An introduction to geological mapping of our world and others

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Abstract: Map-making is a fundamental tool for developing geological knowledge. It involves data collection and interpretation and has its roots in the earliest discoveries in Earth Sciences. It is the starting point for stratigraphic and structural interpretations, metamorphic facies, geochronology and modelling studies – and underpins civil engineering. From the beginning, geological mapping rapidly evolved into far more than being a simple spatial catalogue of observable rock types and landforms on the Earth's land-surface; deductive reasoning allowing this knowledge to infer subsurface Earth structure. The same approaches are down-scaled to deduce processes on the grain-scale; or up-scaled to look out to extra-terrestrial objects. This is an introduction to fourteen papers in this Special Publication that celebrates geological mapping, its historical importance and future directions, and its use in applied geology together with developing knowledge of Earth and planetary evolution and processes. Geological mapping has a long tradition of adopting evolving technologies. This introduction considers the challenges faced in synthesizing interpretations, sharing competing interpretations on maps and the role of open-access digital resources in facing these challenges.

Geological maps are not just simple catalogues of rock outcrops organized in a spatial framework – reading them also provides narratives of geological evolution. They are interpretations that inform understanding of geological processes. And they include far more than geology expressed in terrestrial landscapes. This paper introduces a collection of papers that celebrate geological mapping. Some address mapping as applied to portions of Earth's surface, including tracing of how geological knowledge is acquired through endeavours in the field, and how it is synthesized to gain understanding of geological evolution. Others look at the surfaces of other planets, arguably deducing processes that are poorly preserved, or indeed lost, to the early history of our planet. Other contributions look down-scale, mapping textures on the granular and intragranular scale in rocks. Some papers take historical perspectives, exploring how and why geologists make maps, and how that learning may be applied.

This introduction aims to provide a broader context for the papers in this Special Publication, in part through historical perspectives. Geological maps are created at different scales by different people, from direct observations or by collating the observations of others. There is a laudable drift in geological mapping to open access and associated resources driven notably by various national geological surveys. However, these products are themselves interpretations and not simply inviolate observations. Challenges remain in capturing and sharing alternative interpretations – necessary endeavours for assessment of uncertainty in any one interpretation. There are also challenges, when compiling interpretations from multiple geologists, in maintaining coherent, internally consistent interpretations. For the first time in the history of geological sciences, digital platforms can provide pathways to meet these challenges. In this regard, organizations such as space agencies are leading the way, openly publishing imagery of planetary surfaces, both extra-terrestrial and our own, along with other types of survey.

Geologists have always adopted technologies to assist not only mapping but also for addressing broader research questions. However, this up-take is not always immediate, and can be limited by availability (especially cost) that in turn impacts on the diversity of the geological community able to apply technologies. Examples, which are developed below, include the surveying equipment and computation requirements for creating and sharing so-called 'virtual outcrops'. Another is the dramatic increase in the availability of appropriately

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configured scanning electron microscopes for geological mapping on the millimetre to nanometre scale. And so, maps are made using images from different instruments and for different purposes.

This introductory paper, and the papers in this volume join a body of publications that promote geological mapping: despite recent technological advances, interpretations to produce maps continue to be needed if we are to assess the range of plausible explanations of geology, the better to assess uncertainties in geological knowledge and to provide models for societally relevant applications.

What is a geological map?

We can start by considering geological maps of Earth's bedrock geology on land. For many people, this type of geological mapping began in 1815 with William Smith. Although geological maps had been produced before, especially for showing the distribution of earth resources (see Kozák *et al.* 2016), Smith's (1815) map – *A delineation of the strata of England and Wales with part of Scotland…* is the first to show systematically the geology of a substantial area. More critically, it made three-dimensional geometric, and therefore stratigraphic, sense. Part of one of Smith's finished map sheets (sheet 11), which includes the area around the city of Bath, provides the cover to this Special Publication. It is noteworthy for being the first part of Smith's final map ever displayed in public, in the year before publication (Winchester 2001). Figure 1 here displays the map sheet for SE England. By classifying rocks and grouping them into distinct stratigraphic formations, Smith was able to delineate layers, strata, that in turn displayed the geological structure. He presented this on a base-map created by the cartographer John Cary (Winchester 2001) which shows principal settlements, major roads and rivers. It is only from the rivers that topographic relief can be judged.

As with other parts of Smith's (1815) work, on the map-sheet for SE England, geological boundaries are denoted by the intensity of shading. While lacking the precision of subsequent maps published

Fig. 1. Part of Smith's (1815) map for SE England. It shows the geological units in colour, hand-painted on a monochrome printed base map created by the cartographer John Cary. This shows principal settlements, major roads and rivers.

by others, the approach emphasizes the continuity of geological boundaries and therefore displays elegantly the geological structure. There are no measurements of bedding orientations. However, the dip directions can be deduced, as geology students from their earliest map interpretation classes are shown, from the deflection of the map-trace of boundaries in and out of valleys. And so, the map shows the Wealden antiform (in light pink and blue), with its rim of Cretaceous chalk (in green), defined by the 'Chalk Hills of Surrey and Kent' (dipping northwards) and the 'Sussex Chalk Hills' (dipping southwards). Smith's use of colour shading, stronger on the stratigraphic bases of units, emphasizes the rock sequence and therefore, the structure too. The stratigraphic base not only of the chalk but also of the overlying Paleogene units (in brown, including the London Clay) is shown in this way. However, with respect to the chalk, what Smith is bringing out here are steeper slopes, so the same dark shading emphasizes the incised valleys carved into this unit.

Other parts of Smith's (1815) map are less distinct. The core of the Wealden Anticline – containing sandstone-dominant (in light pink) and mudstone-dominant (in light blue) components of what is now termed the Wealden Group – have very diffuse boundaries. Doubtless this reflects the lack of control on the ground; outcrop is at best, patchy. But it illustrates challenges and uncertainties in geological map-making, that remain to the current day.

For some people, geological maps are considered to be objective constructs, simply showing what is found on the ground, or imaged remotely. However, many decisions involved in compiling ground observations into a useful map involve conscious choices rooted in the experience of the map-maker. Decisions must be made, for example, as to how complexity and natural variations are simplified, for example in defining stratigraphic formations. Defining boundaries between different rock units is not necessarily straight-forward, especially where transitions might be gradational (for example in the variations in composition within a single igneous intrusion). In structural geology, the continuity and connectivity of fault segments, their cross-cutting relationships, all involve decisions. These, and many other uncertainties inherent in the task of making a geological map, mean that all geological maps are necessarily interpretations. We can read Smith's (1815, Fig. 1) map and appreciate his interpretational challenges: the variations in the use of boundary shading perhaps indicate the confidence he had in locating the geological boundaries with precision.

The distinction between imagery and geological maps holds true for surveys based on remote sensing. Remote sensing approaches are used on our planet but they are demanded for interpreting the geology of the surfaces of planets and their moons. We can illustrate this with respect to our own Moon (Fig. 2). An image montage of high latitudes of the lunar northern hemisphere (Fig. 2a) can be compared with USGS's 1:1.5 M geological map (Fortezzo *et al.* 2020) of broadly the same area (Fig. 2b). The grey-scale image (Fig. 2a) shows a vast array of craters from which cross-cutting relationships can be interpreted. Using these relationships, the relative sequence of cratering events, and hence the relative ages of the features on various parts of the lunar surface, can be deduced. These deductions are interpretations, and it is a synthesis of these interpretations that is expressed as the geological map of the Moon on Figure 2b. This map is colour-coded for the interpreted age of various geological formations, using the five periods in the lunar geological timescale (Wilhelms *et al.* 1987). From oldest to youngest, these are Pre-Nectarian (dark brown), Nectarian (lighter browns), Imbrian (mauves, blues), Eratostenian (green and pink) and Copernican (yellows). In this way, knowledge of lunar geology has been built gradually, from observations from Earth, and from images acquired from space telescopes, a series of orbiters and associated space craft. These images have been interpreted, developing lunar chronologies based on the spatial density of craters.

Calibration of otherwise relative lunar cratering chronologies comes from radiometrically-dated samples. There are localities on the Moon that have been sampled first hand by astronauts on the six Apollo missions of NASA that landed on the lunar surface. The Soviet Luna missions returned samples collected robotically from a further two sites. Integrating interpretations of lunar surface imagery with the sample ages established an initial lunar cratering chronology (see review by Kirchoff *et al.* 2013). More recently, robotically-collected samples returned from China's Chang'e 5 mission challenge some of these earlier chronologies (e.g. Yue *et al.* 2022). Therefore, uncertainties remain, not least in the local context of samples; are they derived from the immediate underlying bed-rock or are they far-flung ejecta from a more distant impact crater? These uncertainties in turn motivate re-evaluation of regolith types, deduced from higher-resolution imagery from lunar orbiters. As with data collected on Earth, knowledge of the geology is always incomplete and produced maps, therefore, are merely interpretations of that incomplete dataset – a single milestone along the path of scientific discovery.

Compilation, teamwork and alternative interpretations

William Smith's (1815) geological map, famously, was the product of one man and his decades-long

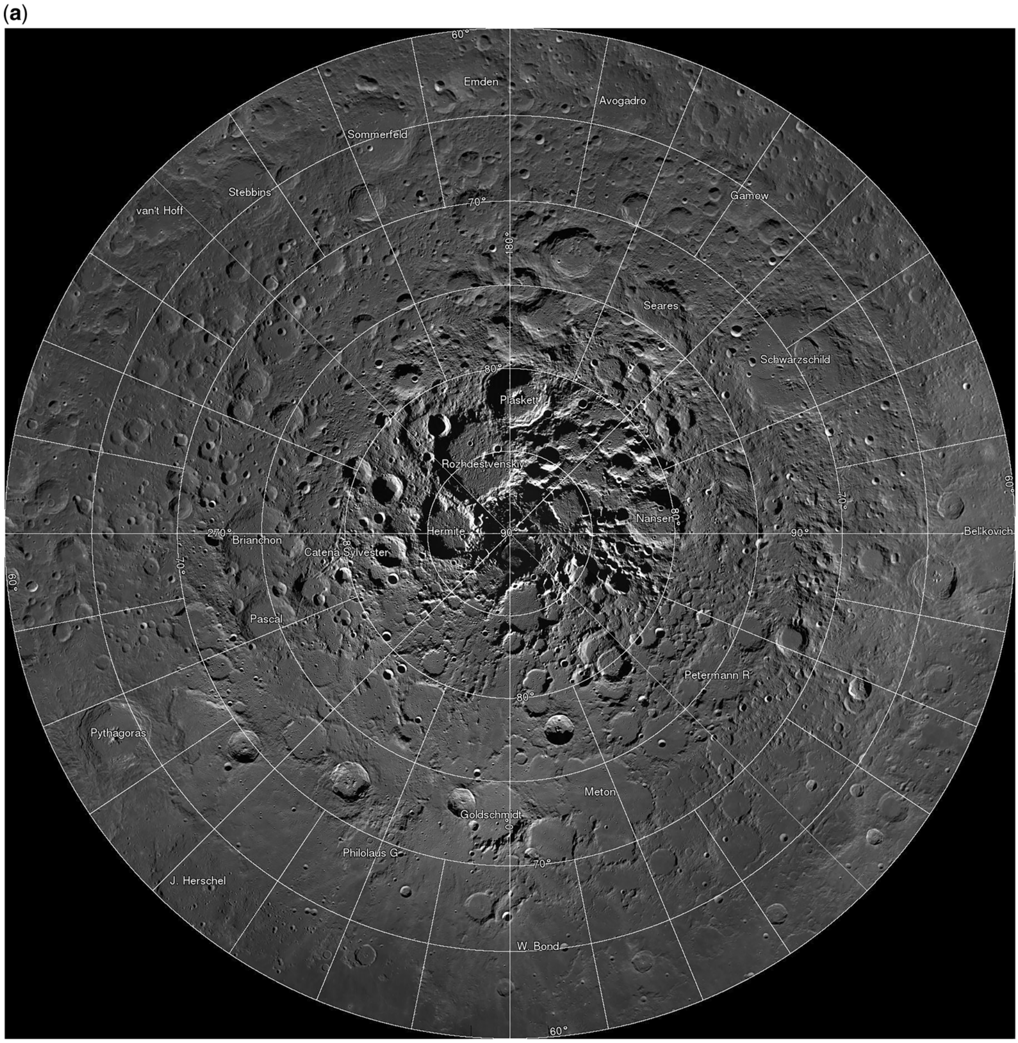

Fig. 2. (**a**) NASA's photomosaic of the lunar surface, centred on the North Pole, based on imagery from Lunar Reconnaissance Orbiter (NASA image: PIA18138), showing latitudes higher than 55 N. As is typical of much of the lunar surface, it displayed superposed impact craters. These provide a framework, through cross-cutting relationships, for deducing a time-scale for geological processes not only on the Moon but the inner planets of the solar system.

effort. It has, therefore, an internal consistency of presentation, and indeed simplification and synthesis. Likewise, the first geological map of Scotland (Macculloch 1836) was the product of a single man's endeavour, albeit published posthumously. Further versions of these maps, formed by the collation of swathe of local maps produced by different individual geologists, were compiled by small teams, often led by individuals. Geikie's repeated revisions of geological maps of Scotland (Geikie 1876, 1910) relied on the endeavours of many members of the Geological Survey of Scotland, of which he was director (and then director general for Great Britain as a whole). This leadership role meant he could impose his own interpretations integrated across the map area. For geological surveys in general, single approaches in mapping, simplification, synthesis and publication have been the rule for much of the history of geological mapping This doesn't mean that the maps compiled in this way are any more accurate than those compiled by larger teams, but at least they are more likely to present geological interpretations that are consistent from place to place. On the other hand, the search for

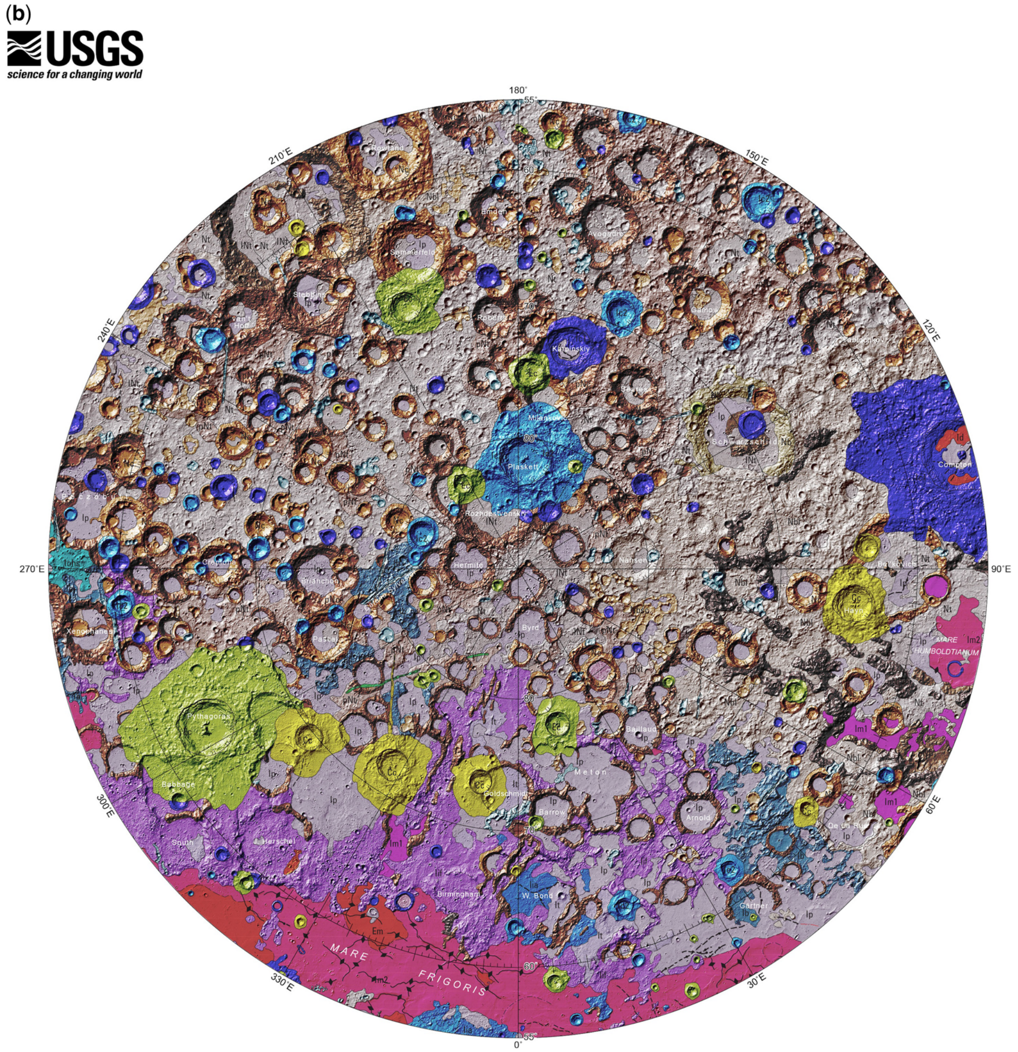

Fig. 2. *Continued.* (**b**) Part of the USGS 1:1.5 M Geological map of the Moon (Fortezzo *et al.* 2020), also centred on the North Pole, showing latitudes higher than 60 N. See text for discussion and identification of geological units.

consistency can obscure uncertainty and alternative explanations – especially of complex geology.

Problems can arise when compiling maps produced by several different individuals or organizations where consistency cannot be agreed upon or imposed. This is illustrated by an early collaborative venture to create a geological map of an entire continent. Smith's (1815) map, along with others created by geologists in other countries, demonstrated the virtues of compiling geological information for large areas, to show continuity of stratigraphic units and hence, in broad form, the tectonic structure of these regions. It was therefore unsurprising that through the nineteenth century there were several attempts to compile geological maps for the whole of Europe. The most highly regarded was the map by Andre Dumont (1875), published in printed colour at a scale of 1:3 800 000. This solo effort in the compilation, led almost immediately to a collaborative project to compile a more detailed map. The International Geological Congress, held in Bologna in 1881 (Topley 1881) established a commission drawn from representatives of various European countries. The product was an exceptional map, arguably the first pan-European collaborative science project (Fig. 3). It was published by Dietrich

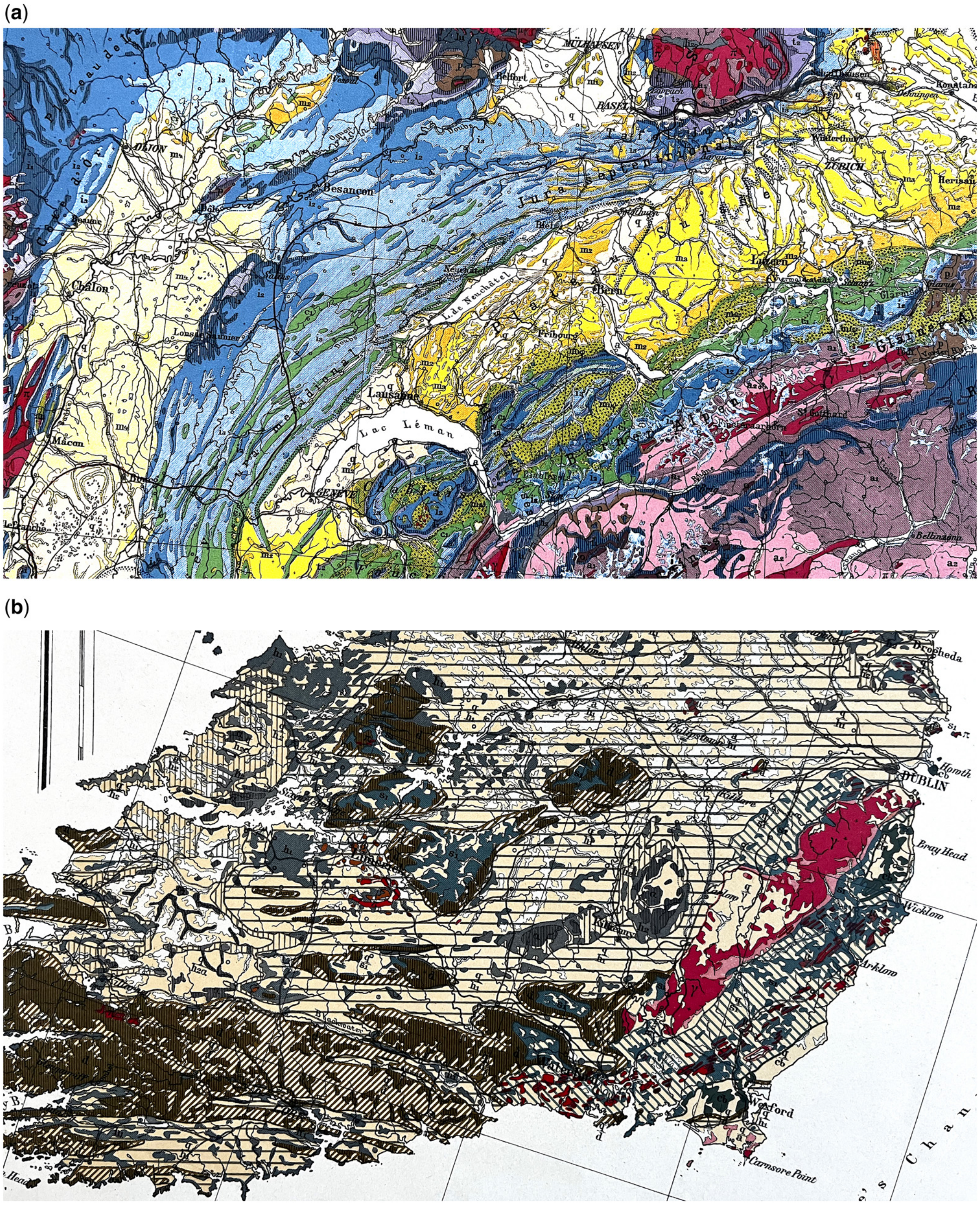

Fig. 3. Scenes from the first International Geological Map of Europe. For scale in these scenes, refer to the grid lines, which are spaced at one degree intervals (both latitude and longitude). (**a**) Much of Switzerland and surrounding parts of France and Germany (then referred to as Prussia). (**b**) Southern Ireland.

Reiner and the Institute of Lithography in Berlin as a folio of 49 sheets at a scale of 1:1 500 000. Although the panels featuring western Europe appeared in the 1890s, the whole venture took 32 years to complete: the last few sheets were only published in 1913. In the meantime, the early leaders of the project, Heinrich Beyrich (1815–96) and Wilhelm Hauchecorne (1828–1900) had passed away. This exceptional gestation reflects the difficulties in creating a consistent whole, striking compromises that are

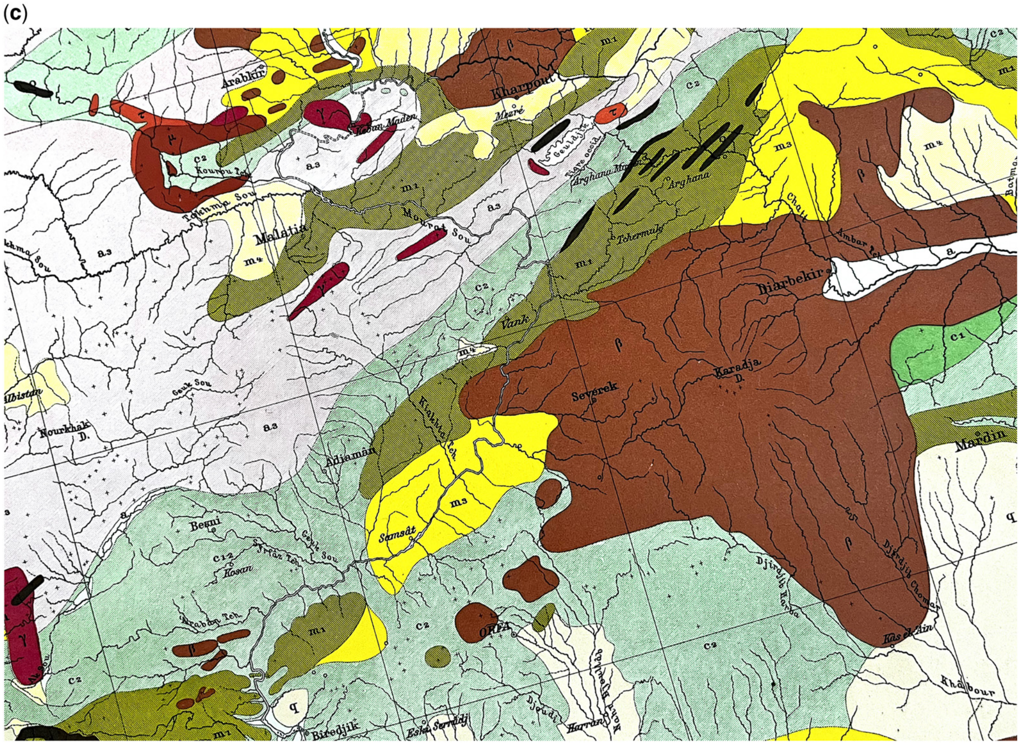

Fig. 3. *Continued.* (**c**) Part of SE Turkey.

acceptable to geologists across different nations. And even in its final version, stratigraphic groups of broadly the same age are assigned to distinctly different units when comparing western Europe with Russia. The problem persists (e.g. Zhamoida 1984) with Russia retaining a stratigraphic framework distinct from much the rest of the World (e.g. the Carboniferous, Alekseev *et al.* 2022). But even allowing for inconsistencies in nomenclature, different map sheets have distinctly different styles (Fig. 3). Consider Figure 3c – which is a segment of SE Turkey that straddles the edge of the Taurus mountain front. In comparing with the broadly equivalent tectonic setting of Figure 3a (for the Alps) – do these represent different types of geology or different types of geologist?

In some regions the scale and style of representation on the maps illuminate the continent's geological structure, such as the basins of France and the margins of the Alps (Fig. 3a). But elsewhere, where the geological detail is beyond the resolution demanded by the published scale of the mapping, compromises obscure the structure. Consider the representation of the geology of much of the south of Ireland (Fig. 3b). There is rather inelegant use of diagonal shading superposed on other units, reflecting the cover of Quaternary deposits (drift) above bedrock of Devonian and Carboniferous strata. This representation, inflected upon swathes of Ireland and Great Britain met with some criticism at the time. Hull (1899) recognized the high quality of map sheets that 'except, perhaps, in the case of the British Isles, fully sustains the reputation of the Lithographic Institute of Berlin' (p. 247).

Regardless of the local shortcomings, the Geological Map of Europe is rightly lauded for being one of the first significant collaborations by scientists, of any discipline, from many different countries. It was completed just in time, for it would be many decades before this diversity of nations established convivial relationships again. After the Great War, a Geological Map of the World was compiled single-handedly by Henry Milner (1921). De Margerie's (1922) excoriating review, highlighting extensive inaccuracies, continent by continent, went on to urge a return to international collaboration via meetings of the International Geological Congress. Rivalries and distrust remained between the scientific communities, certainly across Europe after the conflict (e.g. Fourtau 1919) so such collaborations had to wait until much later in the twentieth century.

Compilations by an individual geologist or small group of researchers might be able to achieve internal consistency, as exemplified by the maps of Smith (1815), Macculloch (1836) and of geological surveys with defined project leadership (including Geikie's 1910 map of Scotland and Fortezzo *et al.*'s 2020 map of the Moon). But unless they draw on diverse geological knowledge, such compilations can be challenged as being inaccurate by those who claim more intimate knowledge of particular areas (e.g. de Margerie v. Milner). In contrast, maps compiled by committee, such as the 1913 Geological Map of Europe, may have intrinsic inconsistencies and unsatisfactory compromises. Ultimately, however, whether a map was produced by an individual or a large group, inherent uncertainties in interpreting and collating geological data mean that compromises and simplifications and, therefore, inaccuracies are inevitable.

In most cases, map production and the choices made as to what to display on the map is guided by its intended use, but the subsequent usage of the initial map can enable refinement of the original interpretations. Geological maps have long underpinned the effective exploitation of Earth resources. For extractive applications such as mining, as resource exploitation progresses, understanding can integrate new knowledge so that subsurface maps can be improved iteratively. These iterative approaches are less practical when the objective behind the mapping is concerned with subsurface engineering, such as for geo-storage sites, where unforeseen interventions may compromise the integrity of these sites. Therefore, for ground engineering purposes it is important to make better assessments of the interpretational uncertainty inherent in a geological map. This can come from exploring the consequences of different versions of a map. Documenting the areas of uncertainty in a map or its accompanying publication should be routinely included in the process of map-making, but rarely are.

While the conduct of geological mapping on Earth has promoted the compilation of single, apparently (but misleadingly-claimed) definitive maps, an alternative framework exists for the mapping of the surfaces of extraterrestrial bodies and of Earth's oceans. Since the 1990s, with the exception of various technical information relating to equipment-testing, NASA has had a policy of complete open-access. Therefore, researchers wanting to create their own maps of, for example, part of the lunar surface, have access to the identical imagery (and sample data) as used by USGS geologists for their map of the Moon (Fortezzo *et al.* 2020). The same is true for other extra-terrestrial bodies. Likewise, bathymetric data for the Earth's seabed are now routinely placed in the public domain by oceanographic institutes.

Alternative geological maps of large regions, such as for Europe, were published by different researchers almost synchronously in the mid-late nineteenth century (compare Dumont 1875 with Murchison and Nicol 1856). In principle, the diversity of academic journals should mean that alternative versions of geological maps should be available. However, publications traditionally do not encourage this and, in general, multiple interpretations are not collated. Most national geological surveys now have open-access policies, but these generally only extend to sharing the geological mapping they have produced, rather than the primary observations or outcrop-level interpretations. Some alternative versions of maps may be available, through comparing a series of historical versions, but this is unlikely to capture the range of alternatives in all but the simplest geological settings.

With open access to primary mapping imagery and data, the challenges now are how to encourage or solicit multiple interpretations and then how to share these. For example, an image of an extra-terrestrial planetary surface is not, on its own, a geological map because geological maps require interpretation, with its inherent uncertainties that arise not just from the resolution of the original imagery but also in the interpretation approach and experience of the interpreter. The rationales behind the decisions made during interpretations are rarely (if ever) documented. A challenge then is to ensure that the interpretational decisions are made consistently, so that different parts of the map may be compared on the basis of the geology they display, rather than of the various interpreters who made them. Internet applications provide opportunities to collate alternative interpretations. On a much smaller scale to maps of planetary surfaces, this is the mission of the Virtual Seismic Atlas (VSA) (reviewed by Carstens 2008). Multiple geological interpretations of subsurface imagery are solicited, shared and searchable on an open-access VSA application. There are no such facilities presently available for geological maps, but this can change, along with ways of communicating and explaining the differences so that choice does not also cause confusion for end-users.

Technology

Remote sensing, particularly of extra-terrestrial bodies, along with the use of internet-hosted applications for openly-sharing geological knowledge and its interpretations are illustrations of how technology provides new opportunities. However, geologists have long tried to use the latest technologies to assist in their mapping endeavours. Smith (1815) used the best-available topographic base-maps upon which to delineate the geology, provided by his collaborator,

Fig. 4. An evolution in field mapping technologies. (**a**) a student group using traditional paper map and notebook to make recordings, in the Assynt district of NW Scotland. (**b**) collecting structural data using traditional equipment (compass-clinometers). (**c**) Midland Valley employees on a field test in NW Scotland (April 2009) using a ruggedised tablet – a reduced version of their structural interpretation software – Move. (**d**) A pilot field test of Midland Valley's FieldMove software on a smart phone (September, 2013). All photography by Rob Butler.

John Cary. As the quality of base-maps improved, geologists were able to display their mapping against topographic contours, which in turn provided far greater precision for extrapolation into the subsurface. The development of aerial photography in the early decades of the twentieth century was especially important. The application of satellite technology has, since the launch of NASA's Landsat Earth Resources Technology Satellite (ERTS) in 1972, been pivotal in mineral exploration and environmental monitoring (see Sabins 1999 for review of early applications). Satellite systems now provide near continuous monitoring of dynamic earth processes and openly accessible 'virtual worlds' such as on the GoogleEarth platform greatly enhance access to these vast sets of imagery.

Digital fieldwork

Back at ground level, technology is changing the ways in which information is gathered and synthesized while mapping on site. The authors of this introduction were trained using materials and equipment that had hardly changed in over a century, including hard-copy maps, notebooks, drawing equipment and magnetic compasses. Geologists engaged in these activities are shown in Figure 4a and b. Over the past 15 years, this has changed. From around 2008, the move to digital recording came from using compact waterproofed computers in ruggedised frames with inbuilt GPS capability (see Fig. 4c). High cost and limited battery-life substantially limited the adoption of these solutions.

However, smart phone technology and the development of compact tablet computing at relatively low-cost (an order of magnitude cheaper than the hardware in Fig. 4c) has opened this market since around 2014. These platforms also allow the use of digital compass and inclinometers. The advantages of portability can be assessed by comparing the ruggedised tablet (Fig. 4c) with the smart phone (Fig. 4d). The transition onto cheaper, increasingly ubiquitous hardware, has also been supported by various software platforms for geological mapping. Some are proprietary, such as Petroleum Experts (formerly Midland Valley's) FieldMove app, and some are non-proprietary, such as Rick Allmendinger's GMDE apps.

While directly recording observations and making measurements in the field digitally greatly facilitates real-time data analysis and synthesis, it remains unclear whether these methods yield geological knowledge that is more accurate or precise than that acquired by more traditional means (but see Allmendinger *et al.* 2017). The reliance on a single digital device such as a smartphone or tablet carries risks. Batteries can run low. Devices can be broken or dropped in water. GPS coverage may be unreliable under cliffs. The accuracy of measurements of geological structures may be compromised by users choosing inappropriate outcrop features or positioning the device correctly upon the feature. The reliance on digital technologies are commonly amplified by mountain rescue teams with respect to wilderness navigation. Of course, the risks are not inherent in the technology itself but in the user themselves, namely – the geologist. Therefore, there is ultimately no guarantee of accuracy of data or of resilience of equipment, regardless whether one uses traditional analogue tools (paper maps and notebooks) or digital devices; and the lesson here may be that one should not rely on a single method or piece of equipment. Doubtless though, in the next few years, the utility of hand-held technologies will continue to develop. These are exciting times for geological field mapping (Tavani *et al.* 2022).

Virtual outcrops

Digitally-captured 'virtual outcrops' add precision when determining the shape and dimensions of geological structures, whether they are tectonic, stratigraphic or igneous. In parallel with digital recording and measurement equipment for fieldwork has come the development of digital surveying equipment. Laser-based, light detection and ranging (LiDAR), was developed in the 1960s, initially for military purposes. Since the 1980s the technique has evolved to include ground-based tools for high-resolution geo-spatial surveying. The high-precision of LiDAR saw application to create precise analogues for reservoir modelling and for training professionals from the hydrocarbons industry (e.g. Bellian *et al.* 2005). However, the cost of basic equipment for surveying, and computation demands for data processing significantly limited the up-take of LiDAR technologies around the global geological community. Accessibility to the technology has improved in the past few years. LiDAR tools are now available on smartphones, albeit only currently suitable for small, close-to-observer objects, rather than larger outcrops.

Nowadays, the drive to create and share virtual outcrops is substantially driven for education needs that extend beyond the training of professional geoscientists (Cawood and Bond 2019; Buckley *et al.* 2022). Central to this expansion has been the application of photogrammetry using so-called structure-from-motion with images acquired from unmanned airborne vehicles (UAVs) and ground-based cameras (see Westoby *et al.* 2012). Accessibility to data-processing on affordable desk-top computers and freely available software means that vastly greater numbers of geoscientists can use the techniques. Not only does this increase the opportunities for creating multiple interpretations of geological outcrops, but it also begins to reduce the sample-bias inherent in relying on a rather small number of 'type-examples' in libraries of outcrop analogues. So digital outcrops not only add precision to the documentation of the shape and dimensions of geological formations but, by openly sharing these digital resources, also allow others to make their own interpretations using the same observable features.

We illustrate the utility of terrestrial photogrammetry using the Spitzhorn fold pair from Switzerland's Helvetic Alps (Fig. 5). The structure was described and illustrated in the memoir by the Alpine geologist Marcel Lugeon and his representation (Lugeon 1916, part of his plate 13, fig. 4) is reproduced here (Fig. 5a). The sketch is part of a suite of serial sections and interpretations of geology exposed on mountainsides. These were published in a suite of memoirs that accompanied the detailed maps of the Swiss Alps completed in the early decades of the twentieth century. Classically, this mapping involved combinations of somewhat extreme hands-on ground-truthing, along with observations from adjacent mountainsides. In later years, the mapping of otherwise inaccessible terrain was facilitated by views from helicopters, still supplemented by varying degrees of mountaineering. Modern photogrammetry provides more complete perspectives, by combining these distant views into a 'virtual outcrop'. The example here (Fig. 5b) was created with ground-based photography and is an oblique view derived from the model. The advantage

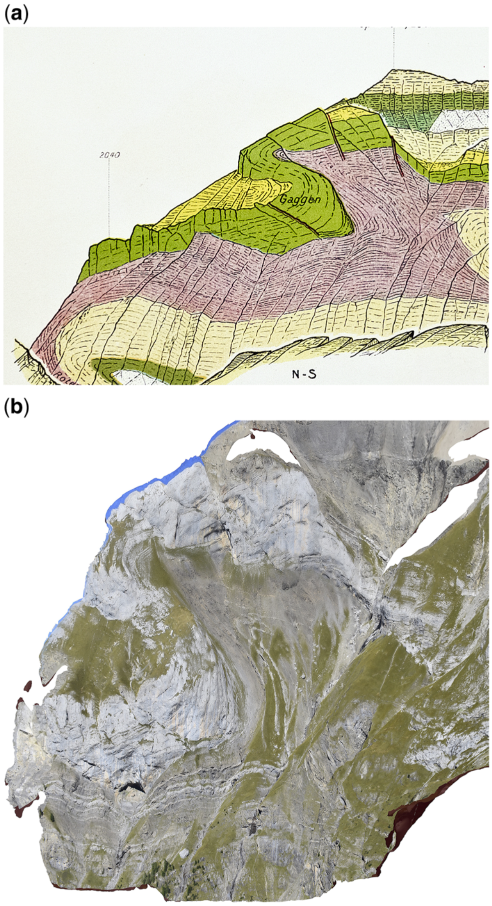

Fig. 5. (**a**) Lugeon's representation of the Spitzhorn fold pair at the front of the Wildhorn Nappe, Switzerland. The folded (and faulted) green layer is designated by Lugeon (1916) as the Urgonian limestone (Cretaceous) cut by faults. It is underlain by thinner-bedded limestones and marlstones (see Cardello and Mancktelow 2014 for more recent structural-stratigraphic interpretations). (**b**) The fold pair represented in an oblique photograph derived from a photogrammetric model. The image, and model were created by Phoebe Sleath, as part of a project investigating the evolution of representations of geological structures in outcrop. The prominent white cliff-formed unit is the Urgonian limestone (Cretaceous). Note the detail of folding in the thin-beds in the core of the fold. The visible cliff height is *c.* 500 m.

of working with the model is that it gives composite views into the structure that are not available from individual viewpoints. Not only does this add precision to the geological interpretation, a photogrammetric model also provides visualizations that are far better at communicating the interpretation to others (though hard to appreciate from the single static view presented in Fig. 5b). Arguably it is their use as communication and educational tools, delivered through the internet, that is driving the dramatic increase in the availability of virtual outcrops.

Microstructure

On the grain-scale, the development of fine-scale imaging techniques are revolutionising understanding of crystal-scale textures. These understandings in turn feed back up to inform large scale geological processes, from the energetics of meteoroid impacts to the process of creep in the mantle. Central to these endeavours has been the widespread adoption of electron backscattered diffraction (EBSD) delivered through scanning electron microscopy. Lloyd *et al.* (2011) show how these types of results, tied to macroscopic rock fabrics, can be used to forecast seismic properties, and these in turn might be used to design geophysical experiments that could determine, remotely, the kinematics of shear zones *in situ* in the deep crust or the dynamics of plate motion.

As with many approaches in the development of mineral physics in the earth sciences, EBSD techniques were pioneered in metallurgy (reviewed for example by Carneiro and Simões 2020). However, the application to the more complex crystallography of minerals makes defining the orientation of crystal lattices (indexing) significantly more challenging. EBSD on earth materials began to take off in the early 1990s. We can consider EBSD developments with reference to Figure 6 an image of a famous sample (PHN1611; e.g. Wallis *et al.* 2019) of garnet lherzolite from the Thaba Putsoa kimberlite, Lesotho. As such it is a rare sample direct from the mantle and it preserves deformation fabrics – largely unmodified from their state *in situ*.

Images of PHN1611 were first acquired by EBSD in the early 2000s with steps of 1 micron across the sample area of 1.5 cm × 1.5 cm. Although individual sites in the sample could be indexed almost instantly, these early approaches were rate-limited by the stability of the sample movement, meaning it took about a second to index each site. The whole survey took around ten days to complete. Such long run-times greatly exceeded the life of the tungsten filaments as electron sources used in the early years. The later development of field-emission guns rather than filaments avoided this problem. With these improvements in electron beam sources, beam scanning (rather than moving the stage in tiny increments), better detectors and cameras, resolution is now claimed down to a few nanometres, with more stable run-times and accordingly far less risk of the beam damaging the sample. And so, it is the ability of modern electron microscopy techniques allied to computers that can index crystal lattice structure and orientation over the hundreds of millions of pixels necessary to map a square cm of sample area that allows detailed work.

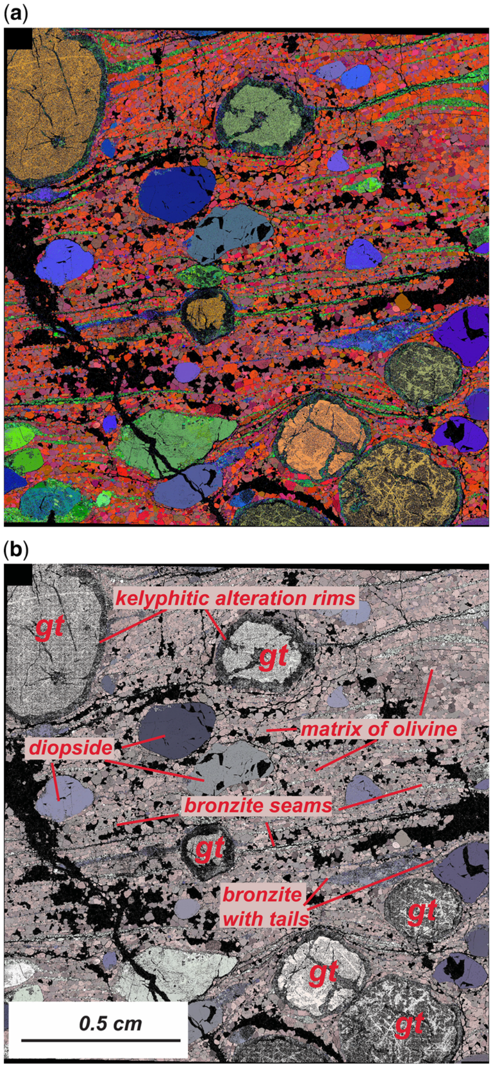

Fig. 6. False-colour electron backscatter diffraction SEM imagery of a sample of sub-continental mantle. This is sample PHN1611 (compare with fig. 2a of Wallis *et al.* 2019) of garnet lherzolite from the Thaba Putsoa kimberlite, Lesotho. (**a**) the sample in false-colour showing crystallography (phase contrast) and euler angles which show crystal orientation; image courtesy of Geoff Lloyd. (**b**) labelled phases and microstructure: olivine (large matrix grains), bronzite (small matrix grains), garnet (with kelyphitic alteration rims), diopside (without rims), plus bronzite clasts showing recrystallization tails. The field of view is 1.5 cm × 1.5 cm.

The image of PHN1611 (Fig. 6) was obtained by an automated scan that ran overnight. It shows different compositions (therefore minerals) and variations in their crystallographic orientation by false-colouring. The structure includes olivine (large matrix grains), bronzite (small matrix grains with recrystallization tails), garnet (with kelyphitic alteration rims) and diopside (without rims). Collectively the images show that grain-size reduction is a feature of crystal-plastic deformation in the upper mantle, creating a macroscopic fabric. These types of fabric, when organized on the cubic kilometre – to tens of cubic kilometres transmit seismic waves at different velocities in different directions, detectable – and therefore mappable in the subsurface, by measurements of seismic anisotropy recorded from teleseismic events by seismometers at the earth's surface. Samples such as PHN1611 and the textures they record, offer calibrations to seismology and, in this way, deformation fabrics in the mantle can be mapped *in situ* and related to motions of the plates.

Notwithstanding the radical improvements in SEM performance for EBSD, allowing for inflation, the cost of hardware has seen a radical reduction. This, and the effectiveness of the methods to return great results, and ease of use, has led to a dramatic increase in the number of practitioners. In the early 1990s, the user-community of EBSD in microstructural studies was restricted to a handful of laboratories. Now there are hundreds. This democratization of the method, and explosion in publications means many more samples are being characterized. One would hope that it would also lead to tests of reproducibility – with different groups analysing the same sample or structure and comparing their interpretations. This is rare however, doubtless inhibited by publication policies of journals that discourage experimental repetition. And as with any sophisticated technique, there is a danger of uncritical use – the 'back-box effect'. These are common challenges that have always arisen during periods of rapid technological advance.

About this special publication

The introduction above argues that the discipline of geological mapping is as important as ever, and as throughout its development, is evolving dynamically. This evolution is represented by the fourteen papers in this Special Publication. They include opinion pieces, case studies, historical accounts and workflows. There are clear synergies between different mapping communities whether working on microtectonics on the crystal scale or striving to understand the evolution of entire planets. And more than ever, with the increasing need for resources to sustain new industries as societies evolve from their current dependency on hydrocarbons, mapping underpins geological investigations just as it did in servicing the first Industrial Revolution. The papers rely on different technologies and imagery datasets for the creation of geological maps – the accessibility to which is dramatically increasing across the global community of geologists.

The collection begins with a typically forthright opinion piece by **Dewey (2023)**. He provides personal reflections on the importance and conduct of field geology and the central importance of mapping geological relationships, regardless of the scale of observation and interest. He bemoans the lack of recognition of this importance amongst some parts of the earth science community and worries that unless expertise is nurtured, it will be lost. He is fearful that the basic skills and indeed ambition to create effective maps are on the wane. Dewey's assessment of the importance, if perhaps not his concerns for the future of the science, are represented in many of the papers that follow. These generally cast a more optimistic light.

Following up on **Dewey's (2023)** core point, that the need for recurrent geological mapping will never end, **Smelror (2023)** provides an overview of the Norwegian Geological Survey and its evolving geological mission. Building on accounts of the survey's early history (Ingvaldsen 1983), he develops a narrative where the Survey, founded in 1858, is 'practically useful, scientifically important and to the honour of the country'. The founding tasks centred on bedrock mapping but, from the 1960s, significant efforts were directed at geophysical surveys of Norway's extensive maritime economic zone, the focus of oil and gas exploration. Moving into the twenty-first century the Norwegian Survey is increasingly tasked with creating maps that chart the country's earth resources and natural hazards. Smelror discusses the importance of open-access publishing, so that maps and other geological resources are available freely, without charge – a welcome priority for many geological surveys around the world.

Historical perspectives of a different kind are provided by **Butler (2023*a*)** in his account of structural mapping in NW Highlands undertaken by the Geological Survey of Scotland that followed the resolution of the so-called Highlands Controversy (Oldroyd 1990). He documents how, in the last fifteen years of the nineteenth century, Peach, Horne and colleagues rose to the challenge of mapping what is today known as the Moine Thrust Belt. The result is widely regarded as one of the finest examples of mapping of complex geological structure ever published. As Butler documents and illustrates, not only the progress of the mapping but also its publication and dissemination could be considered early examples of what is now called 'outreach'. He also reflects on the problems of sharing geological knowledge as new insights are gained when the scientific productivity of the Geological Survey was measured simply by the number of map-sheets that were published.

Historical perspectives continue in **Molli's (2023)** paper on the development of geological understanding of the Alpi Apuane of the northern Apennines of, Italy. The region has attracted geologists for centuries, not only because of its close proximity to ancient university cities but also as it hosts one of the most famous monumental rocks: the Carrara marble. The region also attracted some of the nineteenth century's most influential geologists from across Europe, many of whom were to publish their own accounts of the geology. Through the later part of that century, increasingly anomalous stratigraphic relationships were reported in which rock units were repeated, similarly to those found in other mountain belts across Europe. Molli discusses not only the evidence but also the societal convictions that led local geologists rejecting tectonic ideas proposed by outsiders. Molli argues that this isolationist approach held back understanding of Apennine geology and tectonics for decades. His paper demonstrates how the development of geological knowledge, and of the maps that portray it, can be influenced by preconceived notions and prejudice.

Incremental advances in understanding through successive mapping is common to many applications. An advantage of extra-terrestrial endeavours is that imagery and data are rarely the preserve of a small, isolated group of researchers. Controversies of course exist, but all ideas and concepts can be applied, rather than ignored, as happened for a time in Italian geology. **Head *et al.* (2023)** provide a wide-ranging review of how a succession of missions have slowly revealed the geology of Venus. They show how these endeavours follow the traditions of and motivations for geological mapping and synthesis that date back to William Smith. Like Earth, Venus has seen substantial resurfacing through igneous eruptions, the terrestrial version of which being sea-floor spreading. Unlike Earth of course, the density of impact craters provide a timescale for volcano-tectonic events, and on Venus are not associated with plate tectonics. Current insights are captured on the global geological map of Venus (at 1:10 M; Ivanov and Head 2011), and the methods and approaches in building maps at various scales are reprised here. Head *et al.* conclude by looking forward to future missions to Mars. For these, a broad community of young researchers have gathered under the umbrella of the International Venus Research Group (IVRG) to identify targets for these missions, aimed at understanding specific tectono-volcanic landforms.

Other rocky planets have greater densities of meteor impact craters than Venus and Earth, reflecting the greater preservation potential on bodies less prone of volcano-tectonic resurfacing, **Canale *et al.* (2023)** use images from the MESSENGER mission to Mercury to map out impact-related geological formations associated with the Sibelius crater. They set the scene outlining the insights gained from preceding missions to Mercury. Here they marry morphological and spectral mapping to examine the variety of landforms and deposits associated with the Sibelius crater interpreting various forms of ejecta and substantial volumes of, now frozen, impact melts. They relate the asymmetry of deposits and structures to an inferred low angle of incidence of the impactor that generated the crater. Canale and co-workers discuss the limits of their study – the relatively low-resolution of existing imagery for the southern hemisphere of Mercury and look forward to the future acquisition of higher-resolution datasets.

Remote-sensing – necessary for producing geological maps of planetary surfaces, is of course important on Earth too. Much understanding of the geology of sedimentary basins comes from seismic reflection surveys, whose aim is simply to provide images for geological mapping, albeit in three dimensions. Faults are fundament components of sedimentary basins. Over the past half century substantial advances in understanding, at least for normal fault systems, has come from mapping based on seismic reflection imagery. Access to these images along with the software platforms to interpret them has restricted the opportunity to develop techniques and interpretations to a very small subset of the global earth science community. **Butler (2023*b*)** develops a training exercise for building expertise in mapping faults in three dimensional seismic imagery, using tectonic geomorphology. His example comes from the Afar region, arguably the most dramatic faulted tectonic landscape on Earth that reveals stunning interactions between normal faults. By using virtual globes, students can quickly develop understanding of fault systems without having first to become competent users of seismic interpretation tools.

While bathymetric and seismic imagery may be available for offshore areas, displaying fault and fold systems, it can be difficult to link to outcrop maps onshore because of data gaps in the nearshore. However, the increased availability of high-resolution bathymetric surfaces, especially in locations where superficial, modern sediments are swept clear by vigorous marine currents and waves offers to bridge the data gap. These opportunities are grasped by **Craven and Lloyd (2023)** in their study from SW England, an area that is historically important for developing understanding of folding in well-developed stratal multilayers (e.g. Ramsay 1974). Existing understanding of these folds is essentially two-dimensional, relying on cliff sections. Craven and Lloyd assess the non-cylindricity of the folds and, following Nixon *et al.* (2012), map out fault arrays. But they point out uncertainties in making structural maps, inherent in using bathymetric data; issues that also apply to such interpretations in offshore datasets. As such, their reflections are important for assessing near-surface submarine structure in general, endeavours that are important for some types of hazard-assessment.

Interest in methods for documenting and analysing faulting patterns in regions away from sedimentary basins is likely to increase with the search for the earth resources necessary to support the change in global economies endeavouring to decarbonize. **Gonzalo-Guerra *et al.* (2023)** showcase just such approaches in their case study of structural mapping in the Cantabrian Mountains of Iberia. They show the importance of defining genetic groups of structures, following the methods collated by Peacock and Sanderson (2018). They build a history of faulting stretching from Variscan crustal shortening to Mesozoic rifting, reworked during Tertiary compression, and tying in the region's history of mineralization, especially of lead-zinc deposits.

The importance of following carefully documented workflows when it comes to untangling complex geological relationships is as important in small-scale studies as it is when mapping regions of the Earth's surface. **Webb *et al.* (2023)** make this point in their reconstruction of paragenetic histories from sulfide-bearing hydrothermal ores. Such reconstructions, of relative timing of different phases are critical if analytical results and their implications for metal fluxes are to be interpreted correctly. They show the insights for textural evolution that can be gained from using various electron microscopy techniques, based on overprinting and cross-cutting relationships. These geometric relationships are of course conceptually equivalent to any mapping efforts, including deriving the relative age of impact structures seen on planetary surfaces. In many ways, the key points are equivalent to those of **Gonzalo-Guerra *et al.* (2023)** i.e. it is essential to establish the structural relationships in rocks, be they on the grain scale or on mountainsides.

Scanning electron microscopy has revolutionised the tools available to understanding grain-scale and intragranular processes in rocks. Although many of the techniques have had a long history of development, their use has greatly accelerated in the past couple of decades. Electron microscopy lies at the heart of **Lloyd's (2023)** paper on quartz microstructure. He shows how the orientations of crystal lattices can be determined and then compared between and within individual grains, using electron backscattered diffraction (EBSD). Maps of grain orientations have revolutionised understanding of microstructure of rocks, especially because modern SEM-EBSD techniques are relatively low-cost (e.g. Prior *et al.* 1999). Lloyd providers a step-wise approach for detecting lattice orientations in deformed quartz crystals. The paper applies a new technique for determining the physical and crystallographic orientation of boundaries, using dauphiné twin boundaries as an example.

The collection of papers in this Special Publication concludes with three contributions of distinctly different regional mapping studies. **Ridd (2023)** gives a personal account of a frontier mapping programme in SE Asia in the 1960s. These activities were part of BP's oil exploration ventures in southern Thailand. This mapping was compiled into eight sheets at a scale of 1:250 00 parts of which Ridd reproduces in his contribution to the volume. The work helped to reveal the extent of late Paleozoic glacial deposits that in turn indicated that this area of SE Asia once formed part of Gondwana (Ridd 1971). As such, the mapping directly contributed to geological knowledge of Thailand (e.g. Ridd *et al.* 2011) and informed broader debates on the assembly of SE Asia. The work emphasizes the importance of regional understanding when studying sedimentary successions, placing them in a broader palaeogeographic context. The paper itself is a great example of a historical account written from a first-hand perspective.

Palaeogeographic reconstruction features in **Macdonald's (2023)** exploration of the hypothesis that the Scottish Highlands were covered in Cretaceous times by seawater. It is a proposition that has had significant economic relevance. Cretaceous rocks are important components of the geology in the sedimentary basins that rim Scotland. These basins have yielded vast amounts of oil and gas in the past half century and they may yet provide the storage sites for CO_2. Understanding the provenance and palaeogeography of these sediments informs forecasts of the petrophysical properties of these subsurface reservoirs. By integrating diverse geological datasets, Macdonald is able to map out the maximum Cretaceous shoreline that in turn delimits the Highlands as being subaerial, and a source for detritus in the surrounding basins. Some of these datasets originate in the nineteenth century. As such, the paper is a clear demonstration of the value of legacy data and the pressing need to archive the knowledge we have acquired much more recently for the offshore.

The final paper in this volume addresses the challenges of tracking the structural evolution of regions of the Earth's crust through geological history via 4D digital mapping. **Markwick *et al.* (2024)** note that conventional mapping concentrates on charting the present-day tectonic structure, i.e. the folds and faults, the distribution of magmatic rocks and generalized geological character of the crust structure across a region. To improve understanding, and to increase the utility of this information, they argue that maps need to record the geological structure that preceded the present-day, for example documenting the pattern of rift basins on a former continental margin that existed before contractional tectonics created a particular mountain belt. They further argue that the interpreted geo-tectonic processes that formed the structures are recorded too. Tiered digital mapping products provide opportunities to do this, in ways that are difficult to achieve using traditional, single layer maps.

The collection of papers here covers a wide range of techniques, places and scales. But significant areas are not covered here, such as mapping based on geophysical methods of the world's oceans, deep earth and sedimentary basins. There is only passing reference to geological mapping with satellite technologies and the use of virtual outcrops. Nevertheless, this Special Publication contains an eclectic mix of papers that illustrate some of the diversity of geological mapping and their utility. There are clear synergies between different mapping communities whether working on microtectonics on the crystal scale or striving to understand the evolution of entire planets. There is an increasing need for resources to sustain new industries as societies evolve from their current dependency on hydrocarbons. Geological mapping on all scales remains as important as it was in servicing the first Industrial Revolution.

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