Digital transformation and geoscience education: New tools to learn, new skills to grow

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Digital transformation is a technological and societal trend currently reshaping many scientific and industrial fields. In this paper, we address the challenges and opportunities raised by this digital transformation for the specific topic of geoscience education. We discuss the value of new digital tools and methods for teaching geology, and highlight the digital skills the future generation of geologists will grow. We also underline that geoscience training can open exciting career paths for students and professionals from a computer science background. We illustrate these ideas with on-going practical projects at IFP Energies nouvelles, a French public institute for research and innovation in the energy industries, and IFP School, a specialised engineering school delivering several graduate degree programmes in applied geosciences.

La transition numérique est un phénomène technologique et sociétal qui bouleverse actuellement de nombreux secteurs scientifiques et industriels. Dans cet article, nous abordons les défis et les opportunités engendrés par cette transition numérique dans le domaine particulier des formations en sciences de la Terre. Nous analysons la valeur ajoutée de nouveaux outils et méthodes numériques pour l'enseignement de la géologie, et nous présentons les compétences numériques que la future génération de géologues devra développer. Nous soulignons également qu'une initiation aux géosciences peut ouvrir des opportunités de carrière stimulantes aux étudiants et professionnels issus du monde de l'informatique. Nous illustrons ces idées par des projets concrets en cours à IFP Energies nouvelles, un institut public français dédié à la recherche et l'innovation dans le domaine de l'énergie, et IFP School, une école d'ingénieurs spécialisée délivrant plusieurs diplômes supérieurs en géosciences appliquées.

La transición digital es un fenómeno tecnológico y social que actualmente está transformando muchos sectores científicos e industriales. En este artículo, discutimos los desafíos y oportunidades que genera esta transición digital en el campo particular de la formación en ciencias de la tierra. Analizamos el valor de las nuevas herramientas y métodos digitales para la enseñanza de la geología, y presentamos las competencias numéricas que la próxima generación de geólogos necesitará desarrollar. Por otra parte enfatizamos que una introducción a las geociencias puede abrir oportunidades de carrera estimulantes para estudiantes y profesionales del mundo de las tecnologías de la información. Estas ideas son ilustradas con proyectos concretos en curso tanto en el IFP Energies nouvelles, un instituto público francés dedicado a la investigación y la innovación en el campo de la energía, como en el IFP School, una escuela de ingeniería especializada que ofrece varios títulos superiores en geociencias aplicadas.

Everyone goes digital

The news has recently raised some attention on social networks: to replace a cancelled field trip in Oman, the students of the Petroleum Geoscience MSc programme at Imperial College in London will be offered an outcrop analysis course based on virtual reality and an introduction to machine learning techniques[1]. Beyond the field trip cancellation, the choice of the substitute material appears strikingly representative of a more global phenomenon, commonly referred as "digital transformation".

Digital transformation is a somehow fuzzy concept, for which various definitions have been proposed. However, most authors agree that digital transformation goes well beyond the use of the latest technologies and should rather be seen as a societal trend, which changes our habits and expectations as employees, customers and individuals (Reis *et al.* 2018). Consequently, all scientific and industrial fields are impacted and need to adjust, both to seize new opportunities and overcome potential threats.

Earth sciences and subsurface industries are not being left behind by the digital transformation swing; among all related activities, geoscience education is one that is especially affected. As geoscientists at IFP Energies nouvelles (IFPEN) or teachers at IFP School, we are privileged observers of and actors in the current technological and educational evolution. In this paper, we aim at sharing some insights and initiatives to further discuss how the geoscience education community can make the most of the digital transformation phenomenon. Could it be one of the keys to solve the paradox of growing public engagement in environmental and energy issues but declining enrolment in geoscience degree programmes?

Old rocks, but younger generations

The most classical approach to digital transformation in education is probably introducing devices such as smartphones and tablets in the classroom to increase student engagement. Indeed, much has been written on the learning styles of the younger generations. Students from the so-called Generations Y and Z notably favour autonomy in the learning process and quick direct access to information (*e.g.* Schofield and Honoré 2009). Meeting these demands can be challenging, and as another characteristic of these students is their comfort with technology, it is a logical temptation for professors to rely on it to renew their teaching methods. However, despite promising initiatives (*e.g.* Marçal

1 ***https://www.imperial.ac.uk/news/198915/geoscience-course-stops-running-oman-fieldtrip/*** (last accessed in August 2020)

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et al. 2014), the value of this approach still needed to be demonstrated for teaching geology, peculiarly in the field.

To appraise the assets of numerical devices in field-based teaching, IFP School launched a “mobile learning” experience in 2015. Geology students were provided with touchpads and a dedicated application was developed (***Figure 1***). While in the field, the students could use it to access various georeferenced data (such as thin section pictures, geological maps and surveys, aerial photographs, and even 3D numerical models), utility tools (such as GPS, a compass or cross-section design) and interactive multimedia material (such as videos or quizzes). Several positive effects were then noticed by the professors supervising the experience. The students more easily integrated different observation scales in their reasoning. They also better understood the links between outcrop analogues and subsurface exploration data. Besides, the application encouraged more teamwork and collaboration. Eventually, its use was extended to before and after the field trips, for instance in preparation and debriefing sessions. Similar conclusions were recently drawn from a comparable experience in Norway (Senger and Nordmo 2020).

Figure 1: IFP School students using a mobile learning application during a geological field trip in the Spanish Pyrenees in April 2017. Top left: access to reminders on the geological context. Top right: interactive quiz based on the geological map. Bottom left: landscape sketching. Bottom right: discussion with professors.

Virtual reality, but tangible benefits

If digital technologies can bring data from labs or desks to the field, they can also bring field data to the classrooms. When thinking about this objective, immersive virtual reality will quickly come in the reader’s mind. However it is worth noting virtual geological field trips are not something new, and that the recent technological breakthroughs follow decades of improvement for Digital Outcrop Models (DOM).

DOMs are 3D virtual representations of outcrops with their actual textures and colours. They are usually created from a set of pictures taken from various angles using the convergent photogrammetry principle or a LIDAR (Light Detection and Ranging) acquisition device (***Figure 2***), leading to textured point clouds or triangular meshes. Several dedicated software packages have been developed to help with their geological interpretation, such as LIME (Buckley *et al.* 2019) or Virtual Reality Geological Studio (***https://www.vrgeoscience.com/***).

Figure 2: Common Digital Outcrop Modeling (DOM) techniques. Top left: convergent photogrammetry acquisition process. Top right: LIDAR acquisition device. Bottom: DOM of an eolian sandstone outcrop in Utah.

At IFPEN, DOM technologies were notably developed within the SmartAnalog™ project (***https://www.smartanalog.eu/***). Relying on a proprietary interpretation platform, this project aimed at running similar workflows on outcrop analogs as the ones run on actual petroleum reservoirs: horizon picking, facies interpretation and geostatistical modelling of petrophysical properties (Deschamps *et al.* 2015). Initially developed for better constraining subsurface models in an industrial context, this project also produced interesting educational support for teaching geology and was quickly integrated into IFP School classrooms.

On top of the DOM legacy, virtual geology has recently raised renewed interests globally, driven by the democratisation of immersive environments and growing concerns about physical field trips. Indeed, beyond the current pandemic crisis, opportunities for geological field trips are increasingly limited by their financial cost, carbon footprint, health-and-safety issues, and potentially exclusive nature. Meanwhile, though immersive virtual reality once necessitated a dedicated room or costly equipment, it has become more affordable, with fully independent mobile devices now commercialised below 500 euros.

The objective to integrate digital outcrop models within immersive virtual environments led to the development of several platforms, such as MOSIS (Multi Outcrop Sharing and Interpretation System, Rossa *et al.* 2019) and 3D Gaia (***https://www.imagedreality.com/***). Key features commonly highlighted are flexible displacements around the outcrop, multiple tools for interactive geological interpretation and integration of additional geoscience data in the environment, from field sample pictures up to reservoir models and synthetic seismic profiles.

A similar initiative was recently carried out at IFPEN, using a DOM model of turbiditic sandstones in the French Alps and the immersive JungleVR system (***https://junglevr.io/***). A specific effort was made to add geological data of various kinds in the environment, to be interactively visualised along with the outcrop. This included interpreted horizons, sedimentary logs, sample pictures, informative texts and educational videos (***Figure 3***). Early feedback underlined the value of the multi-data approach for educational purposes.

Eventually, will virtual reality signal the end of physical field trips? Not in our opinion. Analysing actual rocks, outcrops and landscapes should likely remain a key component of geological science. However, we see their virtualisation as a valuable complement, which fosters knowledge sharing, cross-disciplinary discussion and ful capitalisation on results. On this topic, digital technologies are far from threatening the existence of field activities. On the contrary, they considerably broaden the range of students and staff that can practice and understand them.

Artificial intelligence, but natural objects

Virtual reality is not the only emergent technology penetrating geoscience classrooms. Artificial intelligence also presents promising educational potential. Notably, computer vision, a subfield dedicated to automated image analysis, has boomed in the last decade, with applications ranging from facial recognition software to self-driving cars. As geology is intrinsically a science of image interpretation, it provides numerous cases where computer vision algorithms could assist students in their learning. For instance, approaches based on convolutional neural networks were successfully applied to classify field samples between lithology classes (Ran *et al.* 2019) and detect microfossils on core sections (Carvalho *et al.* 2020).

Concretely, how can geoscience education benefit from the current artificial intelligence momentum? Experience from another natural science gives some insights. Launched in 2009 by several French public institutions, the Pl@ntNet project produced a mobile application dedicated to the automated identification of vegetal species from field pictures (***https://plantnet.org/***). Available on the best known app stores, Pl@ntNet has gathered a community of 12 million users (150,000 daily), who increase their knowledge of botanic science through this medium.

At IFPEN, the success story of Pl@ntNet inspired us to start in 2019 a similar initiative for the identification of rock samples, the RockNet™ project. The idea is to provide students and geology enthusiasts with an application where they can take pictures of rock samples and obtain a proposal of lithofacies classification from computer vision algorithms. A first prototype application based on 12 lithology families is currently under testing. We imagine future versions could be used in geology classes, in the same vein as the RockCheck application (Valand *et al.* 2020).

Like any technology, the integration of artificial intelligence in geoscience education is not without risks. In our mind, the main pitfall to avoid is hiding the inherent complexity of geological objects and the irreducible part of subjectivity in interpretation. As the products of millions of years of multi-scale physical and chemical processes, similar geological objects can look extremely diverse and delineating classes cannot be done as easily as for plants.

It is worth noting the technology itself provides some safeguards. Most classification algorithms do not produce a unique answer, but attribute a probability to each possible one. This can be an interesting point to highlight the intrinsic uncertainty of interpretation processes (***Figure 4***, *top*). Moreover, a stimulating research path lies in the association of convolutional neural networks with decision trees. For instance, with this approach the networks are not trained to directly recognise the lithology on sample pictures, but only petrological features such as textures, structures or mineral species. Then these features are combined within a decision tree which mimics the naturalist methodology for rock identification (***Figure 4***, *bottom*). This technique was applied with promising early results (Bouziat *et al.* 2020) and offers some assets in an educational perspective.

More generally, teachers should put a particular emphasis on the critical assessment of the results from artificial intelligence. What they provide is a first-guess analysis, aiming at assisting the students but not at thinking on their behalf. With this mind set, artificial intelligence becomes a helpful ice-breaker which automates a first-level interpretation, which the student is then encouraged to discuss, amend and complete.

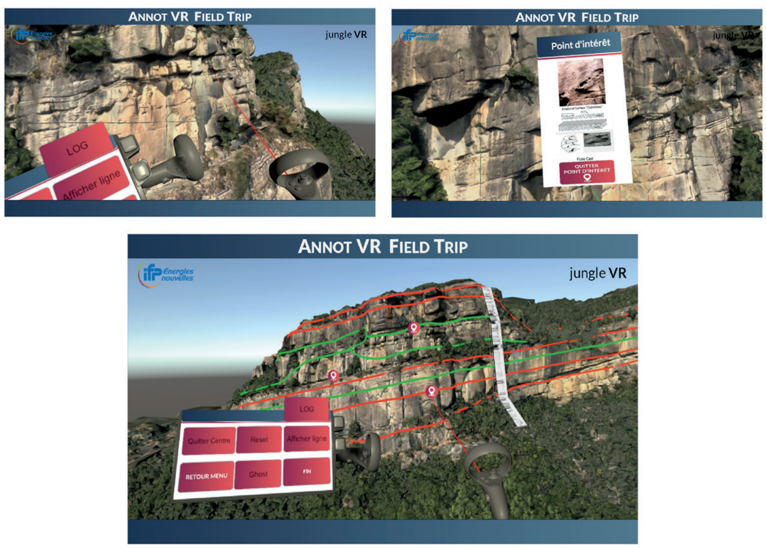

Figure 3: Exploration of the Annot sandstones (French Alps) in an immersive virtual reality platform. Top left: close-up view of the outcrop. Top right: display of geological information on a point of interest. Bottom: landscape view with display of interpreted horizons and a sedimentary log.

In addition, the ice-breaking aspect of automated interpretations is a powerful tool for science communication intended for the general public. For instance, outdoor enthusiasts could use a rock identification app to learn about the rocks and stones surrounding them, and get more insights on natural heritage and subsurface resources. Even the most urban folks can be interested in such democratisation of geological knowledge, as shown by the "London Pavement Geology" project (***http://londonpavementgeology.co.uk/***) or by the geological walk booklets available for several French city centres (***https://www.mnhn.fr/en/node/1375***).

Bridging the gap between geologists and data scientists

The impact of digital transformation on geoscience education does not only concern how we teach, but also what we teach. Earth sciences curricula have for long included subjects like geostatistics or signal processing. And, to a certain extent, geologists have always been some kind of data scientists, collecting data in the field and interpreting it with a combination of methods. However, we consider the need for geologists with a basic proficiency in computer sciences and mathematics to be likely to grow further in the near future. First, these disciplines closely interact with emerging technologies in geosciences, such as remote sensing or Geographic Information Systems. Besides, discussions in communities such as Software Underground (***https://softwareunderground.org/***) and publication logs in journals such as *Computers & Geosciences, Earth Science Informatics* or *Geoscientific Model Development* illustrate that the geoscience community increasingly uses Python for data processing, R for statistical analysis, or custom web services for sharing their results.

Fortunately for the students, there is no need to be an information technology expert to apply the most common techniques in computer and mathematical sciences. Indeed, these techniques have recently seen a tremendous increase in accessibility, notably through the rapid growth in community and open-source programming libraries. For instance, a decade ago, geologists wanting to train a neural network on a data set had to code one more or less from scratch in native Python language. Nowadays, they can rely on at least two stages of higher-level libraries, such as PyTorch (***https://pytorch.org/***) and Ignite (***https://pytorch.org/ignite/***). This considerably reduces the barrier for non-specialists and these geologists may be able to produce their first results with a few dozen lines, simply assembling code bricks already written and optimised by top-class experts.

Figure 4: Automated identification of lithofacies on field samples with artificial intelligence algorithms. Top: direct lithology classification. Each input picture displays the three most probable classes according to the neural network. The first two pictures are archetypal and the probabilities neatly favour a single class. However, the third picture is more ambiguous and the probabilities reflect the uncertainty that a human geologist would face. Bottom: lithology classification combining petrological feature recognition and a decision tree. Adapted from Bouziat et al. 2020.

Nevertheless, there is no point in running numerical methods if you cannot review and trust the results. That is why the increasing accessibility of digital technologies opens new opportunities for geology graduates. With the finest algorithms broadly available, much value lies in the ability to cast a critical glance at the results and analyse them with enough knowledge and subject matter expertise. Industrial companies and research organisations need young professionals who can run numerical models but can also spot potential biases in the input data, estimate uncertainty ranges in the parameters, and discuss the relevance of the model hypothesis for use in a specific case.

Logically, universities are adjusting their geoscience programmes to meet the changing needs. First, new courses are being added in existing programmes, like the machine learning course at Imperial College. At IFP School, Python programming has recently become part of the petroleum geoscience syllabus. Some institutions are even creating new programmes at the crossroads of computer and earth sciences. For instance, the Lassalle engineering school in Beauvais (France) just opened a major in "numerical geology". At the Lorraine University in Nancy (France) a similar major has existed at the school of geology since the 1990s, but students are now offered the chance to spend a semester in the school of information technologies beforehand.

While there are many advantages for aspiring geoscientists to learn some computer and mathematical science, the opposite seems also true. Geosciences involve 4D thinking, numerous data of diverse nature, scale and format and various models with multiple parameters of uncertain values. Thus they are an unexpectedly stimulating playground for students or professionals with a numerical background. Consequently, learning some basics of geology, even at a late stage of their training, can open some interesting paths for scientists with these profiles, notably in the subsurface resources industries. Some

Figure 5: Students from the Petroleum Data Management programme at IFP School acquiring GNSS measurements. They learned how to georeference geoscience data during a geological field trip in Forcalquier (France) in September 2020.

of these students enrol in the Petroleum Data Management programme at IFP School, dedicated to educating specialists in the geoscience data lifecycle. During this one-year programme, students and professionals initially trained in computer science join peers with more geoscience-related backgrounds and learn the essentials of geological science, notably through a week-long field trip (***Figure 5***). Most of them later take advantage of this rare blend of skills in industrial companies.

No reason to fear the wave, let's surf it!

Altogether, digital transformation appears to be a fabulous opportunity to teach, explain and promote earth sciences for students, professionals, recruiters and the society as a whole. It provides new innovative mediums to share geological knowledge and concepts with a broad range of profiles, including the general public. It also offers exciting career opportunities for those geologists ready to add a few numerical methods to their skills set, and to computer scientists ready to learn some geological rudiments.

The stakes at play are enormous. In a context of increased public interest in environmental and energy issues, it seems critical that young people see geology as an attractive, stimulating and rewarding scientific area, so they can develop at least a basic knowledge of our planet and its resources, which will fuel their development as mature citizens. As perfectly phrased in Wadsworth *et al.* (2020), *"our future depends on young people continuing to learn how the planet works"*. If the digital transformation wave can help in this objective, geoscience educators should not hesitate to surf it!

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