Unravelling Earth's story: how crystals reveal the secrets of landscape evolution

Illuminating charge transport in feldspar to measure rates of Earth surface processes.

Our planet's surface is constantly evolving. To understand these changes, scientists seek ways to measure the rates of Earth's surface processes like erosion and sediment transport on different spatial and temporal scales. The LUMIN project focuses on illuminating how charge moves within feldspar, a common mineral on Earth's surface. This knowledge will help create new tools to measure such rates so that the history of Earth's landscapes may be deciphered, thereby helping us predict their future.

The challenge of landscape evolution

Our planet's surface is continuously modified by a complex interplay of climate, tectonics, sea level and biological activity. The action of wind, water, ice and biota sculpt landscapes, disperse nutrients and affect climates and ecosystems. Understanding the rates of Earth's surface processes, like sediment erosion, transport and deposition, across vast expanses of space and time is fundamental. This knowledge is critical for predicting how landscapes evolve, anticipating geohazards, and establishing a natural baseline to assess human impact on Earth's surface and help us co-exist sustainably with our immediate environments.

Despite significant progress in the science of dating past geological events (geochronology), quantifying erosion and transport rates has proven challenging over recent time scales of 10–100 000 years due to a lack of applicable techniques. Thus, landscape evolution remains poorly understood, and this knowledge gap risks major bias in our perception of how Earth's surface has evolved in the recent past, a bias that can be detrimental to predicting our planet's response to rapid environmental change and landscape/resource management.

Crystals: key to understanding landscape evolution

Optically stimulated luminescence (**OSL**) and thermoluminescence (**TL**) from the mineral feldspar—the most common crystal on Earth's surface—offer a key to bridging the knowledge gap in rates of Earth's surface processes.

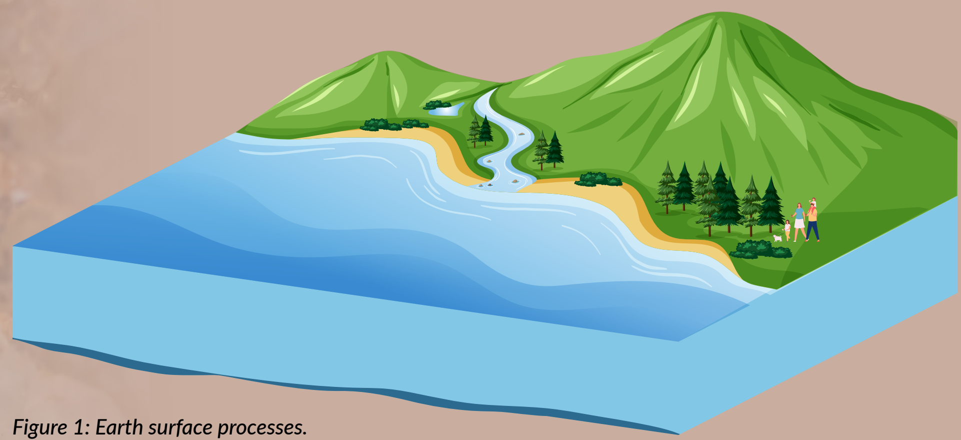

Figure 1: Earth surface processes.

OSL and TL arise from a complex sequence of processes involving the transport of electrons in the crystal lattice. Imagine a feldspar crystal as a rechargeable battery (Figure 1). Exposing the crystal to ionising radiation (alpha, beta, gamma, cosmic) in the natural environment results in charging (storage of energy). Conversely, exposure to the heat or light results in discharging (release of stored energy). The latter is often accompanied by light emission in the form of luminescence: TL if the release was thermally induced and OSL if the release was due to light exposure.

Atomically speaking, charge (electron) transport occurs across the defects (e.g. impurity atoms) in the crystal lattice. Ultimately, luminescence arises from a loss of energy when electrons trapped in the defects are excited by heat or light to escape these traps, and the crystal returns to its original, unexcited state. As a result, heat and/or light exposure results in the emptying of traps, whereas ionising radiation results in the filling of traps.

Since trapped electrons are sensitive to heat and light, they dynamically respond to ambient environmental conditions on Earth's surface, which inevitably includes heat and/or sunlight exposure. For example, during mountain uplift due to

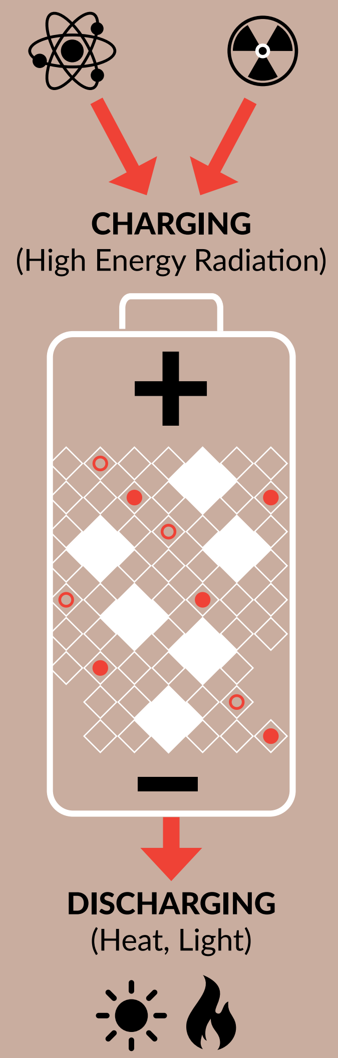

Figure 2: An illustration of battery concept, trapped electrons (dots) and holes (circles).

erosion, a crystal of feldspar rises from depth towards the surface of the Earth, becoming cooler and cooler. As a result, battery charging becomes more efficient than discharging, and the charge state at the time of sampling (analogous to the luminescence signal from the sample) is a function of a particular cooling path (uplift rate) that feldspar crystal experienced.

Similarly, during transport by river, a feldspar crystal is increasingly exposed to longer and longer durations of light, a process where battery discharging is more efficient than charging, and the end state is a function of the sediment transport rate. Cooling due to extensive snow covers will affect the charge (luminescence) depletion on the surface of the exposed rocks, and so on.

These new methods of measuring erosion and transport rates, collectively known as **feldspar luminescence thermochronometry and photochronometry**, are highly promising for deriving rates of Earth surface processes on unprecedented spatial (e.g. erosion of an individual rock) and temporal scales (10–10^5 years).

The knowledge gap

To determine erosion or transport rates from the luminescence measurement, inverse modelling techniques are employed based on our informed guesses of 'how' charging and discharging occur during heat or light exposure. Ultimately, inverse models rely on mathematical equations of electron transport in feldspar when exposed to ionising radiation, heat and light in Earth's surface environments. However, despite extensive efforts, there is no unique mathematical description of how charging and discharging occur in a feldspar crystal. Different models yield inconsistent results and remain debated because of a serious lack of detailed understanding of how atomic scale processes give rise to luminescence. Thus, inevitably, our model choices remain arbitrary, guided by coarse calibration approaches rather than physical insights, and unfortunately, the derived rates of Earth surface processes, based on extrapolations over geological time scales, vary grossly depending on the chosen model. Different permutations of models and model parameters may describe the data obtained on laboratory time scales with similar degrees of success/failure. However, their predictions can diverge considerably on geological time scales (~5-8 orders of magnitude beyond laboratory times).

The detailed understanding of charge transport mechanisms across defects that give rise to luminescence has reached an impasse due to the lack of methods to directly measure electrons trapped at crystal defects. Therefore, the details of their transport, which is responsible for battery charging and discharging, cannot be studied. Furthermore, the physical mechanism must be inferred from averaged macroscopic observations from bulk specimens despite knowing that crystals can be structurally and compositionally heterogeneous on sub-µm scales to nm scales.

LUMIN: pushing the limits

LUMIN's prime objective is to bridge the gap in our knowledge of how latent luminescence evolves in the feldspar mineral in near-Earth surface environments to develop robust luminescence models for accurate quantification of the rates of Earth surface processes.

The fundamental questions for the development of a robust luminescence model for feldspar are related to identifying the relevant traps based on their physical characteristics and understanding their physical behaviour and interactions within the crystal lattice.

A radical interdisciplinary approach is needed to unravel multi-scale charge-transport phenomena to overcome the current impasse in our understanding of luminescence mechanisms. Using the recent breakthrough discovery, which enables high-resolution imaging of trapped electrons through a technique called infra-red photoluminescence (IRPL), LUMIN will, for the first time, observe the spatial and temporal evolution of atomic states participating in luminescence. In combination with novel microscopy, LUMIN will use atomic scale simulations of defect states, aided by deep learning algorithms, to accurately define the defects and understand their physical behaviour in the feldspar lattice. Finally, these novel data and understanding will lead to the development and testing of a unique, comprehensive mathematical model of charge transport and luminescence production in feldspar (the unified model) to accurately quantify rates of Earth surface processes on unprecedented spatial and temporal scales. This research is timely as PI's group has only recently established the potential of IRPL for high-resolution imaging of traps and deconvolution of electron-hole recombination dynamics.

Expected impact

LUMIN is strongly grounded in geosciences, material science and photonics. Through a strong interdisciplinary approach, LUMIN will establish a robust theory of charge transfer for the most abundant mineral in Earth's crust, thereby settling debates on the systematics of the widely used luminescence dating technique. Using a combined experimental-theoretical approach, LUMIN will provide a paradigm shift in our knowledge of the physical mechanisms that underpin luminescence emission in the most abundant mineral in Earth's crust.

Since feldspar is ubiquitous and luminescence measurements are fast, cheap and widely available, the unified model will be routinely used to solve the important challenge of scale bias in landscape evolution research by measurements of currently inaccessible process rates. As a result, LUMIN will enable routine quantification of mass removal and transport rates on Earth's surface.

Such data are essential for:

i. resolving the roles of climate, tectonics, and anthropogenic forcing in shaping our landscapes

ii. field-validation and further development of location-specific landscape evolution models to predict the effects of climate/human-induced changes and so guide management of land use, agriculture and geohazards. The novel model framework will also allow the investigation of charge transport in other phosphors, thus supporting the development of ideal photonic materials for health and the environment.

LUMIN involves high conceptual risk since it has never been possible to observe distributions of trapped electrons in any luminescence chronometer/dosimeter; this has only recently become technologically possible because of the discovery of IRPL by PI's group. High-resolution luminescence microscopy in mineralogically and compositionally heterogeneous insulators like feldspar is a completely new area of research.

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I am thrilled imagining what measurements at submicron scales will reveal and how they will ultimately answer questions on the evolution of Earth's surface. If my hypothesis is validated, LUMIN will deliver a unified model of feldspar luminescence to push the frontiers of landscape evolution research.

Mayank Jain

Conversely, if the hypothesis is falsified, we may not be able to achieve a unified model of feldspar luminescence. Nevertheless, LUMIN will still deliver significant outcomes by providing:

i. the first-ever direct view of the inner workings of luminescence in the most ubiquitous natural mineral and a novel unified model framework that may easily be adapted to other materials

ii. urgently needed fundamental data on trap parameter values, the spatial distribution of traps and its link to crystal composition and microstructure. These data will provide a solid foundation on which to build a comprehensive luminescence model in the future.

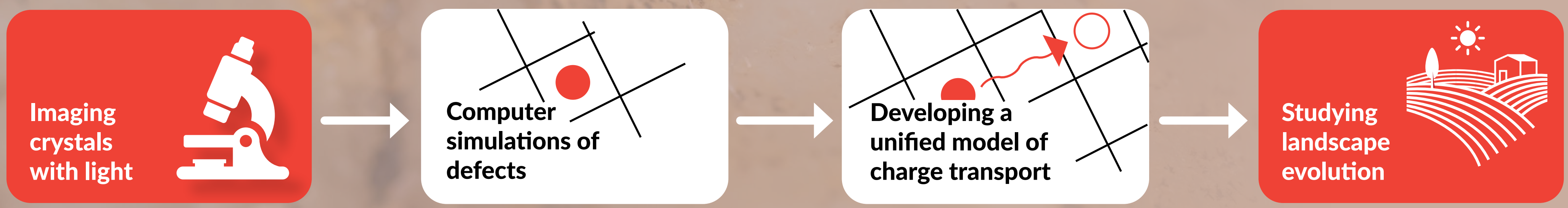

Figure 3: Research: The major steps in the research process, from crystal imaging to landscape analysis.

PROJECT NAME

LUMIN

PROJECT SUMMARY

LUMIN aims to revolutionise landscape research by developing a comprehensive model of luminescence in feldspar, the most common mineral in Earth's crust. The project will examine electron behaviour in defects in feldspar lattice using cutting-edge imaging and simulations and use the results of these investigations to develop a unified model of luminescence. This model will enable the accurate measurement of erosion and transport rates on unprecedented spatial and temporal scales, providing vital insights for landscape evolution studies, geohazard prediction and land use management.

PROJECT PARTNERS

The project is hosted at the Department of Physics in collaboration with the Department of Energy Conversion and Storage, both at the Technical University of Denmark (DTU).

PROJECT LEAD PROFILE

Mayank Jain leads the 'Luminescence Physics and Technologies' section at the Department of Physics, Technical University of Denmark (DTU Physics). He works at the boundary of solid-state physics and geoscience. Jain has contributed significantly to the current, very important position of luminescence dating in Quaternary research; >70 per cent of the publications in the field make use of the methods, instruments and measurement protocols developed by his section. He has contributed widely to the development of new research applications, methodologies and instrumentation based on luminescence in geosciences for applications.

PROJECT CONTACTS

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