using the same low-temperature dataset. Model outcomes show a significant mid-Neogene extensional tectonic event with kilometric displacement along the Têt fault regardless of the topographic scenario considered. This tectonic activity may have had a non-negligible role on the late-stage relief evolution. This example shows that coupled modelling approaches for quantitative interpretation of low-temperature thermochronology data can be relevant to disentangle geomorphological and tectonic components in the upper-crust thermal evolution.

Rates and timing of Earth system processes

INTRUSION AND COOLING HISTORY OF LATE NEOGENE GRANITES IN THE TANIGAWA-DAKE AREA, CENTRAL JAPAN, REVEALED BY GEO-THERMOCHRONOMETRY AND AL-IN-HORNBLENDE GEOBAROMETRY

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Granites are generally emplaced at crustal depths of > several kilometers. Granites younger than ,5 Ma are often exposed along plate convergent boundaries (Harayama, 1992), implying very rapid uplift/exhumation rates in those areas. The Japanese islands, hosting the world's youngest Kurobegawa granite (,0.8 Ma) exposed in the Hida mountains (Ito et al., 2013), are one of such area. The Tanigawa-dake area is located at an arc-arc junction, where late Neogene Tanigawa-dake granites (zircon U-Pb ages: ,4.0–3.2 Ma; Minami et al., 2021) are exposed. In this study, we performed zircon U-Pb, zircon (U-Th)/He (ZHe) and apatite (U-Th-Sm)/He (AHe) dating of the granites to constrain their intrusion/cooling histories. Samples yielded zircon U-Pb ages of 6.0–4.0 Ma, ZHe ages of 3.3–1.4 Ma and AHe ages of 2.8–1.0 Ma. Zircon U-Pb ages together with previous data suggest at least three intrusive events (,6, ,4, and ,3 Ma) for the Tanigawa-dake granites. Based on time-temperature paths, the AHe ages reflect uplift/denudation rather than thermal disturbance by different intrusions. Denudation rates of 0.3–1.4 mm/yr calculated from AHe ages are comparable with those reported from other tectonically active regions in Japan, e.g., Tanzawa mountain (Yamada and Tagami, 2008) and the Ou back-bone range (Sueoka et al., 2017). The spatial distribution of denudation rates suggests that the Tanigawa-dake region might be denuding symmetrically centered around the west-side of Mt. Tanigawa-dake main ridge. In the presentation, further discussion will be provided arising from the results of geobarometry, stress analysis and thermal inversion modeling.

Rates and timing of Earth system processes

SUPERGENE COPPER MINERALIZATION AS A PALEO-ENVIRONMENTAL PROXY

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Copper is one of the most used metals in industries. However, the factors controlling the formation of supergene copper mineralization (SCM) remain unclear. In Chile, most of copper deposits are formed at the end of magmatic activity due to hydrothermal fluids (porphyry-copper system or PCS), and by secondary alteration by surface fluids (supergene deposits). The parameters controlling the formation of SCM are: 1) emplacement of a PCS; 2) tectonics to uplift this PCS; 3) climate to provide enough water for the leaching, transport and precipitation of SCM; 4) erosion to bring the PCS to surface without erasing the supergene profile. As a result, it is clear that these deposits form under specific paleo-environmental conditions and timings. The objective of this project is to constrain the relative impact of each parameter to understand, define and predict these conditions.

In Chile, previous studies have proposed that SCM may occur either during the relief construction, incision or flattening. Therefore, our aim is to understand when during the mountain range evolution, SCM are emplaced and how long after the porphyry-copper exhumation. To reach this goal, we have selected eight porphyry-copper systems from different morphotectonic and climatic contexts to collect samples of SCM and porphyry to used them as archives of the past environmental conditions. By comparing the exhumation histories of the porphyries with the age of the SCM, we hope to understand which parameter(s) play(s) a key role in the formation of these SCM. All the samples have been collected and their petrographic characterization initiated.

Improvements in handling and modeling low temperature thermochronological data

THE OPPORTUNITIES AND COMPLEXITIES OF LEVERAGING MAGMATISM'S IMPACT ON LOW-TEMPERATURE THERMOCHRONOMETERS

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The thermochronology community has long recognized the geothermal gradient's systematic response to landscape evolution and built tools that leverage the resulting spatial-temporal patterns in thermochronologic data. However, the complexities—and opportunities—that arise from rock cooling related to magmatism remain underexplored. Here, I present several approaches to exploiting the spatial (tens of km to m) and temporal (tens of Myr to yr) scales at which igneous activity impacts the thermochronologic record. In some regions, magmatic histories are key for interpreting erosion histories. On the Colorado Plateau (USA), Oligocene magmatism that perturbed sedimentary rocks with a protracted near-surface history helps resolve ,1.5 km of Plio-Pleistocene erosion in rocks collected next to plutons, while simultaneously revealing the ambiguity of a regional signal of Oligocene rock cooling that is either ,1 km of erosion or post-magmatic thermal relaxation. In other contexts, low-temperature thermochronology can quantify magmatic processes. In the Wallowa Mountains (USA), spectacular exposures of dikes that fed eruptions of the Columbia River flood basalts offer an opportunity to constrain the dynamics of a large igneous province. Dike-perpendicular cooling age transects, interpreted using a 1D thermal-chemical diffusion model and Bayesian MCMC inversion, document: (1) individual dike segments transported magma for 0.5-8 years, (2) along-strike variability in magma flow localization, (3) transient doubling of the geotherm for <1 Myr, and (4) how different temperature-sensitive systems variably record these features. More broadly, as tools for modeling how magmatism manifests in thermochronologic datasets advance, so too will our ability to robustly interpret cooling ages in any geologic context.

Advances in noble gas and solid state thermochronology

ARTIFICIAL FORMATION OF ALPHA RECOIL TRACKS USING AN AMERICIUM SOURCE

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Alpha recoil track (ART) is a lattice defect formed by the alpha decay of 238U, 235U, 232Th and their daughter products. In order to apply ART observation to the dating and thermal history study of various minerals, it is necessary to investigate mineral surface properties, appropriate etching conditions, and the ART annealing characteristics upon heating. This research aims to establish a method to form ART artificially so that the shape and properties of ART in variety of minerals can be observed in the future. A 300 Bq americium source was used to irradiate muscovite, in which the ARTs were well observed in previous studies, for several time intervals, and the samples were observed using phase contrast microscopy after chemical etching. There is a linear relationship between the ART areal density formed on the sample surface and the irradiation time. However, the size distribution of the formed ARTs are different from that of the natural ARTs. To find out what caused this difference, several samples of muscovite irradiated for 3 hours were prepared and annealed at different temperatures and times to see the stability of ARTs under the geological conditions.

Developments and challenges in fission-track thermochronology

DENUDATION HISTORY CONSTRAINED BY THERMOCHRONOLOGICAL MULTI-INVERSION: AN EXAMPLE FROM THE EASTERN NEPALESE HIMALAYA

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Understanding the processes of continental crustal denudation in a collision zone has advanced significantly with the development of thermochronological methods. Currently, the most common technique for reconstructing denudation history is to investigate the distribution pattern of a cooling age on elevations or transects. However, this technique is considered to be insufficient mainly in terms of temporal resolution in a collision zone with spatiotemporal changes in the denudation rate. In this study, we attempted to improve the temporal resolution of the reconstructed thermal history of Himalaya by performing the thermochronological inversion, and to quantitatively reconstruct the spatiotemporal variation of the denudation rate by thermokinematic modeling.

Thermochronological inversion was undertaken for new results of fission-track (FT) age and FT length data of zircon and apatite in order to reconstruct the time-temperature (t-T) paths in eastern Nepal. Eight t-T paths calculated along the across-strike section show that the cooling process of the upper crust in eastern Nepal is characterized by: 1) gradual cooling followed by rapid cooling and subsequent gradual cooling, and 2) northward-younging of the timing of the rapid cooling. The observed FT ages and t-T paths were then compared with those predicted by forward thermokinematic modeling. The result of the thermokinematic modeling indicates that:1) the cooling pattern observed in the field mainly occurred when the upper crust overthrusted accompanied with the activity of the plate boundary fault showing the flat-ramp-flat geometry, and
2) its geometry has been stable since the underplating of the Indian continental plate before 9 Ma.

Advances in noble gas and solid state thermochronology

FABRIC ANALYSIS OF PRECAMBRIAN TECTONITES: ASSESSING THE RELATIONSHIP BETWEEN INTRACRYSTALLINE DEFORMATION AND BIOTITE 40AR/39AR DATES

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40Ar/39Ar geochronology of K-bearing minerals such as mica and amphibole is one of the main geochronologic techniques for dating metamorphic and deformation processes in Precambrian rocks. Yet, interpreting tectonic events dated through this technique is challenging, as temperature, deformation, chemical reactions, fluid-rock interactions, and excess 40Ar can affect the occurrence and distribution of Ar in a mineral's crystal lattice. Specifically, the relationships between deformation/metamorphism and Ar mobilization are still poorly characterized, especially in rocks from ancient tectonic settings. In this research, we investigate biotite and amphibole deformation and recrystallization by characterizing their crystal lattice orientation, misorientation, and zoning through an SEM-EBSD system. Samples are Precambrian rocks from the Rae Craton of northern Canada, with lithologies spanning weakly deformed plutonic bodies (monzogranite, granodiorite, and tonalite) to amphibolitic orthogneiss and garnet-micaschist. Existing step-heating 40Ar/39Ar data for the samples indicate complex Ar systematics. Our new information on intracrystalline deformation in biotite and amphibole, combined with geochemical and petrologic data, are used to explore the relationships between microstructures and trace element distribution. These results provide the foundation for ongoing in situ 40Ar/39Ar and in situ 87Rb/87Sr studies that will investigate the relationships between deformation, thermal history, fluid-rock interactions, and Ar (and Sr) reservoirs in these Precambrian tectonites.

Rates and timing of Earth system processes

QUANTIFYING REGIONAL RATES AND TIMING OF EXHUMATION ACROSS SOUTHERN GERMANY FROM PRESERVED STRATIGRAPHY, THERMOCHRONOLOGY, AND COSMOGENIC RADIONUCLIDES

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A search is underway to select a suitable underground storage facility for radioactive waste while decommissioning Germany's nuclear energy program. Limits have been placed on long-term exhumation rates to ensure safe burial over million-year timescales. To constrain erosional histories over different timescales across southern Germany, we compile cooling ages from apatite (U-Th-Sm)/He and apatite fission track data, catchment-averaged erosion rates derived from in-situ-produced 10Be concentrations, and depths of erosion identified from preserved sedimentary cover. Specifically, cumulative erosion through Mesozoic cover strata and underlying Variscan basement ranges from 0-3 km relative to a middle-Jurassic stratigraphic horizon, which is preserved within the Rhine Graben and the tableland in southwestern Germany. Over shorter timescales, catchment-averaged erosion rates derived from 10Be concentrations in river sand range from 20-90 m/My in granitic watersheds to 30-120 m/My in watersheds underlain by Mesozoic strata. Comparing 10Be-derived erosion rates and cumulative erosion depths relative to the middle-Jurassic horizon implies either periods of reduced erosion rates relative to Holocene-Pleistocene timescales integrated by the 10Be proxy or beveling post-middle Jurassic strata that previously covered the relatively flat tableland topography. We investigate these hypotheses with new apatite (U-Th-Sm)/He and apatite fission track samples distributed across southern Germany. Preliminary apatite fission track and (U-Th-Sm)/He data show late-Cretaceous cooling ages across central Germany and mid-Cenozoic cooling ages in southern Germany. Analysis is ongoing; however, reset ages suggest that the post-Jurassic exhumation thicknesses exceed preserved cover strata thicknesses, with different exhumation histories in central and southern Germany.

Developments and challenges in fission-track thermochronology

AUTOMATED SEMI-TRACK LENGTH MEASUREMENTS AS A TOOL FOR PREDICTING ANNEALED DISTRIBUTIONS FOR THERMOCHRONOLOGICAL RECONSTRUCTION

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Apatite fission track thermochronology offers an almost unique insight into not only the timing but also the rate and magnitude of low-temperature thermal events. This additional level of interpretation is possible due to the relationship between temperature and the consequential thermal annealing of fossil tracks. As these interpretations are underpinned by length distributions of confined fission tracks, samples must yield sufficient numbers of confined tracks to be representative of the population, generally considered to be ,100 confined tracks or more. Reaching this target, however, can be problematic in young or low-U samples which demonstrate low spontaneous track densities, or small grains with limited track counts. One method proposed to address this issue is the use of semi-tracks; fossil tracks which breach the etching surface but still retain a measurable partial track within the grain. As described by Laslett and Galbraith (1996), the length distribution of semi-tracks is related to that of confined tracks, and can thus be used to predict the population length distribution for use in thermal history modelling. Advances in digital image capture and automated track measurement now allow thousands of semi-tracks to be measured with minimal human input, reducing both the required time and the scope for analyst bias. Here we present new results measured using FastTracks (version 3.2.29) software from Durango and Fish Canyon Tuff apatite as well as other well-characterised samples, yielding a variety of confined track distributions to evaluate the reliability of semi-track predictions and the applications for real-world samples.

Rates and timing of Earth system processes

ON THE LAGTIME BETWEEN INITIAL DEFORMATION AND ROCK COOLING: AN EXAMPLE FROM THE NORTHERN ANDES.

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The growth of ancient orogens is recorded in syn-orogenic sediments in foreland basins and can be reconstructed by studying their provenance. The southern Eastern Cordillera and the adjacent Putumayo retro-arc foreland basin synorogenic sediments in the southern Colombian Andes show a Late Maastrichtian to Paleocene (75-72) polarity reversal in detrital zircon U-Pb ages corresponding to the shift sources in the Amazonian Craton to Andean arc sources. These provenance changes had been associated with the early stages of the orogenic construction and are often undetectable through low-temperature thermochronometry.

We present 30-20 Ma apatite fission-track and 5-8 Ma apatite (U-Th)/He ages retrieved from the Jurassic subvolcanic arc rocks along the easternmost deformation front of the southern Colombian Andes. Thermal modeling constrains the onset of cooling as Oligocene (30-35 Ma). This 30-40 myr discrepancy between the estimates of the initial uplift and thermal cooling exhumation result from slow initial exhumation, at rates, insufficient to cause measurable cooling with available thermochronometric methods. Oligocene to recent uplift occurred at 5-4.4 °C/km. A similar pattern of cooling lagging behind the initial minor uplift has been documented elsewhere in the northern sector of Eastern Cordillera.

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Rates and timing of Earth system processes

APATITE U-PB THERMOCHRONOLOGY CONSTRAINS CHEMICAL AND MECHANICAL PROCESSES AT THE BASE OF THE SUBDUCTION SEISMOGENIC ZONE

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Dating processes at the base of the subduction seismogenic zone, where large earthquakes nucleate and slow slip occurs, is challenging due to the relatively cool temperatures (300-500 °C) and dearth of in-situ thermochronometers. The Pb* closure temperature in apatite overlaps with these temperatures, and apatite is nearly ubiquitous in rocks along this portion of the megathrust. Apatite dynamically recrystallizes during deformation, dissolves and reprecipitates during fluid flow, and chemically tracks metamorphism and metasomatism. We integrate apatite U-Pb thermochronology, petrology, and microstructural analysis from exhumed subduction complexes including Catalina Island, CA, Andros and Crete islands, Greece, and the Central Alps to date mechanical, chemical, and thermal processes. Petrologic and microstructural analysis reveal multiple generations of apatite associated with prograde, peak, and retrograde P-T conditions. Apatite U-Pb dates from the Catalina Schist coherent amphibolite are 113 ± 16 Ma and overlap with garnet Lu-Hf ages of ,115 Ma interpreted to record peak metamorphism and hornblende and white mica Ar-Ar cooling ages of 107-100 Ma. The apatite U-Pb date from the Catalina Schist epidote amphibolite unit is 111 ± 13 Ma which overlaps with the first record of metamorphism in this unit. We link these dates to process through grain microstructures, textural and petrologic setting, and geochemical zoning. These preliminary data suggest that apatite U-Pb thermochronology records when rocks are at the base of the seismogenic zone filling an important chronologic gap between other geo- and thermochronometers in subduction systems and providing direct time constraints on a range of chemical and mechanical processes.

Rates and timing of Earth system processes

RECURRENT E - W OSCILLATIONS OF THE ICE FLOW DIVIDE IN THE ROSS SEA FROM THE LATE OLIGOCENE TO THE PRESENT DAY

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We present a multidisciplinary provenance study on legacy cores drilled in the 1970s during DSDP Leg 28 at sites 270, 271 and 272, in the Central Ross Sea, Antarctica. The three sites combined provide a discontinuous glacio-marine sedimentary record covering 28 myr, from the first sediments deposited on basement rock up to the Last Glacial Maximum.
The three boreholes are located in a key site, in the middle of the Ross Sea at around 180° longitude, close to the present ice sheet front which represents the divide between the ice flows fed by West Antarctica (WA) and East Antarctica (EA). The study comprises U-Pb dating of detrital zircons and apatites, coupled with apatite fission-track (FT) dating and trace element (including REE) compositions. We applied a recent published bedrock categorization to investigate the lithology of the source based on the geochemical analysis of the apatite.
From DSDP site 270, the data show that the source of the late Oligocene diamictites is a distant region, likely southern West Antarctica, indicating that a substantial continental ice sheet already existed in the late Oligocene. From DSDP 272 and 271 (18 Ma to Present), our data show eight snapshots of the ice flow pattern highlighting a recurrent E-W oscillation of the WA-EA ice flow divide.

Rates and timing of Earth system processes

DETRITAL APATITE FISSION-TRACK DATING OF GREENLAND OFFSHORE SEDIMENTS: EVIDENCE FOR LATE CENOZOIC HIGH-ELEVATED PLATEAU EROSION

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Formation of plateaus in polar regions is largely debated. In particular, whether the high-standing landscape contributed to the sediments production during the Cenozoic is a primary issue in deciphering the impact of glaciation on topography shaping. Southeast Greenland is a suitable location to test the impact of late Cenozoic climate changes on sediment production for the occurrence of a high-elevated plateau, large ice-sheet and for the very little tectonic activity during this time.

Here we show detrital apatite fission-track (AFT) data from Greenland emipelagic marine record. 10 samples have been collected from two ODP cores, site 918 and site 987, that cover a time interval from late Miocene to Middle Pleistocene. Mixture distribution of AFT ages have been decomposed giving populations in agreement with the in-situ data.

Populations P1 (,27 Ma) and P2 (64 to 54 Ma) show a nearly constant age along the stratigraphic record. The populations P3 (141 to 179 Ma) and P4 (206 to 314 Ma) are the most abundant and persistent through the cores and they get older moving towards the younger stratigraphic age, showing an unusual trend.

We interpret this trend as a consequence of relevant contribution of sediment from high-standing plateau that is characterized by older in-situ AFT ages. We compare measured ages with synthetic ages representing an enlargement of the catchment over high standing plateau. We thus confirm the hypothesis that when a large portion of a high elevated landscape is subject to erosion the detrital populations can get older for younger sediments.

Rates and timing of Earth system processes

LOW-TEMPERATURE THERMOCHRONOLOGY REVEALS FAULT-CONTROLLED CENOZOIC EXHUMATION IN THE UPPER HYLAND VALLEY, YUKON

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The Upper Hyland fault (UHF) is one of many assumed-Cretaceous N-NW striking dextral faults in the Northern Canadian Cordillera. However, we lack precise information on the kinematics and timing of Cretaceous and younger structures in this region. Here we use low-temperature thermochronology and thermal history modeling to quantify the timing and magnitude of exhumation in the Upper Hyland valley and to investigate the relationship between exhumation and faulting. Other faults in the area include the Shannon (ShF) and Hyland Valley (HVF) faults, which strike sub-perpendicular to, and are inferred to connect with, the UHF.

We present 24 apatite (U-Th)/He, 10 apatite fission track, and 15 zircon (U-Th)/He ages that generally range 100–40 Ma. Mean fission track lengths range 9.3–13.4 μm. The youngest ages were obtained from the inferred hanging wall of the ShF and footwall of the HVF. Nodal density plots derived from inverse thermal history models reveal coeval pulses of rapid cooling (~13 °C/Myr) in these areas ~60–50 Ma. Samples yield similar cooling histories east and west of the UHF suggesting no differential exhumation occurred across this structure during the Cenozoic. We propose that dextral motion on the UHF reactivated the HVF and ShF as a normal and reverse fault, respectively west of the UHF. We suggest that this translation was driven by the onset of dextral displacement along the Tintina fault, a lithospheric-scale structure that strikes parallel to the UHF ,150 km to the west.

Rates and timing of Earth system processes

APATITE FT-U/PB-REE ANALYSIS BY LA-ICP-MS FOR PROVENANCE AND BASIN EVOLUTION STUDY OF ANCIENT STRATA

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Provenance analysis is a powerful method for studying the ancient sediment pathways, the evolution of basins, and the tectonics of the source. However, detritus in sediments often provide non-unique answers. To address this issue, Sullivan et al (2018) established an integrated technique of U-Pb and multiple trace-element analysis of detrital apatite by analyzing current river sediments. However, the temporal resolution of this tool needs to be checked for ancient sedimentary strata. In this study, we checked the availability of this tool at the well-studied Linxia Basin, which has well-established stratum ages by magnetostratigraphy and source-changing events dated by the zircon U-Pb. We collected 14 detrital samples from the stratum and the catchments, and analyzed them for apatite Fission track, U-Pb, and multiple trace-element (FT-U/Pb-REE) using LA-ICP-MS.

Our results show that as the depositional ages increase, there is an obvious trend changing of AFT peak ages between 12 and 9 Ma, as well as a significant change in detrital apatite U-Pb ages and REE data, representing the event of source change. Subsequently, there is a clear trend shifting of AFT peak ages at 6-4 Ma, indicating a sediment recycling event linked to the time of initial deformation in the Linxia Basin. Our results demonstrate that the apatite FT-U/Pb-REE tool is efficient in identifying the origin of ancient sedimentary strata and the deformation time of the Basin itself.

O'Sullivan, G. J et al., (2018). An integrated apatite geochronology and geochemistry tool for sedimentary provenance analysis. Geochemistry, Geophysics, Geosystems, 19, 1309–1326

Rates and timing of Earth system processes

OVERLAPPING BETWEEN EXHUMATION AND LONG-TERM CONTINENTAL ARC MAGMATISM: TRACKING THE CRUSTAL THICKENING AND UPLIFT OF THE WESTERN CENTRAL ANDES

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The western flank of the Central Andes records the early phases of Andean orogenesis related to inversion tectonics which took place since the Late Cretaceous and hosts the record of eastward migration of the Meso-Cenozoic continental arc magmatism. Currently, a hyperarid climate in northern Chile modulates erosion rates below 0.2 mm /My, which are often extrapolated back into the Neogene and related to an orographic barrier resulting from the Andean uplift. However, the timing of the establishment of that orographic barrier still needs to be constrained. We evaluate the transfer of deformation and shortening from the arc to retro-arc zones in the successive stages of compression imposed by the subduction regime. Low–temperature thermochronology (AFT and AHe) is envisaged to detail the timing of the exhumation of crustal blocks along the main structures of the forearc and thus integrated with thermo–kinematic modelling, and crustal thickening and surface uplift estimations based on geochemical proxies, to better constrain the early phases of orogenesis. The study region extends between the Coastal Cordillera and the surroundings of the Atacama basin (22° and 24° south Lat.). Preliminary results show a protracted early Eocene cooling event in the Cordillera de la Costa and the western flank of the Domeyko Cordillera. Geochemical proxies show paleo-crustal thickness above 40 km since the Late Cretaceous.

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Improvements in handling and modeling low temperature thermochronological data

THINKING BEYOND THERMOCHRONOLOGY: THE "GREAT UNCONFORMITIES" AS CASE STUDIES IN INCORPORATING MULTIPLE TYPES OF DATA INTO DEEP-TIME MODEL INTERPRETATIONS

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The Great Unconformities represent up to over a billion years of missing time in the North American stratigraphic record, have been globally correlated with other Precambrian erosion surfaces, and have been linked with major geodynamic and climate changes in the Earth system. Low-temperature thermochronology has been applied to explore the timing and mechanisms of sub-Great Unconformity exhumation across North America. Given the deep-time, long temporal scale of this feature, it is unlikely that thermochronologic data alone can resolve a single thermal event corresponding to exhumation. Instead, multiple time-temperature models that vary significantly in timing of exhumation-related cooling likely explain the data equally well. By incorporating additional information beyond thermochronologic data, some models can be eliminated, reducing the number of viable hypotheses. We compare studies of the Grand Canyon region, USA and southeastern Ontario, Canada that combine (U-Th)/He dates with non- thermochronologic data including structural and stratigraphic observations, petrologic relationships, Conodont Alteration Index values, and paleomagnetic blocking temperatures. These additional data are used to define exhumation timing hypotheses tested against thermochronologic data. In the Grand Canyon, preserved stratigraphy and faults suggest multiple episodes of Stenian-Tonian exhumation consistent with plume impingement followed by extension and faulting during Tonian- Cryogenian breakup of Rodinia. In Ontario, paleomagnetic heating and petrologic interpretations require extensive exhumation in the Ediacaran-Cambrian, likely associated with plume impingement and opening of the Iapetus Ocean. Though these studies yield different outcomes regarding the timing of Great Unconformity exhumation, both show the importance of using all available data to understand deep-time thermal histories.

Rates and timing of Earth system processes

MESO-CENOZOIC MORPHOTECTONIC EVOLUTION OF THE NORTHEASTERN TIBETAN PLATEAU AND SOUTHWESTERN NORTH CHINA CRATON MARGIN: A THERMOCHRONOLOGICAL INSIGHT AND REVIEW

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The surface uplift and deformation of the North China Craton and northeastern Tibetan Plateau (i.e., Haiyuan-Liupanshan and Western Ordos Arcuate Tectonic Belt area) induced differential evolution of the geology, climate and geography of the western and central China. However, but the reasons that yielded to the thickening of the crust and to the development of abrupt topography remain controversial.

In this study, we summarize new and published hundreds of low-temperature thermochronological data, mostly given by apatite fission-track (AFT) methodology. 'Boomerang' plots and thermal history modeling suggest four cooling events: Late Triassic-early Jurassic, Mid-Late Jurassic-Early Cretaceous, Late Cretaceous-Early Cenozoic and the late Cenozoic. The AFT ages and MTCL distribution maps show: (1) a wide range of values at the margin of the Ordos Basin, indicating a regional difference in the cooling process; (2) AFT ages along three N-NE swath profiles across the Haiyuan-Liupanshan Fault Zone tend to decrease from ca.70 to 7 Ma, indicating a multi-stage activity of this fault. We therefore indicate that above-mentioned cooling events and age pattern of thermochronological data are the results of a complex and long-lived fault activity and deformation. In particular, the formation of Western Ordos Arcuate Tectonic Belt can be traced to the Mid-Late Jurassic, while the arcuate belt was finally shaped in the Late Cenozoic.

Rates and timing of Earth system processes

LOW TEMPERATURE THERMOCHRONOMETERS, BOREHOLE SAMPLES AND QTQT: A WINNING COMBINATION TO RECONSTRUCT PALAEO-GEOTHERMAL GRADIENTS AND EXHUMATION HISTORIES; THE CASE OF THE MIDLAND VALLEY SEDIMENTARY BASIN (SCOTLAND)

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Reconstructing exhumation histories from low temperature thermochronometers is hindered by the lack of constraints on the evolution of the thermal structure of the crust; usually, a temporally and spatially constant geothermal gradient is assumed. Here, we have used QTQt to inverse model apatite fission track and (U-Th)/He data from boreholes in the Midland Valley (MV) Basin (Scotland) to reconstruct their thermal histories and, crucially, the palaeo-geothermal gradient and its variation through time. The MV is an extensive sedimentary mainly consisting of alternating succession of sandstone and siltstone with mudstone, limestone and coal, predominantly of Carboniferous and Devonian age. Low temperature thermochronological data from across the eastern sector of the basin and the UK Geoenergy Observatories borehole in Glasgow indicate a
1) rapid burial in the Carboniferous-Permian; 2) Permian-Mesozoic cooling and a 3) a relatively rapid early Cenozoic cooling, an event that is asynchronous across the basin. Using a combination of forward and inverse modelling techniques, we constrain the palaeo-geothermal gradients and the exhumation history of the basin. The preliminary results from the models suggest that, whereas the maxima temperatures were obtained in the late Carboniferous, the maximum burial was actually in the late Cretaceous – early Cenozoic, due to a decrease in geothermal gradient.

Rates and timing of Earth system processes

ASSESSING THE CORRELATION BETWEEN EXHUMATION AND GEOTHERMAL ANOMALY DEVELOPMENT IN THE WESTERN CANADA SEDIMENTARY BASIN.

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A major geothermal anomaly is present in the Liard Basin, a sub-basin of the Western Canada Sedimentary Basin. The Liard Basin comprises two main sequences, (1) Paleozoic-Triassic passive margin deposits and, (2) Jurassic-Cenozoic foreland basin strata related to the development of the Canadian Cordillera. We aim to investigate how the evolution of the Liard Basin possibly lead to the development of the geothermal anomaly. We will assess the thermal history of the basin strata using apatite and zircon (U-Th)/He (AHe, ZHe) analysis. We focus our study on samples from two regions. In the west, we dated 21 samples across the deformed and undeformed Liard Basin including Devonian, Carboniferous, Triassic, and Cretaceous strata. In the east, we dated 9 samples from Cambrian strata and underlying Precambrian basement of the exposed Canadian Shield. Preliminary results show wide intra- and intersample dispersion in both areas. In the west ZHe dates are partially reset, which sets post-depositional maximum temperatures between 160 and 200°C. Carboniferous strata yield mainly Paleozoic dates, and Cretaceous yield Mesozoic dates. Triassic samples are reset with mainly Cretaceous dates. In the east, ZHe dates from Cambrian strata are mostly not reset, limiting the post-depositional burial temperature <160°C. In contrast, the underlying Proterozoic basement samples present mostly Mesozoic dates. Throughout the study region our data reveal complex radiation damage accumulation and annealing relationships, and parent-daughter imbalance. The next steps of this project comprise forward and inverse thermal modeling to resolve the thermal history of the Liard Basin.

Rates and timing of Earth system processes

LATE PALAEOZOIC COOLING AND EXHUMATION ACROSS THE NORTHERN FENNOSCANDIAN SHIELD AND COEVAL BASIN DEVELOPMENT AT THE FINNMARK PLATFORM

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Norway's Finnmark region comprises the northernmost Caledonian nappes thrusting over the lower topography of the Fennoscandian shield. Scarce previously published thermochronometric data point to late Palaeozoic-early Mesozoic cooling in this area, but its precise timing and nature remain loosely constrained. This work presents Laser Ablation Apatite Fission Track (LAFT), apatite U-Pb (AUPb) double-dating, and trace element geochemistry obtained for the first time at the Geological Survey of Norway from samples collected in a NE-SW transect through the northern Fennoscandian shield. NIST 612 was used as the primary reference material to correct for LA-ICP- MS session drift with MAD and McClure apatites used as standards for AUPb. Durango and FCT apatites were used as LAFT primary and secondary standards, following a Zeta-based calibration approach. Our preliminary results yield AUPb ages comprising ca. 2.7-1.7 Ga from a Caledonian basement window and the Fennoscandian shield, coherent with the Svecokarelian orogeny. Overdispersed LAFT central ages are linked to variable apatite chemical compositions in more pelitic protoliths, whereas granitoids with central ages passing the $\chi 2$ test suggest Fennoscandian shield cooling during Late Devonian-early Carboniferous. Inferred cooling closely precedes the deposition of Carboniferous fan delta deposits of the Soldogg Formation unconformably over the weathered Neoproterozoic Barents Sea Group metasediments in the Finnmark platform. These results suggest Early Carboniferous continental weathering and exhumation in the northern Fennoscandian shield. Future work will involve LAFT track length modeling, 40Ar/39Ar dating, illite K-Ar dating of the weathered basement, and source-to-sink analyses to constrain long-term exhumation patterns in the northern Fennoscandian shield.

Improvements in handling and modeling low temperature thermochronological data

CANADIAN THERMOCHRONOLOGY (CATCH): A RELATIONAL DATABASE FOR CANADIAN LOW-TEMPERATURE THERMOCHRONOLOGY DATA

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Low-temperature thermochronology (LTT) data have become increasingly important in Canadian geoscience studies over the last several decades and are available across numerous publications, reports and graduate student theses. However, since none of these data types are analyzed within the Geological Survey of Canada's (GSC) laboratories, they have not historically been captured by the GSC-hosted Canadian Geochronology Knowledgebase (CGKB). Further, the complex relationship between LTT age, metadata such as mineral chemistry and grain size, and resulting modelled time-temperature histories (which often incorporate additional geological constraints) are at a disconnect with CGKB's "interpreted age result" design that is suitable for other geochronology data types. As part of the GSC's GEM-GeoNorth research program, and in partnership with Lithodat Pty Ltd., all published LTT data from northern Canada have been compiled and incorporated into a purpose-built relational database. This new database includes more than 1400 unique samples, with over 970 fission-track dates and 3230 (U-Th)/He single grain data entries, and incorporates metadata required for thermal history modelling, such as individual fission track lengths and individual grain mineral chemistry. Presently, the GSC is in the process of expanding this database to include the remainder of the LTT data for southern Canada and modelled thermal histories for all Canadian samples. An accessible, complete and functional LTT database will form the foundation for regional and national scale studies of upper crustal processes such as sedimentary basin evolution, brittle faulting, and tectonic- and climate-driven landscape evolution.

Rates and timing of Earth system processes

EXHUMATION PROCESSES DURING ACCRETION STUDIED USING LOW -TEMPERATURE THERMOCHRONOLOGY OF THE WRANGELLIA TERRANE, VANCOUVER ISLAND, CANADA

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Located close to the plate boundary of western North America, Vancouver Island is an ideal place to study the interactions along the interface between the North American and Pacific plates. Uplift of Vancouver Island began with the youngest Cenozoic accretion process and is still active. We measured Paleocene to Eocene (23.3 to 75.9 Ma) apatite Fission track ages and, for the first time, mainly Oligocene (19.8 to 36.6 Ma) apatite U-Th-He ages for 16 bedrock samples of the Wrangellia terrane on southern Vancouver Island. Thermal inverse modelling results suggest a uniform and steady uplift history for over half of the samples (cooling rate <2.5°C/Ma), whereas the remaining samples show an increase in cooling rate (fast up to 16.2°C/Ma) since early Oligocene. The comparison and analysis of the accelerated exhumation recorded in samples from Vancouver Island, Haida Gwaii and southern Alaska suggest the fast cooling probably is not an uplift response of the continental margin by northward translation of the Yakutat terrane as previously suggested. The fast cooling of samples of Haida Gwaii and Vancouver Island instead indicates either an exhumation response of regional magmatism or extensional faulting. The uplift of southern Vancouver Island may be a feedback to the extension or young faulting caused by the oroclinal rotation events following the collision and accretion of Siletz-Crescent terrane to the continent at around 52 Ma. To constrain this hypothesis, more complete thermochronology data across terrane-bounding faults are needed across all of Vancouver Island.

Rates and timing of Earth system processes

PETROGENESIS AND ITS DYNAMIC IMPLICATIONS OF XIFANPING PORPHYRIES, IN TAOZI TOWNSHIP, WESTERN SICHUAN PROVINCE, CHINA

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The Xifanping porphyries are located on the Yangtze platform, east of the Jinshajiang-Red River strike-slip fault, tectonically. It is an important window to study the magmatic response and deep process of the eastern margin of the Qinghai-Tibet Plateau post-collision between Indo-Asian. However, their petrogenesis and tectonic significance remain controversial. Genesis and association with the Sanjiang alkali-rich porphyry belt and strike slip have great significance for the discussion of the remote magmatic response and deep process after the Indo-Asian collision. We present our study of pluton No. 80 and 56 in Xifanping, as well as porphyries never been dated. 9 zircon U-Pb datings with previous studies indicate the emplacement at 29.9-35.8 Ma, contemporaneous with Cenozoic alkali-rich porphyry in western Yunnan. In the Xifanping area, there are at least 3 suites of magmatic activity. Among them, magmatic activity's scale and duration decreased successively. Xifanping porphyries show C-type adakitic rocks' geochemical characteristics, indicates derived from the partial melting of the thickened mafic lower crust beneath the western Yangtze Craton with a small amount of the asthenosphere mantle. Xifanping porphyries with various structures and the emplacement ages are similar and consistent in mineral composition, geochemistry, trace elements and Hf isotope composition of zircon, which are the products of successively ascending from the source.
We conclude that the Xifanping adakite-like porphyries were the response to the lithosphere scale right lateral movement on China continental, as the result of the secondary SN and near EW - trending faults in the western Yangtze Craton following the Indian–Asian collision.

Rates and timing of Earth system processes

BURIAL AND EXHUMATION OF NORTHERN SWITZERLAND SINCE 350 MA

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Siting a repository for radioactive waste requires knowledge on the site-specific thermal and latest burial and exhumation history. The site selection process in Switzerland has narrowed down to three siting areas, all located in northern Switzerland. The host rock is a middle Jurassic clay, located within a Triassic to uppermost Jurassic sediment sequence that lies on top of Variscan crystalline basement and is covered by Neogene sediments of the northern foreland basin of the European Alps. Previous studies, based on the stratigraphic record, on thermochronology and vitrinite reflectance data, have reconstructed the thermal history of the area to gain information on the large time gaps existing in the stratigraphic record. Aspects not yet fully resolved include (a) the potential Jurassic hydrothermal activity affecting basement and sedimentary cover, (b) the role of a Cretaceous (and perhaps Palaeogene) sedimentary cover, and most importantly (c) the onset and amount of a late Neogene exhumation event.

Samples from the crystalline basement rocks (surface, borehole) were collected. Apatite FT ages range from 4.5 to 101 Ma, indicating a fully to partially annealed status, offering the possibility to model the thermal history since the Variscan orogeny with the FT data. In line with previous thermochronological data and modelling results, we infer substantial burial underneath Cretaceous (but not Palaeogene) sediments. Late exhumation of the rock column started after 10 Ma and reached a vertical movement of several km in areas more proximal to the European Alps, while slightly more than 1 km close to the siting areas.

Rates and timing of Earth system processes

THE NIEDERE TAUERN – CONTINUATION OF A TRANSPRESSIVE WRENCH ZONE

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The Eastern Alps were substantially shaped by northward movement of the Dolomites Indenter and eastward extrusion of the orogenic wedge in front of the indenter. A resulting sinistral wrench zone runs through the western Tauern Window (TW) and continues eastward along the Salzach-Ennstal-Mariazell-Puchberg Fault (SEMP). Low-T thermochronological studies demonstrate rapid Miocene cooling of the TW units below ~80°C due to folding and coeval erosion. To the east of the TW, the extensive Katschberg fault system (KFS) decoupled the Gurktal Block (GB) in its hanging wall from folding. The KFS was active between 20 and 17 Ma, in the early Miocene. The GB in the hanging wall preserves Eocene cooling ages below ~80°C. The Niedere Tauern (NT), north of the GB and south of the SEMP line, seem to be structurally closely linked to the TW. The NT show a similar Miocene cooling history; there isn't an intervening Cenozoic structure between the TW and the NT. Preliminary zircon (ZHe) and apatite (AHe) helium ages are around 20-23 Ma and ~15 Ma, respectively. Published apatite fission track ages fall in-between and partly overlap with our results, demonstrating a rapid cooling pulse in the lower Miocene. Published AHe ages of ~6 Ma along the southern margin of the NT relate to late Miocene normal faulting along the Murtal Fault-System. We discuss the linkage between the TW and the Niedere Tauern and characterize in greater detail the exhumation history along the eastern wrench zone.

Rates and timing of Earth system processes

LONG TERM SAN ANDREAS FAULT OFFSET RE-EXAMINED THROUGH A KEY PIERCING POINT

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The San Andreas Fault (SAF) zone is an extensively studied transform fault system used to understand the rates and timing of plate-boundary-scale deformation. SAF total displacement estimates are constrained by piercing points: preserved geologic features separated by fault movement. However, current proposed piercing points yield diverging total offset estimates ranging from 160 to 240km. For piercing points to yield the true displacement, it is imperative that the piercing points were together as one unit until SAF initiation.

This study revisits a key plutonic piercing point, the Triassic megaporphyritic monzogranite bodies of Liebre Mountain and Mill Creek, thought to represent 160km of total SAF displacement. We will apply a multichronometer approach to 1) confirm whether the two granitic bodies were the same pluton and 2) compare the exhumation histories of the two sites, pinpointing when their cooling histories diverge. We use cathodoluminescence and zircon U-Pb LA-ICP-MS dating to determine crystallization ages. We present new apatite and zircon (U-Th)/He and apatite fission-track ages combined with published thermochronologic ages from each site to model the plutons' exhumation since emplacement. Initial zircon U-Pb data indicates that the two sites contain crystallization ages around 240 Ma with ~1.6 Ga inherited cores. Preliminary apatite (U-Th)/He data suggests that the piercing points' thermal histories diverge before apatite He closure temperatures. Results from this study will re-examine the validity of the 160km offset constraint used in palinspastic reconstructions of the SAF for over 40 years and allow us to reconstruct the fault's long-term displacement history.

Rates and timing of Earth system processes

TECTONIC AND EXHUMATION HISTORY OF THE ALBANIDES OROGENIC BELT

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The Albanides orogenic belt in the central-eastern Mediterranean results from the eastward subduction history of the Adriatic microplate beneath Eurasia. The Albanides lie between the Dinarides to the north and the Hellenides to the south and are characterized by external compression, in the west, and internal extension, in the east. They consist of NW-SE oriented geological domains reflecting a polyphasic evolution with an episode of Mid Jurassic ophiolite obduction in the internal zones, followed by the development of a Cenozoic, W-verging, fold-and-thrust-belt in the external Albanides. Evidence of this evolution is provided by tectono-stratigraphic data and by published thermochronological data, many of which are from the internal domains of the orogen. In the external and southern domain of the orogen, there are no thermochronologic data and the available tectono-stratigraphic data suggest an unsteady propagation of deformation possibly from the Late Cretaceous. To investigate the long-term evolution of the Albanides, such as the timing of deformation and the spatio-temporal pattern of exhumation, we present 32 preliminary apatite (U-Th)/He ages. Within the southern external units, we find fully reset ages clustered between 2.5 and 5 Ma in the east and partially- to non-reset ages in the west. In the northern external units, we find fully reset ages ranging from 17 in the east to 3 My in the west. The AHe data will be integrated with AFT data to obtain more detailed thermal histories and with structural data to reconstruct the thermo-tectonic evolution of this orogen.

Developments and challenges in fission-track thermochronology

TRANSITIVITY IN ANNEALING MODELS OF FISSION TRACK THERMOCHRONOLOGY: INVESTIGATING DEVIATIONS FROM ARRHENIUS ACTIVATION ENERGY.

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Annealing of fission tracks in minerals refers to the restoration of crystal structure. This is caused by the thermal recombination of atoms displaced by fission fragments and the vacancies left behind. This leads to track shortening as observed after etching. Annealing kinetics is described by empirical Arrhenius-type equations that relate track length with temperature and heating duration. These equations are fitted to laboratory data but are applied to geological problems on much longer timescales. Different equations fitted to the same data can predict different length reductions when applied to geological times. The trends of the annealing equation encode underlying atom-vacancy recombination mechanisms that can be inferred from an analysis of the empirical Arrhenius activation energy and its reciprocal, the transitivity function. These patterns can be compared with known solid-state chemical processes. For example, constant Arrhenius activation energies are characteristic of single activation energy processes and are described by Parallel Arrhenius models. In this contribution, we focus on the transitivity function and discuss the mechanisms underlying the Parallel Arrhenius, Parallel Curvilinear, Fanning Arrhenius, and Fanning Curvilinear equations, which are commonly used in thermochronological applications.

Advances in noble gas and solid state thermochronology

(U-TH)/HE GEO- AND THERMOCHRONOLOGY OF CARBONATES

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We explore and quantify helium retentivity in speleothem-derived carbonates using independent U/Th and U-Pb ages, step-heating diffusion experiments, microstructural characterization and thermal modelling.
(U-Th)/He ages of aragonite layers which were dated during this study are statistically identical to independent ages and thus indicate that aragonite speleothems as old as 6 Ma are fully retentive to helium at surface temperatures of 0-20°C. Step heating diffusion experiments constrain the activation energy for He diffusion in aragonite to 31.0 ± 1.5 kcal/mol and the log of the frequency factor (D0) to -3.3 ± 0.5 m^2/s. These parameters provide further indications that aragonite of a common grain size (,100 micron) is fully retentive across geological time scales at common surface temperatures (0-20°C). Considering a cooling rate of 10°C/Ma and a diffusion domain radius of 100 micron, the closure temperature of aragonite is ~70°C.
(U-Th)/He dating of calcite speleothems often yields ages which are lower than independent ages, implying that helium loss from calcite may occasionally occur even at surface temperatures as low as 1°C. Step heating diffusion experiments reveal a multi-domain diffusion behavior and suggest that helium loss occurs from diffusion domains which are much smaller than the crystal size. Despite this caveat, the observed microstructure can be tightly linked to helium retentivity. Although the use of calcite as a thermochronometer is not straightforward, it is often feasible. Furthermore, it may be possible to use microstructural data and independent ages to invert helium loss from calcite to near-surface paleo-temperatures.

Developments and challenges in fission-track thermochronology

COMPARISON BETWEEN ANNEALING ACTIVATION ENERGIES OF INDUCED AND SPONTANEOUS FISSION TRACKS IN ZIRCON

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Annealing activation energies can be retrieved from the trends of annealing equations fitted to experimental datasets. The Parallel Arrhenius (PA) equations are generated from the hypothesis that the annealing mechanism is based on a single constant activation energy. Parallel Curvilinear (PC) equations assume that the activation energy varies with temperature. Fanning equations describe multiple processes occurring simultaneously with different activation energies. We studied annealing activation energies in a zircon sample called ZPC (Poços de Caldas Brasil) using both induced and spontaneous fission tracks. The ZPC sample has a fission-track age of about 80 Ma and Th and U contents of 60 and 92 ppm, respectively. The annealing experiments on induced fission tracks were conducted on samples that had been heated to erase spontaneous fission tracks. The annealing experiments on spontaneous fission tracks were conducted on natural samples where tracks were generated while the mineral structure accumulated alpha recoil damage. After fitting the data with the PA and PC equations, we found that the annealing activation energies were higher for induced fission tracks than for spontaneous ones. Our analysis confirms previous results and introduces a new physicochemical approach to studying general annealing mechanisms. We also discuss how alpha recoil damage may influence the observed differences in annealing kinetics.

Rates and timing of Earth system processes

THERMO-TECTONIC HISTORY OF THE SOUTHERNMOST NORTHERN ANDES

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The tectonic patterns of the Peruvian Andes are driving mainly by margin magmatism and ocean - continent plate interactions since Late Cretaceous (Spikings et al., 2015). Nevertheless, heterogeneity in magmatic processes, crustal thickness and dip slab subduction fluctuations are evident from north to south, shown, for instance, by the absence of volcanic activity between 2–15°S during the Miocene to Holocene (Gregory- Wodzicki, 2000) or the Jurassic gap in exposure of magmatic rocks between 5 -17°S (Spikings et al., 2015).
Previous works in the Northern portion of Peru have shown a wide range (Paleozoic to Paleogene) of crystallization ages of the Piura segment of the Peruvian Coastal Batholith (Chew et al., 2007; Diaz et al., 1997; Hama, 1990; Ulrich, 2005; Winter, 2008; Witt et al., 2017) whereas thermochronological data of the surrounding areas within the cordillera exhibit different cooling events from Paleogene to Miocene (Naeser et al., 1991; Wipf, 2006).
This study has being focused on revealing the main mechanisms that took place in the northwestern part of Peru and the interactions among them, in order to disclose the thermo-tectonic history through apatite fission tracks dating, U-Pb ages, geochemical data and Hf and O isotopes.

Improvements in handling and modeling low temperature thermochronological data

AGE2EXHUME: A MATLAB/PYTHON SCRIPT TO CALCULATE STEADY-STATE VERTICAL EXHUMATION RATES FROM THERMOCHRONOLOGIC AGES IN REGIONAL DATASETS

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Several well-established thermal models allow for a detailed exploration of how cooling or exhumation rates, derived from single or multiple thermochronologic systems, evolved in a limited area or along a transect. However, integrating large, regional datasets into such models remains challenging due to spatially variable cooling rates, topographic relief, and surface temperatures. Here we present a thermal model that can be used to rapidly provide a synoptic overview of exhumation rates from thermochronologic data spread over wide areas. The model incorporates surface temperature based on a defined lapse rate and sample elevation relative to a mean relief value dependent on the thermochronometric system of interest. Other inputs include sample age, thermochronometric system, and an initial (unperturbed) geothermal gradient. The model assumes steady, vertical rock-uplift when calculating exhumation rates. For this reason, it does not replace more powerful and versatile thermal-kinematic models like Pecube, but it has the advantage of simple implementation and rapidly calculated results. In our example datasets, we show the results of exhumation rates based on 1785 thermochronologic ages from the Himalaya, and 932 ages from New Zealand, associated with five different thermochronometric systems; results were calculated in under a second on a standard laptop. Despite the synoptic nature of the results, we show how they illustrate several fundamental features of the mountain belt, including strong regional differences that reflect known segmentation patterns. Comparison of the results with geomorphic metrics has helped to probe tectonic and climatic controls on surface morphology.

Rates and timing of Earth system processes

UNVEILING THE CLOSURE TIME OF A PALEO-OCEAN: INSIGHTS FROM DETRITAL ZIRCON U-PB GEOCHRONOLOGY

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The East Junggar orogen, located in the southwestern Central Asian Orogenic Belt (CAOB), is a region that has been intensively studied, yet some key topics are still debated, such as the closure time of the paleo-oceans, the initial intracontinental uplift time, and the tectonic constitution in the area. A geochronology study was conducted using detrital zircon U-Pb dating of sandstone samples from Lower Permian to Middle Jurassic strata in the south flank of the Kalamaili Mountain to shed light on these topics. The age distribution of the samples indicated that the Carboniferous volcanic rocks and granites, northern Early Paleozoic Yemaquan Island arc, the Early Paleozoic Karameli and Armantai ophiolitic belts provided provenance for the sediments. Furthermore, the two stages of uplift that occurred in the Late Permian and Late Triassic correspond to the intracontinental Hercynian and Indosinian movements of the CAOB. The study revealed that the Paleo-Asian Ocean in the Junggar region closed before the Middle Permian. The amalgamation of tectonic units and emplacement of ophiolites in the East Junggar orogeny also occurred before the Middle Permian. The change in sediment sources from Middle Permian to Middle Jurassic indicates an intracontinental uplift and significant deep terrane exhumation of the East Junggar orogeny in the Late Permian. Additionally, combining the published detrital zircons U-Pb dating ages from other areas in the Junggar Basin, we think that a Precambrian crystalline microcontinent might be amalgamated within the Junggar orogeny, although the position of the microcontinent still requires further study.

Developments and challenges in fission-track thermochronology

BASEMENT ROCK THERMOCHRONOLOGY AND SEDIMENTARY BASIN ANALYSES IN THE MONGOLIA GOBI ALTAI MOUNTAINS

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The Gobi Altai Mountains are located in the southwestern part of Mongolia and are the easternmost extension of the Altai Mountain Range. It consists of discontinuous east-west trending mountains with an average elevation of 2-3km. The region was created by the collision of India and Eurasia. As a response to this collision, four major earthquakes occurred in and around the Gobi Altai Mountains in the last century. Gobi Altai is geologically located in the Central Asian Orogenic Belt the largest and longest-lived accretionary orogenic belt in the world from the Middle Triassic to the Neogene. Four samples collected are reddish granitic rocks, and the mineral composition is about 30% quartz, about 10% dark minerals, about 40% alkali feldspar and about 20% plagioclase. Two samples are a gray-red in color, consisting of about 15% quartz, 15% dark minerals, 15% alkali feldspar and 55% plagioclase, and the rock is granitic amphibole. After the conventional mineral separation, apatite and zircon were found in each sample. Characterization of the thermochronology of the Gobi Altai Mountains by fission tracks dating of apatite and zircon, together with U-Pb dating of zircon, will provide the long-term averaged erosion rate of the area. By comparing sedimentation rate found in the Valley of Gobi Lakes, north basin of Gobi Altai Mountains, the material transportation process in the region will be discussed.

Developments and challenges in (U-Th-Sm)/He thermochronology

HE DIFFUSION KINETICS IN HIGHLY RADIATION-DAMAGED ZIRCON: INSIGHTS FROM STEP-HEATING EXPERIMENTS FOR THE (U-TH)/HE SYSTEM

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The zircon (U-Th)/He thermochronometer has been extensively used to study thermal histories in diverse geologic settings. The accuracy of thermal and geologic interpretations relies on a robust understanding of ^{4}He diffusion. Guenthner et al. (2013) parametrized the relationship between ^{4}He diffusion kinetics and radiation damage, which is implemented in the zircon radiation damage accumulation and annealing model (ZRDAAM). This model represented an important step towards a more comprehensive understanding of ^{4}He diffusion; however, lingering questions and avenues for further improvements remain. The present work aims to expand upon and complement previously published diffusion kinetics with new step-heating experiments on high-damage zircon crystals above the rollover point from decreasing to increasing diffusivities (,1–2 × 10^{18} α/g). Accurate characterization of the damage-diffusivity relationship at and above the rollover point is crucial for the continued use of ZRDAAM in deep-time (>1 Ga) thermal history applications. We prepared c-axis oriented, thinly sliced, Sri Lankan zircons for step-heating experiments consisting of specimens GZ8 (2.53 × 10^{18} α/g), G168 (2.92 × 10^{18} α/g), GZ5 (3.97 × 10^{18} α/g), and G4 (4.70 × 10^{18} α/g). We report preliminary kinetic parameter values of E_a = 120.23 ± 0.71 kJ/mol (1σ) and D_0 = (2.20 ± 0.31) × 10^{-3} cm²/s (1σ) for G168, which agree with observed E_a and D_0 data trends from previously published experimental datasets. Although further work needs to be done, results for specimen G168 present convincing evidence for the robustness of the diffusion kinetics of ZRDAAM for high radiation damage levels.

Developments and challenges in fission-track thermochronology

SOME DIRECTIONS TO IMPROVE FISSION-TRACK ANALYSIS IN MONAZITE

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Recent studies highlighted the potential of monazite fission-track (MFT) analysis for ultra-low temperature thermochronology. We present the results of new experiments conducted on various monazite-bearing samples (monazite sand, S-type granitoids, cm-sized single crystals) and designed to improve our understanding of FT systematics in monazite, especially in terms of sample preparation and age interpretation.

Etching. Etching was performed with a H2O:HCl (1:1 by volume) solution at 90 °C. Step-etching is initially recommended on samples of unknown composition to avoid under-/over-etching and limit surface damage that can affect the quality of both reflected and transmitted light images. The majority of grains in this study required step-etching in five-minute intervals and were well-etched after 10-15 minutes, suggesting that etching for up to 60-90 minutes is not always needed.

Density calculation. Monazite commonly shows extensive compositional variations and thus a relatively wide range of densities (4.6-5.5 g.cm-3), which can noticeably influence MFT age calculation. It is therefore recommended to use electron microprobe analyses – a method routinely used to determine monazite composition – to calculate the density of domains used for MFT age determination.

Fission track annealing kinetics. Eighty-eight grains from a heavy mineral sand (NE Sri Lanka) yield individual MFT dates from 3.90 to 0.25 Ma. A fair correlation is found between MFT date and Si content in monazite, suggesting that higher Si (SiO2=1.5-2.0 wt.%) slows down FT annealing. This is supported by a tendency for Si-richer monazite grains to show longer confined track lengths (> 9 µm) than Si-poor ones (< 9 µm).

Improvements in handling and modeling low temperature thermochronological data

THERMOCHRONOLOGIC CONSTRAINTS ON EXHUMATION IN THE NORTHERN PAMIR

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The most important surficial structure bounding the northern and northwestern margin of the Pamir orogen is the Main Pamir Thrust (MPT); however, despite the importance of the structure, surprisingly little is certain about the displacement history of the fault. Constraining the onset of deformation has also proven challenging. We are attempting to resolve this question using QTQt modeling of thermochronologic data from profiles collected along the arcuate margin. The modeled cooling signals reveal 3 cooling pulses: in the Eocene-early Oligocene, early Miocene and latest Miocene. The limited resolution and the variable results caused by grain selection in our preliminary models argues against looking for spatial patterns within the two older pulses. Nonetheless, there are clearly discrete cooling events in the North Pamir. The earlier pulse is apparent across the northern part of the plateau but not on the SW flank. The early Miocene pulse could be related to motion along the MPT. This pulse is not seen in the Taergelake profile, in the immediate hanging wall of this fault. There, the youngest pulse is likely related to motion along the Pamir Frontal thrust. The relatively small amount of exhumation in this profile supports our structural interpretation that the MPT there has a low dip angle and might not have produced pronounced topography. Cooling in all profiles is likely linked to significant exhumation. Mechanisms to explain the intervening reheating episodes are more speculative; burial beneath sediments, beneath thrust sheets, or heating from below are the obvious candidates.

Rates and timing of Earth system processes

CHARACTERISING TURBIDITIC DEPOSITS THROUGH DETRITAL ZIRCONS IN THE AREZZO PROVINCE (NORTHERN APENNINES)

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Turbidites in the Northern Apennines foredeep have been considered as a deep marine deposit connected to a marine-marginal depositional system so they contain detritus from the basin margins, able to provide extrabacinal fragments. Studying this kind of deposit is important to understand what is going on in the margin during the deposition of the turbidites.
This type of work requires a multidisciplinary approach, including sedimentology, petrographic and geochronological analysis. One of the most important aspects to better identify the provenance of the turbidites is to define the age of the clasts taken charge by the turbidites which represent the source area. Due to their resistance to the alteration, both mechanical and chemical, zircons minerals are the best candidates for this purpose.
In this master thesis, about 300 detrital zircons were selected from the Falterona and Macigno sandstones, cropping out in the Arezzo area (Tuscany), extracting crystal grains from rocks through multi-stepped process: from the crashing and grinding up to the selection of specific range grainsize, trough batea and magnetic separator and then using methyl iodide. Cathodoluminescent images have been acquired to date the zircons by LA-ICP-MS analysis.
The obtained data show a different age population: the ancient zircons are about 1-2 Ga, many came from Palaeozoic and Mesozoic era and then between Middle Eocene and Late Oligocene, connected with the formation of late Apennines.

Improvements in handling and modeling low temperature thermochronological data

A FRAMEWORK FOR EVALUATING VARIATION IN (U-TH)/HE DATASETS

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I present here a framework for evaluating variation in (U-Th)/He datasets. The framework is objective, repeatable, and based on compatibility of thermal histories derived from individual (U-Th)/He dates. The structure of this new method includes three fundamental steps. First, the allowable thermal history of each individual grain is quantitatively constrained with a model. Second, the thermal histories of all grains from a sample are visualized on the same axes. Third, the compatibility of the allowable thermal histories of each individual grain is evaluated. This allows a user to assess whether variation among single grain dates can plausibly be explained (referred to here as legitimate) or not (illegitimate). Additionally, this methodology allows for accurate representation of the impact that illegitimate variation has on the thermal history constraints of a sample. We demonstrate the application of this new framework using a variety of examples from the literature, as well as with synthetic data. Modeling presented here is executed using the modeling software QTQt (version 5.6.0) and the He diffusion kinetics based on the radiation damage accumulation and annealing model, but the framework is designed to be easily adaptable to any modeling software and diffusion parameters.

Advances in noble gas and solid state thermochronology

U AND TH ZONATION IN APATITE OBSERVED BY SYNCHROTRON X-RAY FLUORESCENCE TOMOGRAPHY

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The common occurrence of parent isotope zonation is a “known unknown” in many applications of the (U-Th)/He chronometer. Frequent intra-grain age dispersion (,10-15%) that is significantly larger than analytical uncertainties (,3-4%) has led to significant efforts to explore the potential impact of parent isotope zonation on single grain (U-Th)/He ages. While previous studies have explored the impacts of zonation on age calculations, to date no method has been presented for acquiring zonation data in a way that is sufficient to allow for properly integrating measured zonation data into an age calculation on a full grain scale. These previous methods have been three-dimensionally incomplete (and required extrapolation of data from one grain section to a whole grain), and/or destructive (laser ablation). We report here the use of synchrotron X-ray fluorescence microtomography as a means of quantifying the three-dimensional distribution of U and Th atoms within individual, unsectioned grains of apatite. This is a focused-beam technique that measures the intensity of fluorescent X-rays (XRF) excited in a sample during irradiation with a high-energy incident X-ray beam. Applied in a tomographic modality, the technique can provide three-dimensional distribution of selected major and trace elements within single mineral grains with a spatial resolution on order of 1 um3 and without affecting the physical integrity of the grain. The implications of this technique, applied to radiogenic mineral chronometers, are broad and significant, both for (U-Th)/He chronometry and other radioisotopic mineral chronometers.

Rates and timing of Earth system processes

OROGENIC WEDGE ADVANCE IN THE NORTHERN ANDES: DETRITAL THERMOCHRONOLOGY OF THE MIOCENE HONDA GROUP IN THE UPPER MAGDALENA VALLEY BASIN, COLOMBIA

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The Tatacoa Desert (TD) in the intermontane Upper Magdalena Valley of South Colombia hosts the record of Miocene denudation associated with subduction orogenesis in the northern Andes, where the effects of flat-slab subduction are currently debated. Sandstones from the Honda Group were deposited in a humid foredeep during the middle Miocene, shortly their incorporation into the orogenic wedge through major the uplift of the Eastern Cordillera (EC). Such topographic uplift had a profound impact in the north Andean drainage systems, the climate and the biodiversity. We employ detrital apatite fission track (AFT) and (U-Th)/He (AHe) analyses on samples from the Honda Group to assess the basin's response to the EC uplift. AFT age populations throughout the middle Miocene strata include Paleogene and middle Miocene ages, from sediments derived from the Central Cordillera. Growth strata attesting to anticlinal folding coeval with sediment accumulation record initial EC uplift. Thermal histories, considering a thermal gradient of 30°/km, indicated that sediment accumulation reached up to 1.8 km west of the anticlines and less then 0.8 km to the east. Rock exhumation started after 10 Ma at the mean rate of 140 m/My. Thus, unlike the more southern areas, where subsidence continued throughout the Late Miocene, the EC uplift turned the TD into a predominantly erosive environment. This was due to stress propagation along the anticlines.

Advances in noble gas and solid state thermochronology

DETERMINING THE TIMING AND EXTENT OF AGE OFFSET ACROSS AN OROGEN-PARALLEL FAULT IN NEW ENGLAND USING NOBLE GAS THERMOCHRONOLOGY: IMPLICATIONS FOR TECTONIC REACTIVATION

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Thermochronologic age discontinuities along mid-Paleozoic orogen-parallel faults in New England hint at post-orogenic offset across these structures. However, published studies have been localized, and some used thermochronologic techniques now out of date. Regional thermochronologic studies across these faults have implications on how deformation wanes or persists following orogenesis and concentrates along these structures. Namely, this information is critical to developing comprehensive models of orogenic evolution. This study focuses on the Acadian region along the Vermont-New Hampshire border in the United States, specifically along the orogen-parallel Ammonoosuc Fault (AF). While published 40Ar/39Ar mineral and apatite fission track ages across part of the AF have revealed a post-orogenic time-temperature discontinuity, the exact timing and extent of this activity remains an enigma. Here we report on a U-Th/He and Ar/Ar thermochronologic regional investigation both north and south of previous studies to determine the timing, extent, and longevity of post-orogenic fault activity through thermal history modeling. Initial apatite U-Th/He analyses using continuous ramped heating (CRH) (Idleman et al., 2018) show an offset from east to west across a section of the fault from ~90-120Ma, respectively. Like other faults in the region, this may suggest at least local late Mesozoic displacement. Additional thermochronologic analyses will test the significance of this possible age offset. Further, this study supports the utility of the CRH method in apatite U-Th/He thermochronology, providing a detailed record of He release in little more time than conventional single-step heating analyses while allowing grains with anomalous release patterns to be screened out.

Celebration of the research achievements of Rod Brown

TOWARDS A CONSISTENT MODEL OF BURIAL AND DENUDATION ALONG THE NORTH ATLANTIC MARGINS, THE EAST GREENLAND SHELF AND THE BARENTS SEA

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The North Atlantic margins were intensively studies in the past in order to understand the general processes of elevated passive continental margin formation. A standard tool for this is the utilization of apatite fission track (AFT) thermochronology. For complex and protracted histories, however, thermal history models derived from AFT data are non-unique. As a consequence, various published data sets result in a mixture of different and partly contradicting exhumation histories for different portions of the margins. In an attempt to unitize these data, we re-interpreted 173 AFT dates from North and East Greenland, northern Scandinavia, and Svalbard by forward thermal history modelling, under the assumption, that samples belonging to the same tectonic entities should show the same general patterns regarding timing of exhumation and burial. Our models are in agreement with independent geological information and can be reconciled with concepts of episodic exhumation and reburial, involving km-scale vertical movements of passive margins. In conjunction with literature data from the East Greenland shelf and the Barents Sea, mostly based on seismic and borehole studies, we provide coherent and internally consistent denudation models for the conjugated North Atlantic margins and associated basins. These are illustrated as a series of maps for different time intervals from the end of the Caledonian Orogeny until today. The maps highlight the erosional response to large-scale tectonic processes such as rifting periods associated with the opening of the Amerasia Basin, the Eurasia Basin, the Norwegian-Greenland Sea, and the deepening and widening of the Fram Strait.

Developments and challenges in (U-Th-Sm)/He thermochronology

COMPARISON BETWEEN VERTICAL SCANNING INTERFEROMETRY AND CONFOCAL LASER MICROSCOPY FOR MEASUREMENTS OF ABLATION PITS IN LASER ABLATION (U-TH)/HE THERMOCHRONOLOGY

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Laser Ablation (U-Th)/He analysis provides several advantages compared to traditional whole-grain digestion techniques; most notable that (i) it does not require alpha-ejection correction and can hence be applied independent from the grain morphology, and (ii) that it is only micro-destructive, which facilitates the application of double- or triple-dating approaches for detrital grains. One key factor for successful LA-(U-Th)/He dating is the precise measurement of ablated volumes for calculating 4He concentrations. In the literature, measurements by Atomic Force Microscopy, Vertical Scanning Interferometry (VSI) and Confocal Laser Microscopy (CLM) were proposed. For this study, we systematically compare volume measurements performed by VSI (Contour GT-I optical profilometer, Bruker) and CLM (LSM900, Zeiss) techniques. We ablated a glass sample, a specimen of Madagascar zircon, and a specimen of Durango apatite, by using a Resochron 193 nm excimer laser with 10 Hz, 24, 50 and 100 µm beam diameter and up to 50 laser pulses. The pits are slightly asymmetric, bowl-shaped, and with a slightly convex bottom. Measurements by both techniques show good linear correlations between ablated volume and number of laser pulses. Calculated volumes, however, show some differences between the two techniques. Variations and potential impacts on age calculations will be discussed.

Advances in noble gas and solid state thermochronology

TESTING SOME ASSUMPTIONS BEHIND 40AR/39AR THERMOCHRONOLOGY: PETROCHRONOLOGY AND IN-SITU 40AR/39AR DATING

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The 40Ar/39Ar method applied to K-feldspars and muscovite has been frequently used to construct continuous thermal history paths between ,150 – 600°C (e.g. Lovera et al., 1989), which are usually applied to structural and tectonic questions in many varied geological settings. However, other authors contest the use of 40Ar/39Ar thermochronology because they argue that the assumptions are rarely valid. Here we evaluate the key assumptions, which are that i) 40Ar is dominantly redistributed in K-feldspars and muscovite by thermally driven volume diffusion, and ii) laboratory experiments (high temperatures and short time scales) can accurately recover intrinsic diffusion parameters that apply to geological settings (lower temperatures over longer time scales). Case studies are presented from Itrongay (gem quality K-feldspar), Shap (UK) and Mt. Isa (Australia). Our data (e.g. Popov et al., 2020) along with previous studies (e.g. Villa and Hanchar, 2013; McDonald et al., 2016; Di Voncenzo et al., 2001; Nteme et al., 2023) highlight the paramount importance of first accounting for fluid interaction and secondary reaction products via a detailed textural study of single crystals, before recovering thermal history paths via thermally driven diffusion. Furthermore, an expanding database of experimental evidence shows that laboratory step-heating can induce structural and textural changes, and thus extreme caution must be made when extrapolating laboratory derived rate loss constants to the geological past. We conclude with a set of recommendations that include minimum sample characterisation prior to degassing, an assessment of mineralogical transformations during degassing and the use of in situ dating.

Celebration of the research achievements of Rod Brown

FOCUSED CENOZOIC EROSION ON THE SOUTHERN AFRICAN PLATEAU: AN INDICATION OF TOPOGRAPHIC UPLIFT?

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Constraints on the erosion history of the southern African Plateau have been crucial in the debate over the plateau's age and origins. Unravelling the mechanisms driving the evolution of the African landscape was a major contribution of Rod Brown's career. Low-temperature thermochronology by Rod and others has illuminated the Cretaceous erosion history of southern Africa and yielded insight into processes active in the evolution of passive margins and plateau formation. However, Cenozoic erosion patterns remain largely unclear. Here we investigate Cenozoic cooling by exploiting the low-temperature sensitivity of apatites with low effective uranium concentration (eU) from kimberlites and examine a compilation of kimberlite apatite (U-Th)/He dates from across the plateau. Higher-eU apatites have dominantly Cretaceous dates but dates from low-eU (<25 ppm) apatites range from Miocene to Cretaceous. These data patterns are well replicated by thermal history models with a phase of spatially variable cooling in the Cenozoic that ranges from minimal to 25 °C, equating to as much as ~1250 m of erosion. Not all kimberlites record this phase of cooling, but those that do are localized near paleo- and modern river valleys. These patterns are well explained by Cenozoic river incision driven by increased rock uplift that caused accompanying topographic development. This compilation provides the first glimpse of Cenozoic erosion patterns across the plateau surface from thermochronology, but more data and/or different tools are needed to resolve temporal and spatial details.

Rates and timing of Earth system processes

THE DETRITAL THERMAL RECORD OF SNOWBALL EARTH EROSION PRESERVED IN THE MICHIGAN BASIN, USA

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We present new (U-Th)/He zircon (ZHe) data (n=68) from the basement rock underlying the Michigan basin as well as detrital ZHe data from zircons eroded across the continent and preserved in Paleozoic sandstones of the Michigan basin that document erosion during the Snowball Earth event across North America. Zircons from Paleozoic sandstones in the Michigan Basin, a cratonic basin in North America, come from diverse source regions including the Superior craton, the Grenville Province, the Yavapai-Mazatzal Province, and sedimentary and igneous rocks exposed along the inverted Midcontinent Rift. The ZHe thermal histories from zircon crystals derived from all source regions preserve evidence of rock cooling during the Snowball Earth event regardless of the source region. Snowball Earth cooling is recognized in strata deposited from the Cambrian through the Ordovician suggesting that the fossil ZHe PRZ documenting Snowball Earth erosion occupied several kilometers of the upper crust throughout the Paleozoic. This new detrital thermochronology dataset provides powerful evidence that erosion was so significant during Snowball Earth that the pre-Snowball Earth fossil ZHe PRZ was eroded across basement domains and tectonic provinces. By the Cambrian, zircons exposed on the surface of the Earth preserved a thermal memory of Snowball Earth erosion in at least the ZHe system. Although the record of Snowball Earth cooling may have been erased by subsequent annealing in some zircons, modeling studies of ZHe data for zircons derived from North America that are Neoproterozoic or older should consider a possible Neoproterozoic cooling event associated with Snowball Earth.

Rates and timing of Earth system processes

PLEISTOCENE ARIDIFICATION OF THE EASTERN TAURIDES, TURKEY REVEALED BY (U-TH)/HE AGES OF SUPERGENE MINERALISATION FROM ATTEPE IRON DEPOSITS

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The Taurus Mountains form the southern margin of the Central Anatolian Plateau of Turkey and form an orographic barrier separating the cold, semi-arid interior to the north from the mild Mediterranean coast to the south. When and how they formed, and the extent they have influenced regional climate remains poorly constrained. The Attepe iron deposits sit on the northern part of the Eastern Taurus mountains 1.5-2 km asl. They are ideally located to record interactions between climate and tectonics. (U-Th)/He ages of iron oxide-oxyhydroxides from four mines within the Attepe iron deposits record ages of 1-5 Ma consistent with the persistence of hot humid climate conditions throughout the Pliocene and Pleistocene. In mines where samples are measured from different depths the age data are consistent with water table lowering rate of between 12.3 to 6.4 m/Myr. Translating these to rock uplift rates they are close to uplift/incision recorded within the Central Anatolian Plateau over the past 2 Ma, suggesting that the region was already at or close to its current elevation by the late Miocene. The ages constrain the cessation of hot-humid climate to sometime in the last million years and imply that regional climate cooling, rather than surface uplift, was the main driver of aridification.

Rates and timing of Earth system processes

EXTREME EXHUMATION OF THE PLIOCENE-PLEISTOCENE PLUTONS ALONG A HIGH-GEOTHERMAL ZONE IN THE KUROBE AREA, CENTRAL JAPAN, REVEALED BY AL-IN-HORNBLENDE GEOBAROMETRY AND ZIRCON U-PB GEOCHRONOMETRY

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Exposure of young (< a few Ma) plutons has been reported in mobile belts, such as, along subduction zones in the Western Pacific (Harayama, 1992), implying rapid exhumation in the last few million years. We reconstructed the exhumation history of the Pliocene-Pleistocene plutons in the Kurobe area, central Japan (Ito et al., 2013), to better understand the exhumation process and mechanism of such young plutons. Because the application of low-temperature thermochronology to extract exhumation histories in the Kurobe area is challenging due to the complex thermal history/structure related to the recent granitic intrusions, we constrained the exhumation history based on solidification depths and dates of the plutons obtained by using Al-in-hornblende geobarometry (Mutch et al., 2016) and zircon U-Pb geochronometry, respectively. The solidification depths obtained range from ~6 to 10 km regardless of location and solidification age, suggesting a uniform and subvertical exhumation after the solidification of the youngest pluton (~0.8 Ma). The mean exhumation rate since ~0.8 Ma was computed to be ~7-14 mm/yr, which is consistent with the shorter-term erosion rates obtained by other methods (Ohmori, 1978; Matsushi et al., 2014; King et al., 2023). This rapid and local exhumation might be attributable to localization of deformation along the hot and weak crust of the Kurobe area related to the high-temperature geothermal conditions (e.g., Matsubara et al., 2000). This interpretation is being verified by using numerical modeling incorporating the rheology, geothermal conditions, and horizontal compression (Shibazaki et al., 2016).

Celebration of the research achievements of Rod Brown

MELDING THERMOCHRONOLOGY AND GEOMORPHOLOGY: ROD BROWN'S CONTRIBUTION

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At the time Rod Brown began his research career in the late 1980s thermochronology and geomorphology were unrelated disciplines. Geomorphologists had little concern with landscape development over geological timescales, and those developing thermochronological techniques were focussed almost entirely on understanding tectonic events. Beginning with his doctoral project applying apatite fission-track thermochronology to understanding the long-term landscape development of southern Africa, Rod Brown was a pioneer in seeing that the cooling history of the upper crust was mediated through the denudational processes that brought rocks from depth to the surface. In other words any tectonic event – cooling history interpretation had to be understood in terms of how the landscape evolved in response to tectonic and other processes that might affect rates and spatial patterns of denudation, this being a crucial perspective for the passive continental margin settings which were Rod Brown's research focus. For geomorphology, the quantification of regional-scale patterns of denudation over geological time spans made possible by thermochronology began to revitalize the moribund field of landscape evolution and provide insights into long unanswered questions about modes of landscape development. Here I assess how Rod Brown's expertise in thermochronology and his broad perspective on the earth sciences, together with his very open attitude to what unfamiliar disciplines might have to offer, helped to reorientate the fields of both thermochronology and geomorphology and stimulated subsequent research.

Improvements in handling and modeling low temperature thermochronological data

BETTER INGREDIENTS AND GLOBAL TRANSPARENCY FOR FISSION TRACK ANALYSIS

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We report two different selection-criteria-isolated studies to reveal the impact of analyst judgement on fission track analyses.

The first experiment involves the application of two different confined track selection criteria by a single analyst using two different light sources in a step-etch scheme in Durango apatite. The quantity-oriented selection criterion is to include any track with observable tips, while the quality-oriented criterion selects only the sufficiently-etched tracks. Track etch rates decrease from core to tip and some of the apparently sufficiently-etched tracks are under-etched. Applying a two-step, 20+10s etch can ensure that measured tracks are not under-etched, while being correctable to allow interpretation with current annealing data sets.

The second experiment is a new image-based inter-analyst comparison study. We equalized all possible variation factors by inviting participants to carry out fission track analysis on image stacks of a mixture of suitable and unsuitable grains for track density and confined track length measurements. The results of 15 participants show most participants include only the suitable grains to their analysis data sets, while some include unsuitable grains. The analysis results become more relatable with the increase in the overall experience of the participants. Every year numerous research articles are published containing fission track data, yet we discover significant variations in grain selection and validity of confined track length measurements. We strongly stress the necessity of a practical platform for data transparency.

Rates and timing of Earth system processes

THERMAL AND EXHUMATION HISTORY OF THE SONGNAN LOW UPLIFT, QIONGDONGNAN BASIN: CONSTRAINTS FROM THE APATITE FISSION-TRACK AND ZIRCON (U-TH)/HE THERMOCHRONOLOGY

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Significant breakthroughs have been achieved in the exploration of Mesozoic granite buried hills in the Songnan Low Uplift (SNLU) of the Qiongdongnan Basin, which reveals that the bedrock buried hills of this basin have a sound prospect for exploration. Borehole samples from the granite buried hills in the SNLU were analyzed for apatite fission track and zircon (U-Th)/He data to decipher the thermal history of the basement rock, which is significant for unraveling its exhumation and alteration process after formation. Thermal modeling for the sample from the western bulge of the SNLU reveals a protracted cooling event during the late Mesozoic to Oligocene (~80-23.8 Ma), subsequent with a heating stage from the Miocene until present (~23.8-0 Ma). Comparatively, the sample from the eastern bulge experienced a much more complex thermal history: two cooling stages during the late Mesozoic to late Eocene (~80-36.4 Ma) and the late Oligocene (~30-23.8 Ma), alternated with two heating phases during the late Eocene to early Oligocene (~36.4-30 Ma), and the Miocene to recent times (~23.8-0 Ma). The differential in exhumation histories of the two bulges during the late Eocene to Oligocene in the SNLU was attributed to the differential activity of faults. Deviated from typical passive continental margin basins, the SNLU has experienced accelerated post-rifting subsidence commenced , 5.2 Ma. The possible mechanism for this abnormous post-rifting subsidence might be the decay or moving away of the deep thermal source and the rapid cooling of the asthenosphere.

Rates and timing of Earth system processes

TECTONOTHERMAL HISTORY AND EROSION OF PRECAMBRIAN JINCHUAN NI-CU SULFIDE DEPOSIT REVEALED BY MULTI-THERMOCHRONOLOGICAL SYSTEMS

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The world's third largest and China's largest magmatic Ni-Cu sulfide deposit – the Jinchuan ore deposit, is hosted in the Proterozoic basement of the Longshoushan Terrane, a NW-extending elongated orogen on the southwestern margin of the North China Craton. The Paleozoic tectonothermal history of the Jinchuan Ni-Cu sulfide deposit is crucial to understand ore formation and spatial occurrence in the area. Accordingly, this study applies multimineral (hornblende, biotite, and K-feldspar) 40Ar/39Ar and zircon (U-Th)/He thermochronology to the Neoproterozoic Jinchuan ore-hosting intrusion, as well as to the Paleoproterozoic migmatitic country rocks and an early Paleozoic granitic intrusion in the Longshoushan Terrane. Hornblende 40Ar/39Ar ages of 543 Ma and 489 Ma from the migmatitic country rocks constrain the age of amphibolite facies metamorphism in Jinchuan to the Ediacaran to late Cambrian. The presence of nearby Silurian to Devonian sediments suggests that the Jinchuan ore deposit was exhumed to the surface by the Silurian. Exhumation occurred in an extensional setting during the spreading and subduction of the North Qilian Ocean. Syn-orogenic (Qilian Orogeny) magmatic reheating up to , 400 ˚C in the Silurian occurred in the middle of the pre-Silurian surface exposure and Devonian thermal event as illustrated by biotite 40Ar/39Ar plateau ages of 406 Ma and 380 Ma, respectively. The late Carboniferous plagioclase and K-feldspar 40Ar/39Ar mini plateau ages of ca. 318 Ma and ca. 301 Ma, together with Mississippian (ca. 334 Ma) to Guadalupian (ca. 272 Ma) zircon (U-Th)/He mean ages, suggest protracted late Paleozoic cooling to < 150 ˚C, associated with the Qilian orogenic collapse.

Celebration of the research achievements of Rod Brown

END-EOCENE TO MID-MIOCENE UPLIFT AND RETREAT OF THE CENTRAL TRANSANTARCTIC MOUNTAINS GREAT ESCARPMENT REVEALED USING A REGIONAL-SCALE MULTIPLE LOW-TEMPERATURE THERMOCHRONOMETER DATASET

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The uplift history of the Transantarctic Mountains (TAM) remains poorly understood owing to their remoteness and ice cover. The TAM are generally considered to be a rift flank uplift at the margins of the ~100 Myr-old West Antarctic Rift System (WARS). Yet previous thermochronology studies imply only modest uplift and erosion at this time with most uplift and erosion recorded later in the Cenozoic. To constrain more fully the exact timing and nature of TAM uplift and erosion we acquired a regional-scale multiple thermochronometer dataset (apatite and zircon FT and (U- Th)/He) from ~100 samples from the central TAM, including several vertical transects. These data reveal slow cooling following widespread ,180Ma magmatism, a modest cooling event at ~100- 80Ma caused by elevated heat flow and/or erosion during initial WARS formation, with the majority of uplift and erosion beginning at the Eocene-Oligocene Transition (EOT) from greenhouse-to- icehouse climate, rather than in the Paleocene as previously reported. Surfaces of equal thermochronometer age further support that since the EOT, rapid uplift of the TAM was driven by a combination of flexural rift flank uplift due to extensional unloading, and isostatic rebound (peak uplift) in response to localized glacial incision. The central TAM are now dominated by a major escarpment ~50km from the coast. Thermochronometric ages from the coastal plain indicate inland retreat of this escarpment from the coast at ~34Ma to its current position following onset of cold- based non-erosive ice sheet conditions at ~14Ma that provides important constraints on the poorly- known Antarctic Oligocene climate.

Rates and timing of Earth system processes

EXHUMATION IN THE ANACONDA METAMORPHIC CORE COMPLEX: USING DETRITAL THERMOCHRONOLOGY TO CONSTRAIN EOCENE EXTENSIONAL DEFORMATION AND BASIN FORMATION

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Metamorphic core complexes (MCC) provide a rare glimpse into thermomechanical processes in the lithosphere and play a substantial role in the evolution of the crust. The North American Cordillera contains a northwest trending line of MCCs, which have been extensively studied using bedrock thermochronology and modeling approaches to better understand extensional processes related to Cordilleran collapse. While these studies have proposed a wide variety of models to explain the timing and mechanism behind MCC formation, few have considered the syn-deformational basin record, which preserves a unique archive of sediment sources in adjacent MCC highlands. This study focuses on the Deer Lodge Valley, located in the hanging-wall of the Anaconda MCC. We utilize detrital zircon (U-Pb)-(U-Th)/He double dating in the context of stratigraphic and sedimentologic analyses, and HeFTy time-temperature modeling to reconstruct basin evolution. Stratigraphic analysis shows that the basin was dominated by deposition of coalescing alluvial fans, with sediment sourced directly from the footwall of the detachment fault. U-Pb maximum depositional ages indicate late Paleocene to early Eocene proximal basin sedimentation. (U-Th)/He analyses from U-Pb dated zircons range from 194-32 Ma; >70% of dates are Eocene. Preliminary HeFTy modeling shows a period of rapid cooling between 65-55 Ma, which is supported by short (<10 Myr) sediment lag times and inferred rapid exhumation in the MCC. Our findings support a link between MCC exhumation and basin formation. They further depict a potentially earlier period of MCC exhumation than previous work has proposed, indicating an earlier onset of extension in western Montana.

Developments and challenges in (U-Th-Sm)/He thermochronology

CALIBRATING INTRAGRANULAR MICROCRACKING AND SIZE REDUCTION INDUCED BY RADIATION DAMAGE IN ZIRCON

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Although zircon is resistant to physical alteration and chemical weathering, it develops internal microcracks when self-irradiation induced volumetric expansion exceeds lattice failure stress. Fracturing produces domains of variable sizes, effectively increasing the surface-to-volume ratio and enhancing element exchange with surrounding minerals and geofluids. Here we use samples from the Qiman Tagh Range, northern Tibetan Plateau, whose zircons exhibit variable U-Th concentrations between 500 and 10000 ppm, to investigate intragranular microcracking and domain size reduction as a function of radiation damage. We found that microcracking occurs at an alpha dose of ,0.55*1018 alpha/g, and is controlled by oscillatory zoning. Cracking induced domain size reduction increases exponentially with alpha dose and saturates at a value of 0.3-0.4 with a dose of ,3*1018 alpha/g. We speculate that, at high levels of radiation damage, dilation reuses, widens and lengthens existing microcracks rather than forming new ones, leading to the observed saturation in domain size reduction. Our results have important implications for the interpretation of zircon U-Pb and (U-Th)/He data.

Rates and timing of Earth system processes

METAMORPHIC P–T CONDITIONS, IN-SITU LA–ICP–MS BIOTITE–MUSCOVITE RB–SR GEOCHRONOLOGY, AND TECTONIC IMPLICATIONS OF TWO-MICA–QUARTZ SCHIST FROM THE KUANPING COMPLEX IN THE NORTH QINLING OROGENIC BELT

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The Kuanping Complex is an important lithotectonic unit in the North Qinling Tectonic Belt, which has experienced metamorphism from greenschist to high amphibolite facies, and is of great significance in defining the orogenic process of the Qinling orogenic belt. This study presents the results of petrology, geothermobarometry, phase equilibrium modelling, in-situ laser ablation inductively coupled plasma mass spectrometry (LA–ICP–MS) biotite–muscovite Rb–Sr analysis, for the two-mica–quartz schist of the Kuanping complex in the Hongtuling and Heihe areas. These results are employed to better understand their metamorphic P–T conditions and ages, as well as geological implications. Garnet-bearing two-mica–quartz schist in the Hongtuling area records a clockwise P–T trajectory on the basis of phase equilibrium modelling, with peak P–T conditions of ~600 °C and ~0.85 GPa. In addition, the Ti-in-biotite thermometry yielded metamorphic temperature conditions of ,578–580 °C and ,590–596 °C for the garnet-bearing two-mica–quartz schist from the Hongtuling area and the two-mica–quartz schist from the Heihe area, respectively. These results indicate that metamorphic temperature conditions in both areas are higher than the closure temperature of the Rb–Sr isotopic system of muscovite and biotite. In-situ LA–ICP–MS biotite and muscovite Rb–Sr analyses yielded three groups of isochron age, i.e., ca. 410 Ma, ca. 360 Ma, and ca. 320–300 Ma. On the basis of previously published data and the data in this study, the Kuanping complex underwent ca. 440 Ma regional metamorphism in the NQB, retrograde cooling at ca. 410–360 Ma due to exhumation, and ca. 320–300 Ma tectonothermal overprinting.

Developments and challenges in fission-track thermochronology

REFINING CONFINED TRACK-LENGTH MEASUREMENTS FOR THERMAL HISTORY MODELING: POTENTIALS AND CONCERNS

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Aslanian et al. (2021) measured the etch rate (vR) as a function of orientation for Durango apatite etched in 5.5 M HNO3 for 20 s at 21 °C. This permits the estimation of the effective etch time (tE) of individual confined fission tracks. Extending their work, we measured vR for apatites from fourteen natural samples in a Dpar range of 1.4 to 2.6 µm. We calculated tE for confined tracks, measured in the course of step-etch experiments with immersion times ranging from 20 to 60 s, depending on the sample properties (track densities, etch rates). We find that tE-calculations for different geological samples give overall reliable estimates. We discuss practical implications for the required track-width measurements and the tE-calculations for T-t modeling. Using an effective etch-time window instead of a standard etch protocol provides an explicit selection criterion that makes confined track sampling and the resulting track-length distributions more reproducible. Tracks suspected of being under- or over-etched can be identified and excluded. Using the effective etch-time calculations allow using longer immersion times, which multiplies the number of measurable tracks. Based on a new etch model (Jonckheere et al., 2022), the shapes of over-etched tracks in prism faces provide the direction of the apatite c-axis. We compare the results of conventional T-t-modeling, using tracks etched at 20 s, with modelling results based on length measurements of confined tracks in the effective etch-time range of 15–30 s, and discuss if the latter length data are consistent with existing annealing equations.

Rates and timing of Earth system processes

SOUTHWESTERN TIAN SHAN: 2. TIMING OF CENOZOIC MOUNTAIN BUILDING, INTRA-MONTANE BASIN INVERSION, AND RELATION TO LITHOSPHERIC MANTLE INDENTATION

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Cenozoic reactivation of the Paleozoic thick-skinned fold-thrust belt of the southwestern Tian Shan has—as the Afghan-Tajik Basin inversion—been interpreted to reflect Indian mantle-lithosphere indentation beneath the Pamir. We date the reactivation and explore its temporal and spatial variations. Three Domains emerged. In the Central Domain (Zeravshan-Gissar, Vashan), apatite fission-track (AFT) data—aided by Raman-spectroscopic chemical-composition discrimination of detrital apatites and vitrinite-reflectance paleotemperature estimates—record a 13–10 Ma onset of shortening and >4 km exhumation. The Northern Domain, with the southerly-bounding N-Zeravshan Fault as a major Cenozoic structural divide reactivating the Paleozoic Zirabulak Suture, exhumed from <4 km, but apatite (U-Th)/He (AHe) ages suggest a similar reactivation history as in the Central Domain. The synchronous structural reactivation implies rapid shortening propagation from the Pamir indenter across the Afghan-Tajik fold-thrust belt into the Tian Shan. In the Southern Domain (Paleozoic Gissar Batholith), 7–9 Ma AFT and ~4 Ma AHe ages suggest southward shortening propagation from both northern Domains and anew thrust generation. In the hanging-walls of major southwestern Tian Shan thrusts, 3–7 Ma AFT ages record significant and persistent exhumation. Zircon (U-Th)/He data limit exhumation to <6 km. Most of the Southern and Central Domains cooled monotonously but temperature-time models indicate northward-decreasing reheating by syn-orogenic deposition, consistent with stratigraphic data. The refined timing supports the synchronous building of the Cenozoic Tian Shan and the India-Asia cratonic collision under the Pamir and western Tibet, and the immediate transfer of shortening across a ,1000-km-wide foreland area, facilitated by structural reactivation.

Advances in noble gas and solid state thermochronology

ELECTRON SPIN RESONANCE (ESR) THERMOCHRONOMETRY OF RHYOLITES FROM THE YELLOWSTONE HOTSPOT: YOUNGER AGES BY EROSION OR GEOTHERMAL ACTIVITIES?

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The Yellowstone hotspot migrated northeast for the last 17 Ma due to the motion of the North American Plate, causing volcanism and transient uplift. The current Yellowstone Caldera was formed at 2.1 Ma and three major caldera-forming eruptions established the Huckleberry Ridge Tuff (2.1 Ma), the Mesa Falls Tuff (1.3 Ma) and the Lava Creek Tuff (0.63 Ma). Investigating the landscape response to tectonic uplift of Yellowstone during the Quaternary by low-temperature thermochronology is challenging due to the young ages of the bedrocks. Here, we test electron spin resonance (ESR) thermochronology on quartz using four samples from the three rhyolites. Quartz ESR ages are calculated using two impurity centres, the Al and Ti centres. For all samples, the ages obtained from the two centres are consistent. The natural ESR signal intensity for both signals is well below the signal saturation level with the saturation ratio (n/N) ranging from 0.25 to 0.38, indicating the applicability of ESR thermochronology for these samples. All ESR ages were significantly younger than the eruption ages; 0.4 Ma for the Huckleberry Ridge Tuff and 0.3 Ma for the Lava Creek Tuff. Two samples of the Mesa Falls Tuff, taken from the ridge at the top of the section and the valley floor are 0.4 and 0.3 Ma, respectively. This may indicate the influence of erosion with an elevated geothermal gradient or other geothermal activity. We will present cooling histories of these rhyolites and discuss possible causes of the younger ESR ages than the eruption ages.

Developments and challenges in (U-Th-Sm)/He thermochronology

QUANTIFYING GLACIAL RELIEF DEVELOPMENT USING 4HE/3HE THERMOCHRONOLOGY: AN UPDATE FROM THE COOLER PROJECT

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The topographic and erosional response of mountainous topography to late-Cenozoic climatic cooling culminating in Quaternary glaciations, and the potential couplings between these processes, remain poorly constrained. Advancing our understanding requires the development of tools that record erosion rates and topographic relief changes with higher spatial and temporal resolution than the current state-of-the-art, and the integration of newly obtained data into next-generation numerical models that link observed erosion-rate and relief histories to potential driving mechanisms. Within the ERC-funded COOLER project, we are building a new 4He/3He thermochronology lab in Potsdam, developing numerical modelling tools that incorporate the latest insights in kinetics of thermochronological systems to make sample-specific predictions, coupling these tools to glacial landscape-evolution models to enable modelling of real landscapes with real thermochronology data as constraints and, finally, studying potential couplings between glacial erosion, relief development, and tectonics in selected field areas. Here we provide an update of our progress three years into the project: the 4He/3He thermochronology lab is up and running; it is fully automated with a new protocol for temperature-controlled laser step heating. In collaboration with the Helmholtz-Zentrum Berlin, we have developed a new protocol to implant high concentrations of 3He homogeneously with a narrow, relatively low-energy but high-flux proton beam. A new version of the PECUBE code, which includes sample-specific predictions and a user-friendly graphic interface, has been developed. Finally, we have sampled several glacial landscapes in the European Alps and Norway; we will present our first results from these sites at this meeting.

Developments and challenges in fission-track thermochronology

CROWD SOURCED FISSION TRACK DATING WITH GEOCHRON@HOME

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Conventional fission track analysis is difficult and slow. It necessitates a significant number of hours of training to learn which grains/counting areas to select, how to discriminate between tracks and non-track features, and how to maintain consistency. However, even after extensive training, the identification of fission tracks remains a subjective process. This is reflected in interlaboratory comparison studies, which consistently exhibit excess dispersion beyond the formal analytical uncertainties. The reasons for these inconsistencies are unclear as conventional datasets only provide limited information such that it is not possible to evaluate track counting. Fortunately, the advent of digital microscopy presents a solution to this problem. Geochron@home is an online platform to store and analyse digital fission track imagery. It:

1) acts as an archive of 'raw data', allowing anyone to check the quality of published fission track data;
2) provides a mechanism to crowd-source fission track counting. Calibration studies have shown that the average of multiple fission track counts on the same sample is more accurate than any individual estimate;
3) serves as a tutorial for new fission trackers;
4) generates training data for future AI algorithms.

We will use Geochron@home to carry out a crowd-sourcing experiment at Thermo2023. Please come to our poster and count some fission tracks on a laptop. The results of this experiment will be announced at the end of the conference.

Advances in noble gas and solid state thermochronology

U-TH-RAMAN THERMOCHRONOLOGY BY INTERNAL ISOCHRON REGRESSION

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The accumulation of radiation damage in actinide-bearing accessory minerals is thought to exert a first order control on the diffusive behaviour of helium in zircon and apatite. It is difficult to quantify the effects of this radiation damage on the U-Th-He system, especially when samples exhibit three dimensional compositional zoning. However, it is easy to measure the two dimensional extent of the radiation damage itself, using Raman spectroscopy. Combining Raman spectroscopy with LA-ICP-MS produces paired maps of radiation damage and U,Th-concentration, with micron-level resolution. Even in the presence of compositional zoning, these paired maps look like identical twins. The data contained in them define a surface in U-Th-Raman-space, which can be approximated by a line in eU-Raman space. This line defines an isochron whose slope corresponds to a cooling age. The isochron method offers better precision and accuracy than previous attempts at U-Th-Raman thermochronology. Laboratory experiments have shown that Raman signals may experience different stages of annealing at different levels of radiation damage. The presence (or absence) of such complexity can be verified through the absence (or presence) of a clearly defined isochron. In other words, in the case of U-Th-Raman thermochronology, compositional zoning is a friend and not a foe.

Rates and timing of Earth system processes

SHATTERING OF THE CALABRIAN ARC: UNTANGLING DRIVERS OF EXHUMATION OF A LONG-LASTING RETREATING SUBDUCTION ZONE

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The Calabrian Arc has witnessed the interaction of climatic, tectonic, and geodynamic (mantle-related) processes on its long-lasting journey to its current position since the last 30 Ma. Therefore, it has been the focus of studies addressing its present-day architecture, tectonic evolution, stratigraphy of basins associated with long-lasting roll-back dynamics, and topographic evolution under a changing climate. These studies show long-term exhumation of discrete blocks linked to variations in the regional stress and geodynamic configuration in the subduction zone. Additionally, the region has experienced spatially extensive Quaternary uplift showing the highest value in the Central Mediterranean (>1.4 km/Ma). However, it is still unknown whether uplift is episodic and tied to phases of increased tectonic activity, continuous and tied to slab roll-back only, or has fluctuated with climatic variability.

Here, we aim to explore the landscape evolution of the Calabrian Arc by quantifying uplift and exhumation rates on different time scales. To carry this out, we present a set of different analyses that include: (a) morphometry of marine terraces, (b) geomorphological indices, and (c) time-temperature models of a compilation of existing low-temperature thermochronological data. Our new models show that asymmetric exhumation during the late Miocene (~0.2–0.4 km/Ma) has been controlled by longitudinal deep-crustal structures playing a main role in the tectonic fragmentation of the Calabrian Arc, followed by late rock uplift (~ .6 km/Ma) of the southern Calabrian Arc that can be related to fluctuations in different mantle-related processes.

Rates and timing of Earth system processes

ALPINE LOW-TEMPERATURE EVOLUTION OF THE VEPOR-GEMER BELT (CENTRAL WESTERN CARPATHIANS) REVEALED BY 87RB/87SR ISOCHRON DATA ON BIOTITE, ZIRCON AND APATITE FISSION TRACK DATA

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The Central Western Carpathians (CWC) consist of a nappe stack of thick-skinned nappes/units (Tatric, Veporic, and Gemeric), incorporated into the Upper Cretaceous collisional wedge and overlain by thin-skinned nappes. The thick-skinned nappes are composed of Variscan basement and upper Palaeozoic to Mesozoic cover sequences. The thin-skinned nappes in the inner zone of the CWC show an imbricated structure with the nappe stack arranged from bottom to top: the Bôrka Nappe, Meliata, Turňa, and Silica units. The 87Rb/86Sr biotite dating, zircon and apatite fission track (ZFT and AFT) thermochronology were selected to derive quantitative constraints on the low-temperature evolution of the inner zone of the CWC. Alpine peak metamorphic conditions were reached in the Early Cretaceous (~140–115 Ma) related to Late Jurassic subduction followed by Early Cretaceous N–S convergence forming the Eo-Alpine nappe stack. The Veporic crystalline basement yields 87Rb/86Sr biotite ages in the range of 81 to 76 Ma and the Gemeric one, predominantly composed of Permian granite, yields 87Rb/86Sr biotite ages 115–95 Ma. ZFT ages range from 108 to 73 Ma, while AFT analyses yield ages are 73–59 Ma. The Gemeric Unit experienced a thermal overprint of ~350 °C during the Alpine metamorphism. Track-length modelling shows that the Gemeric Unit stayed at a temperature of 350 – 200 °C during the 115 – 75 Ma time interval. Final cooling of both, the Gemeric and Veporic units below the apatite partial annealing zone occurred during 70 – 60 Ma.

Developments and challenges in (U-Th-Sm)/He thermochronology

INFLUENCE OF FLUID FLOW, LOCALIZED EROSION AND PROVENANCE ON APATITE (U-TH)/HE AGES

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The folded and thrusted part of the central European Alps, the Subalpine Molasse has been recognized as a key area for our understanding of mountain belt dynamics. Consequently, it has been the focus of multiple studies, stratigraphy and tectonic setting are well-known, and the time-temperature evolution of the basin has been constrained using vitrinite reflectance, as well as low-temperature thermochronological data. Thermochronolgical data show offsets of cooling ages across faults within the Subalpine Molasse. However, variations of the cooling pattern are observed locally ranging between 50 to 100°C without any indication for faulting. Different hypotheses can be put forward to explain the age pattern: glacial scouring, provenance history, or hydrothermal fluid flux.

We test these hypotheses using a new high resolution (U-Th)/He data set. Results show that while glacial scouring cannot be responsible for the age distribution, provenance history and fluid flow provide potential explanations. On a larger scale, the lack of correlation between cooling rates and elevation, relief and glacial erosion may mean that exhumation is predominantly the result of a separate long-wavelength process, like flexural readjustment to changes in erosion in the alps or changes in the subducting European plate.

Rates and timing of Earth system processes

MESOZOIC UPLIFT AND EXHUMATION HISTORY OF THE QINLING OROGENIC BELT, CENTRAL CHINA: INSIGHTS FROM MULTIPLE GEOCHRONOLOGICAL DATA OF THE GRANITIC GRAVELS IN ADJACENT BASIN

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Qinling orogenic belt is a most important mountain rang to divide China into north and south regions. Due to the drastic uplift and denudation since Late Mesozoic, the bedrock thermochronology is ineffective to reveal its exhumation history soon after its formation. However, the early uplift and exhumation process is of great significance to comprehend its evolution history. In this study, granitic gravels (shallow buried in the Early Cretaceous of Ordos basin that adjacent the belt) which come from the Indosinian pluton of the belt were taken as the agency and multiple geochronological methods (such as zircon U-Pb, zircon U-Th/He and apatite FT) were used to disclose the early uplift and exhumation history. The results show that the zircon U-Pb ages are mainly concentrated in 212~222 Ma, the zircon U-Th/He ages range from 187 Ma to 194 Ma and the AFT ages range from 107 Ma to 113 Ma with the mean confining track length at 9.7,10.7μm. Thermal history modeling, based on the multiple geochronological data, show ~18.75 ℃/Ma cooling and ~750 m/Ma exhumation during Late Triassic-Early Jurassic, then followed by the ~3.17 ℃/Ma cooling and ,126m/Ma exhumation from Middle Jurassic to Early Cretaceous. As a whole, our new data and thermal history inversion modeling provide new insights on the prolonged pre-Cenozoic cooling history as well as the intracontinental deformation of the Qinling orogenic belt. which were mostly related to Paleo-Tethyan subduction and the collision process of North and South China block.

Rates and timing of Earth system processes

DIFFERENTIAL POST-MINERALIZATION THERMAL EVOLUTION OF THE JIAODONG AND LIAODONG AREAS, EASTERN CHINA: AN INDICATOR OF REGIONAL TECTONIC ACTIVITY

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Post-mineralization thermal evolution is an integral part in the study of mineral deposit. As two important gold mineralization regions in eastern China, the thermal histories after ore-formation of the Jiaodong area is debated while that of the Liaodong area are scarce. Given that the two areas are not only in similar tectonic settings but also have gold deposits that formed in association with the thinning and destruction of the North China Craton, a comparative study can be made. Here new zircon and apatite (U–Th)/He and apatite fission track ages are presented to reconstruct the post-mineralization geological evolution. Four periods of rapid uplift and denudation happening during the 110–100 Ma, 80–70 Ma, 42–38 Ma and 35–32 Ma are defined in Liaodong, and two such periods happening during the 100–95 Ma and 80–72 Ma in Jiaodong. The small timing difference of the rapid uplift (110–100 Ma versus 100–95 Ma) can be explained by the elevation difference of the respective samples. Hence, the evolution processes between the Jiaodong and Liaodong areas are very similar during the Cretaceous, but show marked differences during the Cenozoic. After ore-formation, the erosion amount in Liaodong and Jiaodong is estimated at 4.8 and 4.7 km, respectively. Moreover, the denudation intensity in Liaodong shows an increase from southeast to northwest. The westward convergence of the Pacific Plate and associated multi-stage activity of the Tanlu and Yalujiang faults are inferred to have induced the regional-scale rapid uplift of the Jiao-Liao areas.

Rates and timing of Earth system processes

LOW-TEMPERATURE THERMOCHRONOMETRIC CONSTRAINTS ON LATE CENOZOIC GLACIAL EROSION IN THE EASTERN ALPS

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Improving our understanding of spatio-temporal patterns and rates of erosion plays a key part in answering longstanding debates on how climatic influences couple with tectonics and subsurface dynamics to control the morphology of mountain belts. In the context of heavily debated increased late-Cenozoic erosion rates linked to long-term climate cooling, a better insight into erosive patterns in glacial and periglacial landscapes with constrained tectonic overprinting is integral to informing our knowledge of climatic-erosional feedbacks and variabilities in such landscapes. The well-studied European Alps are an ideal natural laboratory to isolate these interdependent effects due to a west-east gradient in exhumation rates but mostly comparable present uplift rates, which only slightly decrease eastwards. The western Tauern Window in the Eastern Alps presents a prime real-world case study location due to its simple rapid Miocene exhumation history as a crystalline block between two major thrusts. Measuring exhumation histories via low-temperature thermochronology to separate spatio-temporal erosion signals overprinted on known uplift histories is the most fitting method to address these questions, as it is independent of the preservation bias of erosion in sedimentary records. We report new constraints on late-Cenozoic exhumation along elevation transects in the Italian Ahrntal and the Austrian Floitental from apatite (U-Th)/He data, with the view of comparing these data to the western Alps, which have experienced similar past glaciation but different exhumation. This study also provides an initial insight into an area we intend to investigate further in higher resolution using 4He/3He in future.

Rates and timing of Earth system processes

ESR AND OSL-THERMOCHRONOMETRY IN THE WESTERN EUROPEAN ALPS

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The western European Alps are characterised by deeply incised valleys, however the timing of their formation and the impact of Quaternary glaciation on rates of erosion remains disputed. This is mainly due to a lack of geochronological methods that cover the timespan of 103-106 years. Trapped-charge thermochronometry has high potential to fill this temporal gap because of its low closure temperature (<100 °C), potentially allowing changes in erosion rates to be related to glacial advance and retreat.

We took surface rock samples for ESR and OSL-thermochronometry from two elevation transects in the Rhône valley, Switzerland. ESR thermochronometric ages of seven samples from Sion range between 240 kyr and 650 kyr, while Ti centre ESR signals of samples from Visp are saturated. Although the lithology of the two sites is similar, the characteristic dose (D0) values of samples from Visp are 2-3 times smaller than those measured at Sion. The first luminescence measurements on the samples from Sion yielded saturated values, demonstrating the additional potential of ESR-thermochronometry in these kinds of settings.

Preliminary inversion of the Sion ESR data yield consistent cooling histories, except for the valley bottom sample that suggests more rapid rock cooling. These data show that the low closure temperatures of the Al and Ti signals in quartz allow the Late Quaternary exhumation of the Alpine valleys to be resolved. The combination of ESR and the existing thermochronometric data as well as numerical modelling approaches will provide the new insights into the valley incision during the Quaternary.

Developments and challenges in fission-track thermochronology

AFT STUDY OF A DIKE INTRUSION, NAVAJO NATION: A JUNIOR HIGH SCHOOL PROJECT

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A state-of-the-art mobile Apatite Fission Track (AFT) laboratory is operational at Diné College on Navajo Nation. For outreach to local Junior High School students, AFT analysis was applied to samples related to a Tertiary dike intruded into Lower Jurassic Navajo Sandstone, near Boundary Butte, southern Utah, Navajo Nation. AFTs in the dike and adjacent reset sandstone constrain post-intrusion time-temperature (t-T) paths. AFTs in one nearby sample constrain heating due to dike intrusion to between 275-325°C (assuming 1-2 months duration). AFTs far from the dike constrain pre-intrusion and post-intrusion t-T paths.

Several Chinle Junior High School 7th Grade students have been provided the AFT-based t-T histories summarized above and an Excel workbook containing Visual Basic code that solves the infinite sheet heat flow equation (Carslaw and Jaeger's (1959, equation 9, page 56). The students have been tasked with matching the AFT-based and heat-flow-equation-based t-T histories. Student and professional experiences with this project are being documented and will be polled. Lessons for students will reflect the Arizona Beyond Textbooks standards as an afterschool extracurricular project. The ultimate objective of this project is to demonstrate to these curious students links between AFT sciences and the rich natural history of the Navajo Nation.

Field work on the Navajo Nation was conducted under a permit from the Minerals Department. Any persons wishing to conduct geologic investigations on the Navajo Nation must first apply for and receive a permit from the Minerals Department, P.O. Box 1910, Window Rock, Arizona 86515 and Telephone No. (928) 871-6588.

Rates and timing of Earth system processes

THERMAL, TECTONIC AND LANDSCAPE EVOLUTION OF THE CENTRAL AND EQUATORIAL ATLANTIC AFRICAN MARGINS: INSIGHTS FROM APATITE FISSION-TRACK AND (U-TH/HE) DATA

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With a combined temperature sensitivity of c. 120 – 30°C, apatite fission-track (AFT) and (U-Th-Sm)/He (AHe) thermochronology can resolve rock cooling histories over geological timescales. These thermal history constraints have been used to estimate the temporal and spatial patterns of erosion across extensional continental margins. This, in turn, has provided insights into the response of surface processes to changes in tectonics, climate, and thermal events in the upper crust. Transform margins have received comparatively less attention.

Here, we present recently published AFT and AHe data and thermal histories from Guinea, Ivory Coast and Benin (Wildman et al., 2019, JoGS; 2022, Gond. Res.), and interpret these data alongside the regional thermochronological record published elsewhere to contrast the thermal history of the extensional Central Atlantic margin and the transform dominated Equatorial Atlantic margin. Our data show the thermal influence of the Central Atlantic Magmatic Province does not extend to Benin, where surface processes seem to have focused erosion seaward of the present-day drainage divide. We constrain the magnitude and spatial patterns of denudation attributable to syn- and post-break-up tectonic and surface processes and mantle driven dynamic uplift during the Cenozoic.

Finally, we integrate our thermochronology derived interpretations on the onshore erosion with the onshore geomorphology, weathering profile chronology, palaeogeography reconstructions (Ye et al., 2017, Geosphere) and offshore sediment accumulation volumes. In this way, we attempt to reconstruct the tectonic evolution and source-to-sink history across the West African margin over the last 200 Myr and highlight where knowledge gaps and analytical challenges remain.

Celebration of the research achievements of Rod Brown

THERMOCHRONOLOGY AND LANDSCAPE EVOLUTION OF THE AFRICAN CONTINENTAL MARGINS AND INTERIORS

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Africa formed following rifting and breakup of Gondwana during the Mesozoic. However, quantifying how the topography of the African continental margins and interior responded to competing tectonic, mantle, and surface processes during the pre-, syn-, and post-rift phase is still not fully resolved. The long-term continental erosion history is intrinsically linked to these geodynamic and geomorphic processes, so constraining the timing, magnitude and spatial patterns of erosion can help us understand the relative contribution of the driving forces creating and destroying topography over time. The application of low temperature thermochronology (LTT) techniques has been and continues to be an essential tool for constraining the long-term erosion history by providing information on rock thermal histories.

Here we review the LTT record along the Atlantic African continental margin and their adjacent interiors and its implications for the tectonic and geomorphic evolution. Stemming from the seminal work of the late Roderick Brown, we present examples from the southern African high-elevation margins and interior plateau and new data from the Equatorial West African transform margin, studies in which Rod's role as a collaborator or supervisor played a pivotal role.

Through these examples we assess the relevance of conventional concepts of tectonic geomorphology in non-orogenic settings, interpret expressions of post-rift tectonic reactivation and dynamic uplift, and discuss challenges and opportunities of applying LTT to further advance our understanding of the landscape evolution of the African continental margins and interiors.

Rates and timing of Earth system processes

KEEPING THE THERMO- IN THERMOCHRONOMETRY

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Thermochronometry attains value as a constraint on geologic processes through its integration with thermal models. A thermal model of the Earth's interior is essential to the inference of kinematic parameters and accuracy in the thermal model is just as important as accuracy of age data in the estimation of exhumation rate. We review the state of knowledge of thermal data and processes within the lithosphere and discuss processes and parameters that are essential to thermochronometry modeling. Heat flow data and thermal property data and can be augmented by geophysical data such as magnetic field constraints on Curie depths. Heat flow is variable even across stable cratons and we provide examples. Heat flow is rarely steady in tectonically active regions due to heat advection. The degree of thermal transience is characterized by a Peclet number reflecting the competition between diffusion and advection and we show that perturbations to lithospheric geotherms are significant for Peclet numbers above a specific threshold. We define the conditions where transient thermal perturbations are significant in terms of erosion rate and duration of erosion to determine when it is necessary to use transient thermal models. With 2-D or 3-D kinematic models, processes such as downward and lateral advection or concentration of heat production become important, and we document how this affects simpler models of exhumation. Finally, thermal models allow us to extract more accurate information from thermochronometric data as the physics of heat flow in the lithosphere provides additional constraints on t-t paths.

Rates and timing of Earth system processes

RIFT PROPAGATION IN SOUTH TIBET CONTROLLED BY UNDERTHRUSTING OF INDIA: A CASE STUDY AT THE TANGRA YUMCO GRABEN (SOUTH TIBET)

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Active graben systems in south Tibet and the Himalaya are the surface expression of ongoing E-W extension, however, the cause and spatio-temporal evolution of normal faulting remain debated. Here, we reconstruct the exhumation history driven by normal faulting at the southern Tangra Yumco graben using new thermochronological data (Wolff et al. 2023, Journal of Geological Society, https://doi.org/10.1144/jgs2022-090). The Miocene cooling history of the footwall of the main graben-bounding fault is constrained by zircon (U-Th)/He ages (16.7±1.0 to 13.3±0.6 Ma), apatite fission track ages (15.9±2.1 to 13.0±2.1 Ma), and apatite (U-Th)/He ages (7.9±0.4 to 5.3±0.3 Ma). Thermo-kinematic modelling of the data indicates that normal faulting began 19.0±1.1 Ma ago at a rate of ~0.2 km/Myr and accelerated to ~0.4 km/Myr at ,5 Ma. In the northern Tangra Yumco rift, re-modelling of published data shows that faulting started ~5 Ma later at 13.9±0.8 Ma. The age difference and the distance of 130 km between the two sites indicates that rifting and normal faulting propagated northward at an average rate of ~25 km/Myr. As this rate is similar to the Miocene convergence rate between India and south Tibet, we argue that the underthrusting of India beneath Tibet has exerted an important control on the propagation of rifts in south Tibet.

Rates and timing of Earth system processes

PHASES OF ENHANCED EXHUMATION DURING THE CRETACEOUS AND CENZOIC OROGENIES IN THE EASTERN EUROPEAN ALPS: NEW INSIGHTS FROM THERMOCHRONOLOGICAL DATA AND THERMOKINEMATIC MODELING

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Austroalpine nappes in the Eastern European Alps have preserved the record of orogenies in the Cretaceous and the Cenozoic but their cooling and exhumation history remains poorly constrained. Here we use low-temperature thermochronology and thermokinematic modeling to unravel the exhumation history of the Austroalpine nappes in the Gurktal Alps. Our data reveal marked differences in the exhumation of two crustal blocks, controlled by their position relative to the Adriatic indenter. The northern block (located farther away from the indenter) cooled through the zircon fission track closure temperature already in the Late Cretaceous. Apatite fission track ages cluster around 35-30 Ma, indicating that rocks resided at depths of ≤5-6 km since the Eocene/Oligocene. In contrast, zircon fission track ages from the southern block (located near the indenter) indicate cooling during the Eocene; apatite fission track ages cluster at ~15 Ma. Thermokinematic modeling of age-elevation profiles revealed that the northern block experienced a phase of enhanced exhumation (~0.60 km/Ma) between ~99 and ~83 Ma as a result of syn- to late-orogenic Late Cretaceous extension. After a period of slow exhumation (~0.02 km/Ma), the exhumation rate increased to ~0.16 km/Ma at ~34 Ma. In contrast, the southern block was rapidly exhumed (~0.76 km/Ma) from ~44 Ma to ~39 Ma during an Eocene compressional event that preceded the Europe-Adria collision. After a phase of slow exhumation (~0.13 km/Ma) between ~39 and ~18 Ma, the exhumation rate increased to ~0.27 km/Ma in the wake of Miocene escape tectonics in the Eastern Alps.

Rates and timing of Earth system processes

CONTINENTAL EXHUMATIONS COUPLING TO THE STATUS OF SUBDUCTED PLATE: STUDY ON THE SOUTHERN GREAT XING'AN RANGE, CHINA AND NE ASIAN FROM MIDDLE MESOZOIC

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The linkage between deep subduction of the ocean plate and continental orogenic uplift/exhumation is a problem to be explored. Large thermochronological data sets enable orogen-scale investigations into the spatio-temporal patterns of erosion and exhumation, and can provide additional constraints on crustal deformation, magmatic and tectonic processes. We present a high-resolution T-t constraints on exhumation processes in the southern Great Xing'an Range (GXR), NE China by utilizing multiple thermochronometers and one geochronometer (zircon U-Pb, (U-Th)/He; apatite U-Pb, (U-Th)/He; titanite U-Pb). The inverse model results demonstrate that the southernmost segment of the GXR experienced enhanced cooling and exhumation during the early Cretaceous (c. 155-130 Ma) accompanied by high-flux magmatism. This superficial rapid exhumation was in response to the thinning and delamination of the deep lithosphere caused by the roll-back of the Paleo-Pacific Ocean (PPO). Furthermore, our compilation of available hundreds of low-temperature thermochronological data spanning ~500 km of the NE Asian continent margin shows three episodic exhumations and associated topographic evolution, which coincides well with the changes in the subduction state of the PPO and the Pacific Ocean since the late Mesozoic, thus exhibits the coupling between the subducted plate and overriding continent margin.

Developments and challenges in (U-Th-Sm)/He thermochronology

DEVELOPMENT OF REFERENCE MATERIALS FOR IN-SITH (U-TH-PB)/HE DOUBLE DATING

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In-situ laser (U-Th)/He and U-Pb double dating technique for U-Th bearing accessary minerals such as zircon and apatite has been proven to be a powerful and efficient tool for sedimentary provenance studies. The recently developed laser microanalysis technique offers some advantages over conventional bulk crystal chemical methods such as higher spatial resolution, more productivity, and higher safety by avoiding usage of concentrated hydrofluoric acid. To achieve this, matrix-matched reference materials with homogeneous composition (especially parent nuclides such as U, Th, and Sm isotopes) and (U-Th)/He age are urgently needed. We developed new apatite (MK-1 apatite from Mogok metamorphic belt, Myanmar) and zircon (SA01 zircon from South Africa) in-situ laser (U-Th)/He and U-Pb double dating reference materials in the last few years. Structural observations and micro-probe chemical analysis revealed that these two materials are homogeneous. Inter-laboratory comparison shows that they yield consistent and reproducible (U-Th)/He and U-Pb ages. Comprehensive analysis indicates that these two minerals could serve as new potential reference materials for in-situ (U-Th)/He, U-Pb double dating and traditional solution (U-Th)/He dating techniques.

Rates and timing of Earth system processes

THE EXTENSIONAL HISTORY OF THE CUONA RIFT, SOUTHERN TIBET: IMPLICATIONS FOR THE UPLIFT OF TIBETAN PLATEAU

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The north-south trending rifts (NSTRs) govern the E-W extension of northern Himalaya-southern Tibet and are a focus for active tectonics within the Tibetan Plateau. They are primarily composed of grabens and a set of high-angle normal faults that formed in the mid-Miocene. Understanding the deformation history of the NSTR is key for constraining the uplift mechanism of the Tibetan Plateau.

As the only rift in the eastern Himalaya, the Cuona rift in southern Tibet warrants greater attention, particularly in light of current research showing the eastward younging trend of the NSTR. Despite its significance, the investigation of the Cuona rift remains poorly studied. Here we present apatite fission track (AFT) and (U-Th)/He (AHe) and zircon (U-Th)/He (ZHe) ages from the southern segment of the rift in order to reveal the cooling history of the footwall of the normal fault. New AHe ages imply that active rifting continued in Late Miocene to Pliocene. This initial is significantly later than the other main NSTR. Integrating this with newly acquired AFT and ZHe data will enable us to determine the long-term extensional history of the Cuona rift, thereby help us identify the genetic mechanism responsible for the entire rift system, as well as the latest evolution of the India-Asia continental collision.

Advances in noble gas and solid state thermochronology

U-TH/HE SYSTEM BEHAVIOR IN PYRITE

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Recent advances in understanding the behavior of radiogenic helium in metals (Shukolyukov et al., 2012) allows to suggest high helium retention in pyrite. This proposition was reinforced by the results of step-heating experiments, which have shown almost complete He retention in pyrite in a range of its thermal stability (Yakubovich et al., 2019). The U-Th/He dating of pyrite has successfully applied to various types of the ore deposits and sedimentary rocks (e.g. Yakubovich et al., 2020, 2021, 2023; Ivanova et al., 2023).

The presentation will cover the factors that contribute to high helium retentivity in pyrite which are (a) cubic crystal lattice; (b) packing density; (c) semiconductivity. The methodological aspects of U-Th/He dating of pyrite will be addressed as well.

Given the abundance of pyrite in ore deposits and its occurrence in igneous and sedimentary rocks, it has a great potential as a geochronometer.

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Ivanova et al., Vestnik SPbU: Earth Sciences (2023) (in press); Shukolyukov et al., Petrology 20.1 (2012): 1; Yakubovich et al., Petrology 27 (2019): 59-78; Minerals 10.7 (2020): 629; Geosciences 11.10 (2021): 408; Doklady Earth Sciences (2023) (in press)

Advances in noble gas and solid state thermochronology

NEW 4HE REFERENCE MATERIAL: DETRITAL PLATINUM ALLOY GRAINS FROM THE SANTIAGO RIVER, ECUADOR

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Mineral reference materials are essential for accurate measurements as well as monitoring of the instrument performance. The alpha-decay of 190Pt has been used as a dating tool (e.g. Yakubovich et al., 2022) and has the added advantage that PGE alloy grains may be a simple reference mineral. Detrital native platinum alloy grains (RS-Pt) from the Santiago River, Ecuador, are mineralogically simple and appear to originate from a single mineral deposit. Grains (500–1000 mkm) analyzed at the SUERC (n=8) and IPGG RAS (n=9) He laboratories produce overlapping 4He concentrations yielding weighted mean of 215 ± 2.0 x 10^11 at/g (2s) and 190Pt-4He age of 39.6 ± 0.7 Ma (2s). This implies the He concentration of RS-Pt grains is more homogeneous than the other He mineral standards (BCR-2 basalt, Knyahinya meteorite, CRONUS-P pyroxene).
The ease of analysis makes RS-Pt suitable as a rapid way to determine instrument performance during apatite/zircon He thermochronology analysis programmes. We are keen to provide other He laboratories with RS-Pt grains to contribute to an inter-calibration exercise and use as they wish. Samples of the Santiago River Pt concentrate are available on request from the SUERC laboratory (contact fin.stuart@glasgow.ac.uk).

Yakubovich, O., Kutyrev, A., Sidorov, E., & Travin, A. (2022). 190Pt-4He dating of platinum mineralization in Ural-Alaskan-type complexes in the Kamchatka region: evidence for remobilization of platinum-group elements. Mineralium Deposita, 57(5), 743-758.

Developments and challenges in fission-track thermochronology

AUTOMATIC IDENTIFICATION OF SEMI-TRACKS ON APATITE AND MICA USING A DEEP LEARNING METHOD

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Fission track dating is a widely used thermochronological approach to constrain the thermal history of rocks.
Conventionally this approach requires manual identification of fission tracks under the microscope which can be time-consuming and labor-intensive. In this study, we proceed with the newly developed approach to identify fission tracks on transmitted light images based on a deep learning method. In this new approach, we use a convolution neural network (CNN) to extract semi-tracks through image semantic segmentation. Considering the boundary ambiguity inherent in the CNN, we also extract the multi-scale boundary of the images in order to refine the semantic segmentation. We then calculate an area threshold of semi-tracks to determine whether semitracks are overlapping or not. These non-overlapping tracks are counted directly from the refined semantic segmentation images. For these overlapping tracks, we develop a boundary-superimposed method by using the refined semantic segmentation and the multi-scale boundary images with the help of the reflected-light images to split them before counting. We used 101 images of spontaneous fission tracks and 7 images of induced fission tracks for training with this new approach and tested the resulting convolutional neural networks on 114 spontaneous fission track images and 60 induced fission track images. Most of the test samples show high precision, recall, F1-score, and overall accuracy, highlighting the potential usage of this approach to identify fission tracks automatically.

Rates and timing of Earth system processes

FISSION TRACK THERMOCHRONOLOGY CONSTRAINTS ON UPLIFT AND EXHUMATION OF THE CHAKABEISHAN ORE DISTRICT IN THE NORTHERN MARGIN OF THE QAIDAM BASIN, CHINA

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The Chakabeishan area is located in the northern margin of the Qaidam basin, Northwest China. A total of 11 apatite and zircon sample results are achieved, dividing to 4 age groups of 159–144 Ma, 114–100 Ma, 72 Ma and 52–32 Ma. Thermal history modelling reveals 3 episodes of 120–60 Ma, 60–18 Ma and 18–0 Ma. In the first stage the Southern Qilian Mountains subduct southward due to collision between the Lhasa and the Qiangtang blocks, resulting in rapid uplift in this area. The second stage is tectonic quiescence period. The third stage shows rapid uplift caused by the collision of the Indian and Eurasian Plates. The average uplift rate and total uplift amount of the three stages calculated according to the geological thermal histories are 0.039 km/Myr and 3.27 km. The exhumation rate has been calculated as 0.034–0.148 km/Myr from zircon closure–temperature of 250 °C to apatite 100 °C and 0.049–0.076 km/Myr from the apatite closure–temperature of 100 °C to 15 °C of surface temperature. The exhumation rate is fastest from the Late Cretaceous to Eocene and has then changed a little since the Eocene, with the average exhumation rate of about 0.059 km/Myr. This area is characterized by multi–stages mineralization and the metallogenic age is mainly in the Late Jurassic–Cretaceous.

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Rates and timing of Earth system processes

THERMO-TECTONIC HISTORY OF THE HAILAR BASIN, NORTHEASTERN CHINA, AS CONSTRAINED BY FISSION-TRACK ANALYSIS

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The extensive intracontinental extensional tectonic setting characterizing northeastern Asia during the late Mesozoic is classically ascribed to the closure of the Mongolia-Okhotsk Ocean and the subduction of the Paleo-Pacific plate. However, the spatial and temporal impact of these processes in the region still remains an unresolved issue. The Hailar Basin, located in the Erguna block of Northeast China, is a crucial area where the Mongolia-Okhotsk oceanic plate domain and the Paleo-Pacific domain meet. However, the basin's thermo-tectonic history has not been thoroughly studied, which hinders the further development of regional tectonic research.

In this study, we conducted fission track analyses both on drilling core and cutting samples collected from seven depocenters of the basin and on magmatic rocks exposed on the basin margin and local uplift. We plan to combine fission-track data with the interpretation of seismic and log data. Our aim is to reconstruct the thermo-tectonic history of the Hailar Basin since the Late Jurassic, reveal potential variations in different regions of the basin, and explain the underlying mechanisms within the framework of the closure of the Mongolia-Okhotsk Ocean and the subduction of the Paleo-Pacific plate

Rates and timing of Earth system processes

DEFORMATION OF THE EASTERN-SICHUAN-XIANG'EXI FOLD-THRUST BELT (YANGTZE BLOCK, CHINA) SINCE THE LATE MESOZOIC AND UNDERLYING MECHANISMS: CONSTRAINTS FROM LOW TEMPERATURE THERMOCHRONOLOGY

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The Eastern-Sichuan-Xiang'exi fold-thrust belt is a major geological feature of the Yangtze block in China, covering an area of approximately 132000 km2 from the Xuefeng uplift to the Huaying Mountains. The region's NE-trending fold-thrust combination, characterized by well-developed Jura-type folds, has intrigued geologists for years. The Qiyue fault divides the study area into two parts, with the Eastern-Sichuan thrust-fold belt located to the west and the Xiang'exi fold belt to the east. The Eastern-Sichuan thrust-fold belt chiefly includes Lower Paleozoic and Triassic strata, whereas the Xiang'exi fold belt is characterized by Middle-Lower Triassic and Middle-Upper Jurassic deposits. According to earlier studies on the structural deformation characteristics and thermochronology of the region, the deformation began in the Late Triassic and reached its climax in the Middle Jurassic-Late Cretaceous. The deformation pattern shows a progressive renewal from southeast to northwest. Furthermore, the degree of basement involvement or caprock slippage varies across various tectonic units, resulting in distinct uplift/denudation rates for each unit. However, the evolution of the regions and the underlying mechanism behind it remain controversial. To address these issues, we performed zircon (U-Th)/He analyses on 18 sandstone samples from various tectonic units in the study area. Our results, when combined with previous thermochronologic data, reveal differential uplift within the study region since the late Mesozoic, and provide new insights on the dynamics of the thrust-fold belt.

DENUDATION HISTORY OF GREAT XING'AN RANGE, NORTHEAST CHINA: GEOCHRONOLOGICAL CONSTRAINS ON MESOZOIC MAGMATIC ROCKS

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Uplift and subsidence of the earth's surface are closely related to deep processes and regulate the climatic evolution such as in the cases of monsoons and ocean currents. The Great Xing'an Range (GXR) is a more than 1000 km long and hundreds of kilometers wide orogenic chain in northeast China, with more than 75% of the area covered by Mesozoic magmatic rocks. Tectonically, it belongs to the eastern section of the Central Asian Orogenic Belt, which is one of the largest and long-lived accretionary orogen in the world. Specifically, the GXR is the northern boundary of the east Asian monsoon thus it plays an essential role in the climate evolution of northeast China. However, the uplift history of the Great Xing'an Range, in terms of when and how it took place, remains poorly understood. Here we present an integrated approach based on zircon U-Pb, apatite fission track dating, and whole-rock geochemistry of Mesozoic magmatic samples collected along the GXR. Our data provides detailed constraints on the thermo-tectonic history of the GXR, thus giving new elements for the debate on relationships among climatic, tectonic, and surface processes in northeast China.

Rates and timing of Earth system processes

Geochronologic Constraints on the Rubidium Deposit of Zhongba, Guangdong, China

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The South China Block is characterized by the widespread of Mesozoic igneous which are closely associated with numerous precious metal deposits. A large-giant independent Rb deposit has been recently discovered in Zhongba, Guangdong Province. The area is located on the southeastern margin of the Nanling metallogenic belt, adjacent to the West Pacific tectonic realm. The orebody consists of weathering crust ore body and primary ore body, which was hosted in Zhongba granite. The granite is a complex pluton and there is a lack of reliable isotopic data on them. Granite samples were collected from a drilling core (SZK023-92 and ZK023-96, the third epoch), while others from the outcrops of greisens within the third epoch granite (BC1705 and BC1706). The zircon U–Pb dating analysis was performed by LA–MC–ICP–MS and yield weighted mean 206Pb/238U ages of 135.38±0.57Ma（MSWD=0.99） and 136.96±0.88 Ma（MSWD=2.2）, 135.5±1.4 Ma（MSWD=0.36） and 139.4±1.4Ma（MSWD=2.3）, respectively. The ages of the greisens are consistent with that of the surrounding rock, implying a contemporaneous product formed by the upwelling of hydrothermal fluid in depth during the third magmatic crystallization. Except the barren sample (SZK023-92), others are Rb-bearing granite, therefore, we infer that the formation age of the primary Rb deposit is 135-140 Ma; On the other hand, the age of BC1702 from granite weathering crust is 128±4Ma (MSWD=3.5), indicating a late mineralization.

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