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Determining diffusion timescales in olivine and pre-eruptive processes from a recent Flores (Azores) lava flow

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Diffusion chronometry is a powerful tool used to gain insight into the timescales of magmatic and volcanic processes. It is most often used to obtain estimates of residence times in a magma chamber or to estimate the time between magma mixing and subsequent eruption (Costa et al., 2020).

In this study, bulk-rock geochemical data were obtained for 24 basalt samples from a single lava flow on the island of Flores (Azores), using X-ray fluorescence. Optical and Scanning Electron Microscopy was used for textural analysis of the basalt samples. Electron Probe Microanalysis (EPMA) was used to obtain concentration profiles of Fe-Mg (forsterite) in olivine crystals. These profiles were used for diffusion chronometry to obtain timescales of diffusion within the olivine crystals.

Through our geochemical and petrographic observations, three groups of olivine were identified. Type 1 olivines have cores with high forsterite (Fo) content (89–90%), and have normally zoned rims with (Fo content = ca. 82%). Type 2 olivines are matrix microcrysts that show a lower core Fo composition (ca. 82%) than the type 1 phenocrysts. Their rims grade more gradually towards lower values of Fo (ca. 77%), implying growth of the crystal during magma cooling or differentiation. Type 3 olivines exhibit reverse zoning with low-Fo (<70%) cores. They originate either from the wall-rock or from a more evolved magma chamber and are evidence of magma mixing.

Our method of diffusion modeling is based on Fick's second law of diffusion and the diffusion coefficients calculated by Girona & Costa (2013). Monte Carlo simulations were used in order to incorporate the variability of thermodynamic variables. We used values of P = 2500 bar ± 500 bar and fO_2 = QFM+1. Type 1 crystals were modeled with T = 1140 ± 20 °C, type 2 crystals with T = 1105 ± 20 °C and type 3 crystals at 1125 ± 20 °C. We obtained an average diffusion time for type 1 crystals of 23.5 days, which we believe to be the most representative for the time between magma mixing and eruption. The average diffusion time of type 2 crystals is much shorter (4.8 days)—these profiles were probably strongly affected by crystal growth. Reversely zoned crystals have diffusion times in between these values. The total range of diffusion timescales is from 1.2 to 58.2 days. Our results are minimum estimates, as we did not obtain Electron Backscatter Diffraction (EBSD) data of the olivine profiles. Higher temperatures yielded shorter diffusion times.

Based on our textural indications in the samples and the diffusion times obtained from modeling, we come to the following model: magma with primitive (type 1) olivine crystals was sourced from near-mantle conditions and brought to a shallower magma chamber. There, it mixed with a colder, more evolved magma, creating disequilibrium textures in olivine (type 3) and plagioclase crystals. Type 2 olivine grew from the mixed magma. Convective processes played a role in the occurrence of complex zoning in olivine and oscillatory zoning in plagioclase. The mixing of both magmas was what triggered the eruption on the island of Flores.

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Mineralogical and geochemical study of the Au mineralization at Imonga, Maniema (DRC)

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Imonga (Democratic Republic of the Congo) is located in a geologically complex region, where the Mesoproterozoic Karagwe-Ankole Belt and Kibara Belt and the Paleoproterozoic

Rusizi-Ubende Shear Belt meet (Fernandez-Alonso et al., 2012). Various magmatic events affected the region. The area is part of a metallogenic province known to host various types of mineralization including Sn-W-Nb-Ta-Li-Au.

Near Imonga, alluvial and eluvial gold deposits were exploited. In 1953, three drill cores were collected near the Imonga mine site (Kazmitcheff, 1961). Representative samples of two cores were conserved as part of the Kazmitcheff collection of rock samples at the Royal Museum of Central Africa (RMCA) in Belgium.

This study focuses on the reconstruction of the formation history of gold mineralization, present as both disseminated Au and Au in quartz veins, in the host rocks at Imonga. The available samples were studied by means of petrographic and geochemical techniques. A detailed petrographic and paragenetic study was carried out, focusing on the characterization of the host rock, the different mineralization phases, alteration types and vein generations, and on the temporal relationship between the mineralization phases, vein generations and alteration types.

The host rocks at Imonga underwent deformation and intense alteration (linked to four observed vein generations) and are classified as metasedimentary and metamagmatic rocks. In addition to foliation, various post-foliation tectono-metamorphic minerals were observed. The second vein generation is composed of quartz, ferroan dolomite and chlorite, and is associated with abundant mineralization, including observed gold mineralization in close association with sulphide mineralization. Andalusite porphyroblasts formed prior to, as well as after, the second vein generation and were used as the main P-T proxy for the formation conditions of the vein mineralization. Quartz deformation structures observed in these veins were used as additional P-T proxy. Indications of crack-seal mechanisms were also observed. The third vein generation consists of ferroan calcite, quartz and chlorite, and is also associated with mineralization. Sulphide mineralization was mainly observed in the form of pyrite, chalcopyrite and arsenopyrite. Mineralization also occurs in the form of iron-oxides/hydroxides and alteration of sulphide mineralization occurred.

The characteristics of the mineralizing fluid were investigated by studying primary fluid inclusions of the second and third vein generation by means of microthermometry, Raman spectroscopy and computer modelling. A pressure-temperature formation window for the timing of mineralization was determined. Finally, a metallogenic model for gold mineralization at Imonga was proposed.

The results of the microthermometric study indicate a fluid with an H_2O-NaCl-KCl-CO_2-X composition. The Raman spectroscopic analysis of the gaseous phase indicates the presence of a CO_2-N_2-CH_4-H_2S gaseous system, compatible with a metamorphic fluid composition. Increase in N_2 content is interpreted to result from reactions during metamorphism and fluid-rock interactions during fluid circulation. The presence of H_2S is characteristic of fluids carrying Au in reduced sulphur complexes. Modelling of the data resulted in fluid salinity values ranging between 3.1 and 5.2 eq. wt% NaCl and density values ranging between 0.74 and 0.94 g/cc. A formation window for the veins ranging from 350 °C to 400 °C, was established, based on constructed isochores and P-T proxies. At 350 °C, an upper pressure limit of 240 MPa is proposed, corresponding to a burial depth of 9.2 km, and a lower pressure limit of 90 MPa, corresponding to a hydrostatic pressure at equal depth. The derived pressure variation between lithostatic and hydrostatic pressure and the observed crack-seal mechanisms can be explained as the result of fault-valve activity.

The comparison of all obtained results to the literature allows classifying the gold mineralization at Imonga as an orogenic gold deposit. Gold was most likely transported as gold-sulphur complexes, which destabilized due to interaction with Fe-rich host rocks, resulting in the precipitation of Fe-sulphides and gold.

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Focal mechanism determination for earthquakes in and around Belgium based on P-wave first motions

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The World Stress Map compiles data from the different stress regimes based on information obtained from different stress regime indicators (Heidbach et al., 2016). One of the most important and easy-to-use indicators is the earthquake focal mechanism solutions (FMS) obtained from seismic data from emplaced seismometer networks. The Royal Observatory of Belgium (ROB) has an in-house code based on an older FORTRAN code (Camelbeeck, 1993), which determines the FMS for earthquakes in and around Belgium. The goal of this thesis is to develop a similar code written in Python that can obtain similar results as the ROB's in-house code. The method applied in the developed code is a P-wave first motion analysis. To develop this code, an extensive literature study is conducted to understand the applied method and become familiar with its different formulas. The code consists of two parts. The first part is used to plot the points that represent the stations on a stereonet. The second part is used to determine the orientation of the two possible fault planes of the earthquake (nodal planes). To determine these orientations, the two planes are rotated from a starting orientation using quaternion rotation. The rotation is done in two steps: a first guess with low accuracy (10–20°) and a final result with higher accuracy (1–2°). This is done to save computational time. The score value used to obtain the possible nodal plane orientations is the ratio of correctly positioned points over the total number of points used. From the obtained FMS, only qualitative stress regime data is obtained.

The developed code uses three types of data, namely station, waveform and event data. The station data comprises information regarding the different Belgian seismological stations and some international stations (e.g., location and name). The waveform data is the polarity of the P-wave measured in all seismometers registering a specific event. Lastly, the event data comprises the information regarding all studied earthquakes (e.g., magnitude, location and time). In total

37 earthquakes are studied in this thesis. Most of them are located in the Ruhr Valley Graben, while others are located near the southern border of the London-Brabant Basement, the Ardennes region or the Ochtendunger Fault Zone near Koblenz.

For each earthquake, the FMS for the earthquake depth obtained by the ROB is determined. Due to the simplicity of the score value, the program returns all possible solutions where this value reaches a maximum. Therefore, a multitude of possible orientations is returned with the variability in solutions depending on the configuration of the stations surrounding the earthquake. The obtained results are compared to results found in the literature or provided by the ROB. Comparing these to the obtained results shows that the program can provide accurate FMS. However, this is only the case when the number of seismic stations measuring a P-wave polarity is high, and they have a good distribution around the stereonet. When these criteria are lacking, the variability in obtained solution is high, and it becomes difficult to determine an accurate FMS. In addition, a sensitivity analysis is conducted to obtain the influence of a change in earthquake depth on the final solution. Therefore, the depth is varied in a range of +6 to -6 km in steps of 2 km. Results show that there is no significant influence of a change in depth on the FMS.

Based on the FMS for each earthquake and the geological context of the region, the most likely nodal plane responsible for the earthquake is discussed. These findings are generally in accordance with other publications. The stress regimes for each earthquake, obtained from the FMS, are placed in their geographical context to determine the regional stress regime. The Ruhr-Valley Graben is dominated by NNW-SSE striking normal faults along which ENE-WSW extension takes place, possibly along antithetic faults. In addition, Late Oligocene WNW-ESE striking faults were likely activated under transtension. The region of Court-Saint-Etienne, the London-Brabant Basement, is characterised by WNW-ESE striking faults under sinistral strike-slip. The Ochtendunger Fault Zone is likely characterised by dextral strike-slip occurring on ENE-WSW striking faults. Lastly, the Ardennes are characterised by highly variable FMS. This possibly indicates a complex regional stress field in this area, which is likely the result of the complex nature of the Ardennes Subsurface.

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On the use of the machine learning algorithms for automatically classifying cross-correlation functions - Application to the seismic data obtained around the Vatnajökull icecap, Iceland

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In Iceland, the sources of seismic noise are numerous and diverse (glacial, volcanic, hydraulic, oceanic ...) and thus are complex to identify and classify. Yet, these sources can be associated with natural disasters such as floods. Their monitoring could therefore prevent these hazardous events. These are the objectives of the IS-noise and IS-tremor projects, in parallel with which this work takes place.

Interferometry of the ambient seismic noise is used to generate cross-correlation functions. In these functions, trends in the amplitudes of the correlations over time are observed. These trends have been interpreted by Nowé et al. (2021) as different sources of noise. One is seasonal, occurring each year in spring and ceasing just before winter. It is assumed to be related to glacier melting, supplying rivers and waterfalls. Its detection in the cross-correlation functions is restricted by the large amount of data, difficult to be processed by a human operator. Machine learning, a branch of artificial intelligence, is a technique increasingly used in geosciences that can overcome this difficulty.

This work proposes a workflow involving several machine learning algorithms to discriminate this seasonal seismic noise source from other noise sources appearing in the cross-correlation functions automatically and quickly. It consists of data exploration using a hierarchical clustering algorithm, features extraction via the algorithm of Hibert et al. (2017), and automatic classification with a Random Forest classification algorithm. A secondary objective of this work is to examine the features and information extracted during these steps to gain a better understanding and characterization of the seasonal ambient noise.

This work shows that machine learning algorithms can identify the difference between seismic noise sources in cross-correlation functions and proposes points of reflection for further exploration of this data.

This workflow can be used on other data sets to discriminate noise sources. The presence of a potential precursor sign preceding the arrival of the seasonal noise signature discovered in this work shows that it can be used as a basis for the implementation of a natural disaster monitoring tool.

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Correlation between lithostratigraphy and karstic speleothems at the cave of Han-sur-Lesse (Rochefort, Belgium)

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As part of a Master thesis, a study was made with the objective to investigate the correlation between speleothems (secondary carbonate deposits in caves) and rocks in which they were formed in the cave of Han-sur-Lesse in Belgium. To answer this problem, a lithostratigraphic study of the Givetian host rock in which the speleothems were set up was based mainly on the studies of Bultynck et al. (1991) and Coen & Coen-Aubert (1971). The study showed that the geological formations present in the cave (Touristic network and "Réseau Sud") are essentially those of Mont d'Haurs and Fromelennes. The Fromelennes Formation, itself is composed (down to up) of the Flohimont Member, Moulin Boreux Member and Fort Hulobiet Member. Particular attention has been given to Flohimont Member since it is entirely present in the Big Artificial tunnel (Touristic network) and in the Salle de la Pentecôte ("Réseau Sud").

Moreover, the "Réseau Sud" lithostratigraphic study and more particularly of the Salle de la Pentecôte reveals the presence of normal and reverse faults, unexpected at this place. These faults are the witnesses of tectonic Hercynian and post-Hercynian events.

In a second time, Laser Induced Breakdown spectroscopy (LIBS) and Raman spectroscopy, investigations were made to understand if speleothems of the Salle de la Pentecôte can be geochemically associated with the geological formation in which they formed. Raman spectroscopy showed that aragonite speleothems (puffy matt white) and calcite speleothems (translucent white) are both present in the Salle de la Pentecôte but at different places.

LIBS on speleothems and associated rocks showed that rocks are mainly composed of Ca, Mg, Al, Fe, Si, and C with the possible presence of Sr and Ti and this composition appears directly reflected in speleothems that are associated with these rocks. This phenomenon is especially visible for Ca, Mg, Al, and C. In addition, LIBS investigation showed that aragonite contains more Al than calcite and that the wavelength peak of 285, 3 nm characterizing Mg is more important for aragonite than calcite.

Finally, on the base of the lithostratigraphic study, a geological map has been drawn at the altitudinal level of the galleries of the Han-sur-Lesse cave, which shows slight differences with the surface geological map and better takes into account the observations at the cave level. This map proposes that the Salle de la Pentecôte and the Salle du Corail were formed following the Flohimont Member of which part was offset along a fault plane, most probably during Hercynian and/or post-Hercynian events.

Otherwise, the geochemical results of the Salle de la Pentecôte have been combined with the geological map made in this Master thesis and clearly show that aragonite speleothems were formed exclusively in the Flohimont Member of the Fromelennes Formation. In opposition, calcite speleothems are present in the Mont d'Haurs Formation and Moulin Boreux Member of the Fromelennes Formation.

We can therefore conclude that the investigation based on a lithostratigraphic approach combined with specific geochemical analyses of karstic rocks and speleothems show that a clear geochemical and mineralogical link is present between the host rock and the speleothem formed within. Nevertheless, this should be further confronted with a similar approach to other contexts to be definitively concluded.

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Quarry development simulation in Tournaisis: merging Antoing and Lemay quarries

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The Lemay and Antoing quarries are two contiguous open pits, located in the province of Hainaut (Belgium), in the village of Vaulx. They belong to the Sagrex company, a subsidiary of the HeidelbergCement group. The limestone resource to be extracted within the limits of the current permit tends to be exhausted as the boundaries assigned to the exploitation are almost reached. The company therefore needs to extend the life of the operations to maintain the workforce and meet the growing demand of the building materials market. Between the two quarries is a residual rock mass erected as a "wall" and constituting a significant part of the reserves still mineable by the company.

The problem that arises is the following: how to exploit the "wall" between two quarries which have different production objectives? What are the different scenarios and possible steps that could lead to mine out the wall optimally and safely, taking into account the geology, the chemical and mechanical quality (presence of discontinuities) of the deposit? The objective of this Master thesis was to answer these questions by 3D numerical simulation using a mine planning software (SURPAC).

Three steps were necessary to answer these questions: the construction of a realistic 3D geological model including geological layers and faults; the setup of a block model of the geochemical properties necessary for the selection of rocks to be used for cement or crushed materials; and a planning of the exploitation in both quarries to determine the future evolution in terms of benches and ramps.

The geological drillings carried out on the site were used to build the geological model (CTP, 2020). The lack of data in some areas required the creation of new "virtual" drill holes based on the knowledge of geology. Considering the "Gras Délit" as a geological marker (Camerman, 1944), it was used as a reference to position the different geological units within these "virtual" drill holes located on several key points of the study site. The sub-vertical Coucou Fault crossing the two quarries was also implemented in the 3D geological model (Hennebert & Doremus, 1997). This allowed to understand the thickness evolution of geological layers, which was essential to understand the evolution of geochemical parameters in the ore body.

The second step was to create a block model of the geochemical parameters. The content of different minerals (CaO, SiO_2, K_2O) is essential for classifying rocks to be used either for cement ("rich stones") or aggregate production.

Therefore, understanding the distribution of these contents is crucial for planning extraction operations. Based on geochemical data from drill holes, a discretization of the ore body in blocks and the application of inverse distance weighing, a 3D geochemical model was created to understand the variation of the content of useful minerals in the ore body.

The last step of this study was dedicated to planning the open-pit exploitation of the wall based on geological and geochemical models (Tshibangu, 2019). A scenario was proposed to achieve the operating company's objectives, which require keeping a permanent passage between the two quarries during the exploitation, sending the "rich stones" from Lemay to Antoing quarry, and compensating these with aggregates from Antoing quarry. The exploitation follows the pace of the current steps and is carried out in seven successive horizontal sections. According to the planned pit, the total quantity of material to reach the lowest point of the current pit is 30 Mt, i.e., 17.8 Mt on the Lemay side and 12.2 Mt on the Antoing side. This final study provided both quarries with a plan to carry out the rest of their operations in the wall area. This work allows the operator to better understand the destination of the stones (Antoing or Lemay, cement or construction materials) and the future implantation of benches and ramps.

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The **Geologica Belgica Master Day** is a yearly event of the scientific association Geologica Belgica to give the opportunity to recently graduated students in Geosciences to present their Master thesis research in a competitive inter-university context. The 2022 edition of the Master Day was held on October 21 in KU Leuven.

The six graduates who presented the results of their Master thesis during Master Day 2022. They come from KU Leuven, ULB and UMons.

The award winner of the Master Day, Tobias Hendrickx, receiving his diploma from the president of Geologica Belgica.