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**UPSCALING OF 2D MINERALOGICAL INFORMATION TO 3D VOLUMES FOR
GEOSCIENCE APPLICATIONS USING A MULTI-SCALE, MULTI-MODAL AND
MULTI-DIMENSIONAL APPROACH**

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Alan Butcher's current research interests focus mainly on the study of natural earth materials and man-made products (geomaterials), which have significant commercial importance. His specialism is in the field of applied mineralogy, where 2D electron beam-based technologies (SEM and EPMA) are integrated with 3D and 4D imaging and analysis (X-CT), allowing for the ability to observe features over various length scales. This approach is required in order to upscale (or downscale) features of interest from the microscopic level (nm- μ m-mm) to larger industrially-relevant scales (mm-cm-m-km).

Specifically, Alan has been involved in the development of automated electron beam technologies (QEMSCAN, MLA, for example) since 1998, and is best known for his novel and innovative application development of these technologies, including: the use of mineral and petrographic data to provide commercially useful information for successful mineral processing; new insights into reservoir quality; fingerprinting soil particulates from crime scenes to establish a connection to a person, place or exhibit; archaeological forensics to establish provenance; fugitive dust analysis for medical geology purposes; and extra-terrestrial material characterisation for future human habitation, in association with NASA. Alan is currently Professor of Geomaterials and Applied Mineralogy at the Geological Survey of Finland.

1. INTRODUCTION

There have been significant recent advances in the way geologists examine rocks both mineralogically and petrographically. Traditional 2D methods, such as light microscopy and electron beam-based techniques, were for many years largely analogue, and have now thankfully been fully digitised, allowing for huge improvements in the efficiency of imaging, analysis, interpretation, and reporting of polished surfaces and/or thin slices of rock samples (Fig. 1).

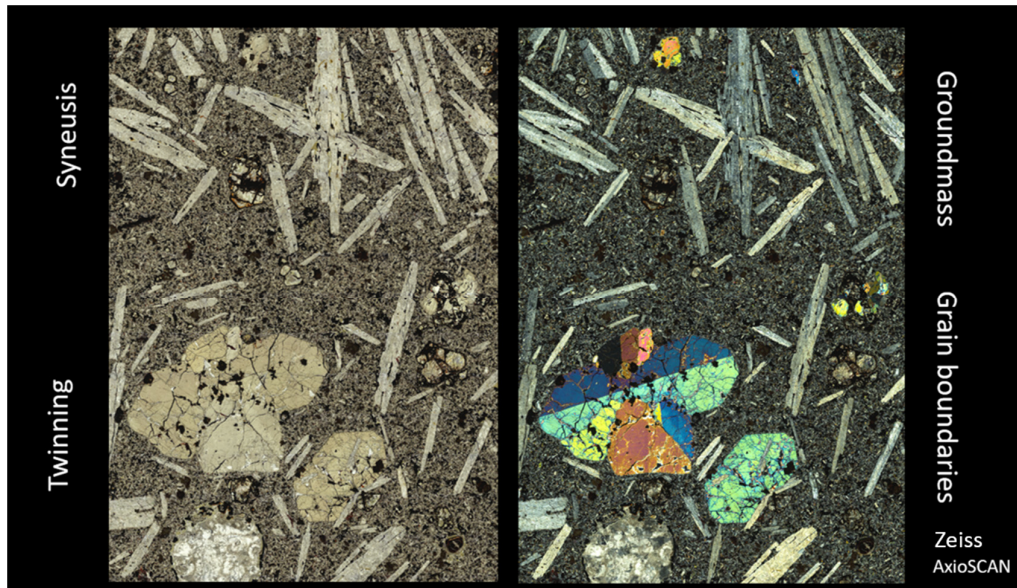


Figure 1. Recently developed technology allows for the automated collection of high quality, full colour, digital images of rock thin sections, both in plane and polarised light, allowing textural features such as zoning, twinning, and crystal and groundmass behaviour to be observed and recorded.

With the emergence of new cutting edge scanning XRF and hyperspectral imaging techniques, geoscientists are now able to scan geomaterials (such as drill cores) at increasingly larger scales than that covered by a single petrographic thin section. This has allowed us to start to bridge the different scales of geological observation, from the mega- to the nanoscale, that previously were not easily accessible to most earth scientists (Fig. 2).

2. THE EMERGENCE OF CROSS-DISCIPLINARY ACTIVITY

We are living in an age of digital communication, whereby scientists and engineers can freely communicate and share their ideas. Cross-disciplinary collaboration often leads to extraordinary developments and breakthroughs.

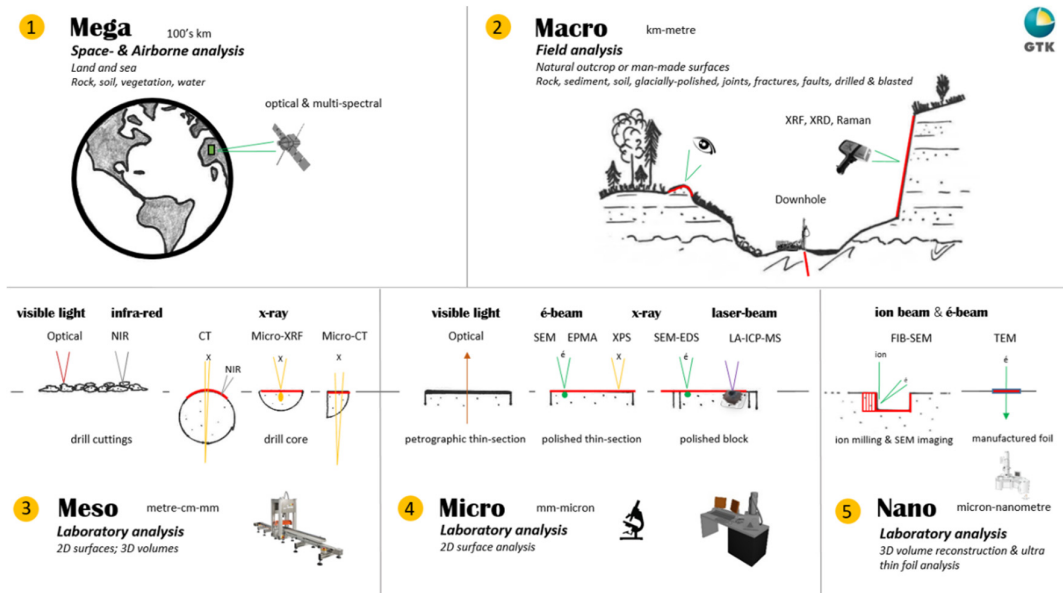


Figure 2. Generalised view of the study of geology in terms of scales of observations and technologies used to examine different features

As geologists, we are taught to think in 3D, and it has always been a limitation that we have been mostly restricted to examining rocks in the laboratory using 2D surface-based technologies (SEM, EPMA, LA-ICP-MS, etc.). But this has all changed in the last decade. By using so-called workflows, borrowed and adapted from allied disciplines (including materials and biological sciences, and petroleum science and engineering), geologists can also now image rocks using powerful X-ray computed tomography-based techniques (X-CT) and focussed ion beam SEM technologies (FIB-SEM).

3. LESSONS FROM THE OIL INDUSTRY

By way of example, cuttings and cores from a hydrocarbon reservoir drilling programme are the only way to know what is actually beneath the ground. There is no chance of digging a trench, or opening up a trial pit, as in mineral exploration and mining. Making the most of every centimetre of core, or gram of ditch cutting sample, is a key driver for innovation and development in the oil industry, especially when it comes to rock and mineral analysis. Nothing is left to chance, the risks are too big, and aspects such as correct stratigraphic correlation and rock sequence prediction must be as accurate as possible in order to reduce the chances of placing a gas or oil well in the wrong place.

As a result, just about every possible geo-analytical technique is used to characterise the physical properties of the overburden, cap rock, reservoir, source and even the basement. It all starts with geophysics, moves to petrophysics, then reservoir quality, and finally petroleum engineering.

Every physical attribute of a rock or mineral is exploited to further understand what is present and how it will behave at reservoir conditions – these include: mineralogy, texture, 3D grain network, pore structure, rock density, magnetic susceptibility, radioactivity, conductivity, density, brittleness, and response to NIR, X-ray and electron beams – to name just a few parameters that are typically measured.

From experience, the key to success in the petroleum industry seems to be a multi-scale, multi-dimensional, and multi-modal approach to rock imaging, analysis and interpretation. There is no one technique that can be considered all encompassing (Fig. 3). Only by the integration of technologies can a complex problem of, say, multi-phase flow in porous geomaterials, be fully understood. Even then, this apparently rigorous approach is sometimes not enough. Mistakes are made. Unforeseen problems occur because of the essentially 1D nature of drilling into what are actually complex 3D sedimentary basins, often undertaken precariously on offshore rigs, typically to great depths, and where sedimentary facies can change rapidly over short lateral distances, without notice, and unconformities or faults can unexpectedly change even the most robust and cherished depositional models of the reservoir geologist.

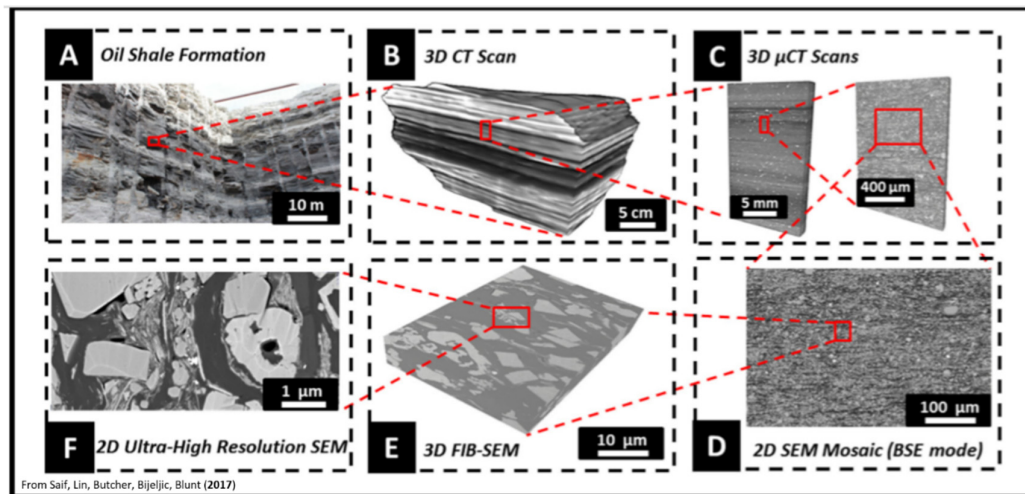


Figure 3. Multi-scale, multi-modal, imaging and analysis study carried on oil shale to allow for upscaling of features of commercial interest such as pores, cements, fractures, and bedding structures (from [1]).

4. APPLICATIONS TO MINERAL EXPLORATION

In the mining world, we clearly face similar but also different challenges. Having undertaken airborne or ground geophysical surveys, observations and interpretations to select a target, everything in mineral exploration still has to be ultimately ground-truthed. Potential targets need to be drilled to prove the presence (or not) of an ore-rich interval, as perhaps indicated by the

physics. But once we have hit the zone of interest, do we make the most of our core? Is every length of core that is pulled from the ground fully digitally scanned before it is cut, split or sawn in half and quartered? Definitely not. Why not? Well, one reason is that the budgets and risk factors in mining are not on the same scale as in the oil industry. But accepting this, we can still learn much from each other.

The concept of digital rock analysis, whereby a digital rendition of a real sample is used to visualise and model rock properties, is an excellent potential cross-over concept for mining, now widely used in the petroleum world. By creating a 3D version of a core, based on reality and not a model, it is now possible to perform virtual experiments and observations without damaging the original.

With this mind, consider the case of a high-grade ore-rich exploration drill core sequence (Fig. 4). Imagine being able to visualise the 3D structure of the core, along with the minerals of commercial interest within it, and calculate their grain size, see their associations, and provide a degree of prediction of processing performance, initially without cutting open the rock. Once regions-of-interest have been found, they can then be further investigated by destructive techniques such as slabbing, crushing, or thin section preparation. Automated 2D imaging and analysis technologies can then be used to calibrate the original 3D volumes, as well as digitally capture what the grains of gold, platinum or sulphides (or whatever) actually look like in extreme detail, down to and beyond the micrometre-scale, and provide quantitative micro-compositional information on them as well.



Figure 4. Example of a mineralised drill core taken from an exploration core tray and imaged rapidly using X-ray computed tomography technology (X-CT), to reveal 3D textural and mineralogical information without any damage to the sample.

Even the most highly mineralised ore, containing massive sulphides and precious metals, can now be imaged and rendered into a useful 3D digital volume, which can be later interrogated, quantified, archived and retrieved, using advanced image processing and data storage know-how (Fig. 5).

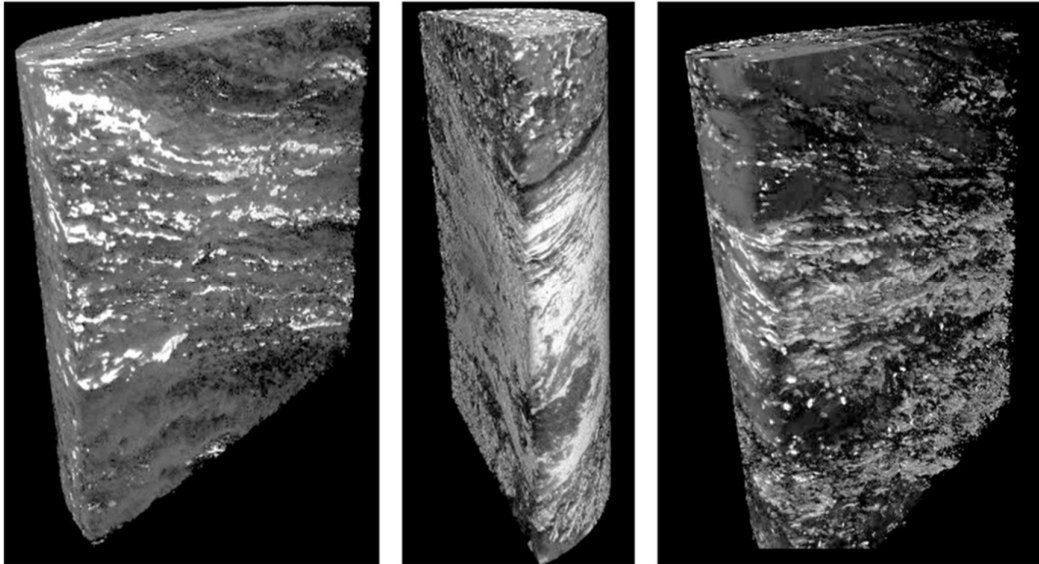


Figure 5. Three exploration drill cores – all containing multi-deformed pyrrhotite layers (bright phases) – within a silicate matrix (greys). Such images allow areas of special interest to be highlighted and can guide thin section area selection. Samples courtesy of Mawson Resources.

5. SUMMARY

Multi-scale, multi-modal and multi-dimensional workflows have opened up a whole new world of analytical possibilities to us as a community. For the exploration geologist, it means that their valuable drill core intersections can now be examined and archived before it goes off for destruction (slicing with a diamond saw and crushing of half core for routine chemical assaying), thus preserving all the contained characteristics (bedding, layering, folding, mineralisation) (Fig. 6).

For the mineral processing engineers, 3D liberation analysis is now a real possibility, something that has been requested by them for many years. And to the ore deposit geologist, it allows for a superior textural and structural understanding of mineralised rocks, all the way from the field (mega- and macroscale) to the laboratory (micro- and nanoscale).

New Characterization Workflow

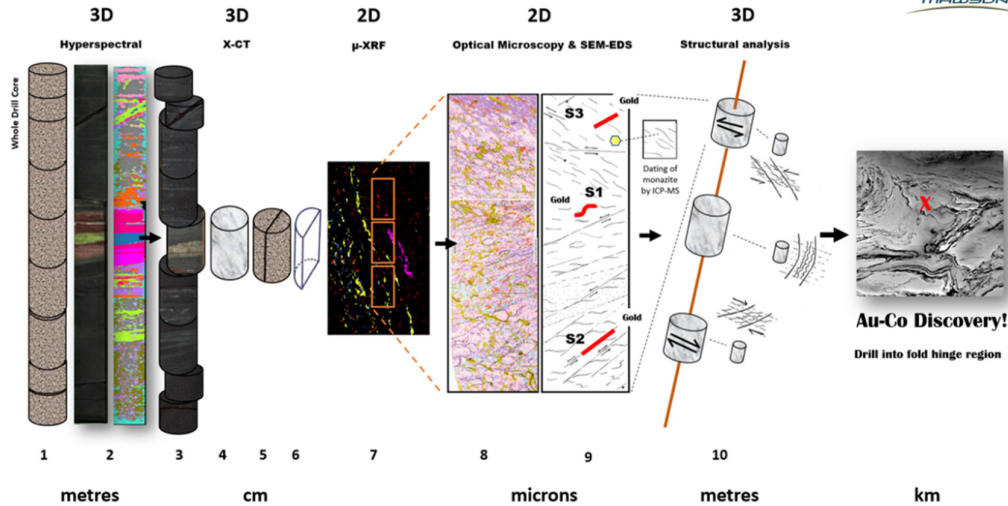


Figure 6. Multi-scale, multi-modal, multi-dimensional workflow used to characterise exploration drill core in order to optimise the discovery of gold and cobalt mineralisation. Example courtesy of Mawson Resources, and developed in collaboration with Camborne School of Mines (University of Exeter), and Hippo Resources.

This workflow approach is currently being implemented at the Geological Survey of Finland in order to reduce the risks in mineral exploration; gain insights into the commercial mineralogy of ores; contribute to smarter and greener mineral processing behaviours; and to overall improve mineral deposit knowledge and understanding via an integrated 2D - 4D approach.

Once these workflows have been properly and securely set up, it is then possible to generate databases that can be used to create realistic ore body models that are based not only on grade, or mineralogy alone, but also on, for example, more enlightened aspects such as ore paragenesis. This in turn can lead to better predictive metallurgical models, because the geologist and metallurgist will together now have a full understanding of the nature of minerals of commercial importance, from grind size estimate, to liberation behaviour, and finally elemental deportment. This is key information that exploration companies ideally need upfront, at the time they are investing heavily in costly drilling campaigns, as it reduces their risk and uncertainty, and improves understanding of the yet-to-be-fully-discovered ore body (Fig. 6). Menace minerals, either from an environmental viewpoint, or purely a practical processing aspect (poor separation potential), can be flagged up early on in the exploration life cycle, and therefore save much pain later on down the track. This information is also invaluable if it can be made available prior to blasting activities in operational mines.

6. *THE FUTURE*

Finally, the world of material science is another much under-utilised area of expertise and knowledge used by geologists. It typically involves bringing together the doers (technologists) with the knowers (scientists), which is not commonly practiced for some reason. There is much literature and experience that can be readily borrowed from technologists and brought to bear on the study of earth materials – such as fracture analysis, crystallisation and annealing processes, and micro-chemical reactions – all of which can lead to a better understanding of minerals and rocks, their discovery, extraction, and recovery potential.

7. *ACKNOWLEDGEMENTS*

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8. *REFERENCES*

- [1] Saif T, Lin O, Butcher A R, Bijeljic B and Blunt M J 2017 Multi-scale multi-dimensional microstructure imaging of oil shale pyrolysis using X-ray micro-tomography, automated ultra-high resolution SEM, MAPS Mineralogy and FIB-SEM. *Appl. Energy* **202** 628-647