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FLUID-ROCK INTERACTIONS IN THE EARTH'S INTERIOR

LUCIE TAJČMANOVÁ

The processes taking place inside rocks of the Earth's crust are characterised by a complex interplay of reacting solids and fluids. Mineral reactions and phase transitions within the Earth's interior are responsible for geological events like volcanic eruptions, earthquakes, and mountain building. Studying rock microstructures reveals how the Earth could have evolved. Combining field studies and innovative laboratory experiments with numerical modelling, researchers at the Institute of Earth Sciences of Heidelberg University aim to advance our understanding of the chemical transport, mechanical properties and behaviour of rocks by studying the physico-chemical processes that govern fluid-rock interactions.

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The continents are largely composed of ancient mountain belts that are made up of rocks which are now exposed at the Earth’s surface. These rocks incompletely record key processes within the Earth. Such processes take place in the deeper parts of the Earth’s crust and in the uppermost mantle – also known as the lithosphere – that forms the outer 100 kilometres of our solid yet dynamic planet. Mineral reactions and phase transitions within the lithosphere, involving deformation and fluid or melt flow, are responsible for volcanic eruptions, earthquakes and mountain building. Recrystallisation and phase transformations that occur with changing pressure and temperature in rocks within the lithosphere are referred to as metamorphism. Metamorphism reflects the style and intensity of global plate tectonics, i.e. movements of the Earth’s lithosphere, which in turn control mountain building processes. Knowledge about the interplay between rock deformation, metamorphism, and fluid or melt flow in the lithosphere is thus key to a better understanding of large-scale dynamic processes in the Earth’s interior.

Zooming into the micro-world

“Nature uses only the longest threads to weave her patterns, so each small piece of her fabric reveals the organization of the entire tapestry." This quote from famous 20th-century physicist Richard P. Feynman (1918 to 1988) excellently characterises the fact that we need to understand processes taking place on small scales ("the small pieces of the fabric") to better understand processes taking place on global scales ("the entire tapestry of Nature").

Petrology, the study of rocks, can be viewed as the materials science of the Earth. Since minerals are solid compounds that make up rocks, and thus most of the Earth, earth scientists must understand the mineral properties of rocks so that they can make reasonable inferences about how these rocks will behave under different conditions. Studying rock microstructures is therefore a cornerstone in the field of earth sciences. Microstructural data provide important insights into how the lithosphere could have evolved, within seconds and across million-year timescales. Data obtained from rock microstructures serve as important input for geodynamic models, which simulate the large-scale behaviour of the Earth.

In the last 100 years, work on mineral reactions and microstructures in rocks has focused on inverse and forward chemical modelling of processes related to chemical gradients, which are believed to control mass transfer in rocks. Significant advances have also been made in the development of analytical techniques. Recently, high-resolution analytical devices, predominantly developed in materials science, have become more available to earth scientists. Using these techniques, we can reveal the three-dimensional size, shape and distribution of microstructural features of rocks down to the nanometre scale. Interestingly, the smaller the scale considered, the more heterogeneous an apparently uniform rock sample turns out to be. This heterogeneity is not only characterised by variation in chemical composition but also in mechanical properties. This needs to be accounted for.

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When rocks and fluids interact

Fractures or zones of fractures between two blocks of rock are preferred pathways for fluids in the Earth's interior. The physical and chemical interactions between fluid flow and structures in the surrounding solid material strongly influence the mechanical behaviour of the whole system at different space and timescales. The fluid flow in the Earth's interior tends to be localised in space and time. Permeability, a measure of the ability of a material to transmit fluids, changes dynamically. Dynamic permeability changes may be caused by a coupled interaction of fluid flow with deformation, or a reaction of the solid material, or a combination of both processes. These coupled flow-deformation-reaction processes may be critically important for understanding processes such as the formation of fracture planes and the transport of heat and matter. Deformation and reactions may enhance or inhibit each other, because fractures allow reactive fluids to reach previously inaccessible volumes of rock. Chemical reactions may also affect mechanical rock properties and strengthen or weaken the rock. However, the effect of fluid flow on the long-term mechanical behaviour of rocks is still unexplored in models that simulate processes inside the Earth.

Even though they are among the key processes that occur in the Earth's interior, fluid-rock interactions belong to one of the most difficult processes to simulate because the hydraulic properties during initiation of rock fracturing can vary by orders of magnitude. Such extensive changes in hydraulic properties result in a locally rapid flow, where the fluid immediately reacts with its surroundings, which can affect the fluid's composition. This transition from a closed to an open thermodynamic system typically occurs in response to geodynamic processes such as earthquakes, dehydration or melting of rocks.

Microstructural changes including mineral reactions and deformation need to be considered in any computer simulations of processes inside the Earth. In past years, the increased use of computer models has added significantly to our understanding of complex processes related to fluid-rock interactions. Mechanical models of fracture nucleation and growth require very high numerical resolution to capture the fracture localising process, and must also be computationally fast to handle the wide range of timescales associated with the underlying thermodynamics, chemistry, and fluid flow. Nevertheless, when computer models are not tested against natural or experimental data, they have limited predictive power.

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Experiments as a window to the Earth's interior

Unfortunately, we cannot go deep enough into the Earth's interior to study these processes directly and we mostly rely on obtaining the appropriate observations from rocks now exposed at the Earth's surface. However, we can also simulate the extreme conditions of the Earth's interior via laboratory experiments by compressing and heating very small samples. Such experiments provide important insights into the conditions at which mineral reactions take place, and shine a light on mechanisms controlling localised deformation, which is comparable to deformation in the deep Earth. Experimental exploration is a dynamically evolving field, where the aim is to constantly improve experimental set-ups to better characterise complex geological processes. Therefore, it is not surprising that experiments also play an essential role in understanding fluid-rock interactions and processes.

For example, new experimental set-ups are needed to systematically investigate the effects related to the expansion and compression of supercritical fluids in contact with minerals. Appropriately designed experiments can then simulate how the quick expansion and compaction of fluids during rupture processes under high pressure affect the dissolution and precipitation of minerals under controlled conditions. Will the mineral growth and dissolution be an order of magnitude faster than commonly expected? This is the fundamental question for such experimental tests. If the process of mineral precipitation were much faster than

ZUM TANGO GEHÖREN IMMER ZWEI

DIE WECHSELWIRKUNGEN ZWISCHEN GESTEIN UND FLUIDEN IM ERDINNEREN

LUCIE TAJČMANOVÁ

Inwiefern werden die Vorgänge im Inneren der Erde von Materialeigenschaften beeinflusst? Das ist eine der wichtigsten Fragestellungen für die Geowissenschaften im 21. Jahrhundert. Um die Abläufe im Erdinneren zu verstehen, benötigen Wissenschaftler:innen eine qualitative Beschreibung aller wichtigen Beobachtungen sowie eine quantitative Einschätzung der physikalischen Prozesse über alle räumlichen und zeitlichen Skalen hinweg – von Kilometern bis Nanometern, von Jahrmillionen bis Sekunden. Dieses multidisziplinäre Forschungsfeld umfasst die Thermodynamik und Mechanik sowohl fester als auch fluidgesättigter Medien ebenso wie Analysetechniken aus der Materialwissenschaft und Computersimulationen.

Der heutige Aufbau des Erdinneren lässt sich mithilfe diverser geophysikalischer Bildgebungsmethoden darstellen. Gleichzeitig gewähren auch Beobachtungen von Mikrostrukturen im Gestein wichtige Einblicke in die mögliche Entwicklung der Erde. Gerade die Untersuchung dieser Mikrostrukturen liefert unmittelbare und grundlegende Informationen über die Geschichte und die Zeitskalen geologischer Prozesse, etwa die Entstehung von Erdbeben, die Auffaltung von Gebirgen, globale Kreisläufe flüchtiger Komponenten und die planetare Entwicklung. Auch für die kurz- und langfristige Vorhersage von Vulkanausbrüchen sind diese Daten unerlässlich.

Die physikalisch-chemischen Prozesse, die den Wechselwirkungen zwischen Fluiden und Gestein zugrunde liegen, spielen meist die wichtigste Rolle bei den genannten Naturphänomenen. Das quantitative Wissen zu diesen Wechselwirkungen findet zunehmend nicht nur in der Grundlagenforschung Anwendung, sondern auch im Bereich des Geoengineerings, etwa bei Fragen zur Nutzung geothermischer Energie, zur Speicherung von Wasserstoff und CO_2 oder zur Entsorgung radioaktiver Abfälle. Folglich ist das Verständnis komplexer Fluid-Gestein-Prozesse im Mikroskalenbereich auch wesentlich für Umwelt, Gesellschaft und Wirtschaft. ●

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expected, this would have important consequences for our understanding of seismic events because the process would consequently alter the short-term mechanical properties of the rock and their evolution.

So far, deformation experiments at ambient conditions, i.e. conditions that are relevant for seismic events, have been carried out at low deformation speeds in the millimetre per day range and commonly in fluid-deficient environments. Experimentally investigating the mechanisms that occur during quick mineral dissolution and precipitation processes, i.e. processes which occur at speeds of less than one second, can improve mitigation measures for seismic hazards by complementing the existing physical framework used for quantification of rupture processes. More specifically, it may allow us to break seismological processes down into physically more elementary softening and weakening cycles, related to processes of mineral formation and dissolution that are faster by orders of magnitude.

Societal relevance

Fundamental research on microstructures involving fluid-rock interactions is essential in order to make better predictions for sustainable geo-engineering development because the lack in our understanding of such processes could have far reaching environmental, societal and economic consequences.

Fluid-flow-induced deformation and reactions need to be quantified to overcome problems in a wide range of industrial operations – such as CO_2 sequestration or hydrocarbon exploration – and ensure safe long-term storage of gaseous or liquid waste. In fact, research in this direction can also contribute to better predictions of geothermal experiments. An example of an unsuccessful geothermal drilling experiment occurred in the city of Staufen im Breisgau in the state of Baden-Württemberg in 2007. The geothermal drilling to extract the earth’s heat crosscut a geological formation below the city that is composed of anhydrite (anhydrous calcium sulfate). The associated addition of water to anhydrite led to swelling of the underground due to the solid volume increase during the anhydrite reaction to gypsum, which is calcium sulfate containing water in its structure. The volume increase of up to 60 percent caused considerable uplift and, as a consequence, damage to the entire town. Besides the uplift due to the swelling processes, future problems, related to the fact that the gypsum is dissolving due to the continuous groundwater contact, may arise. This can lead to the development of sinkholes and other karst-related phenomena. The damage mitigation costs for such a failure have been enormous, including the priceless damage to the historical heritage of the town.

The research related to dissolution-precipitation processes conducted by my group with the help of new experiments involving instantaneous decompression may bring insights into similar effects in commonly used engineering materials, such as ceramics. This may lead to the development of innovative manufacturing techniques. ●

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