The Virtual Geoscience Revolution: From William Smith to Virtual Outcrop

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In 1799 an English surveyor named William Smith published the World's first geological map. This map, which covers the whole of England and Wales, fundamentally changed the way that geologists visualised the subsurface (Winchester, 2001). For the next 200 years, field geologists across the World worked in much the same way as Smith had done, tracing geological boundaries on the ground and using ink pens and coloured pencils to record the surface expression of the geology onto paper and maps (Fig. 1A). Even today, the largest single component of any undergraduate degree in the UK is a "mapping project", where students make detailed maps of a selected area in this way. There can be very few sciences where there have been no significant changes in the basic data collection methods for over 200 years. However, since the turn of the 21st Century we have seen a quiet revolution in the way in which field data are being collected, analysed and displayed. We call this the Virtual Geoscience Revolution and it has come about in a number of discrete phases, each of which have resulted from the development of a number of distinct but parallel technologies.

Stage 1 – Satellites and GPS.

It's not easy to remember a world without GPS, but in the mid 1990's to locate yourself on a map, orienteering with a compass and landmarks was standard practice. Early GPS units were cumbersome and inaccurate, but towards the end of the 90's small handheld units became affordable and usable in the field. The application still relied on transposing coordinates onto a paper map and had errors that meant they were not good enough for detailed mapping, but this was the first stage of digital data collection. At the same time, more expensive differential GPS systems started to appear that relied on a stationary base station to correct satellite drift (postprocessed or in real time) from a rover unit position. For the first time it was possible for a geologist to trace a field boundary and record it digitally.

Stage 2 – Early Virtual Outcrops

Whilst walking out geological boundaries was the start of digital mapping, it was time consuming. Shortly afterwards, the virtual outcrop, a whole new school of digital geology was born. With a virtual outcrop, the entire outcrop is captured in a 3D picture where the exact location of every pixel is recorded. The earliest attempts (that we are aware of) came when researchers at Statoil tried to use photogrammetry (more about that later) to capture cliffs in Utah and Spain as part of the original SAFARI Project (Dreyer et al., 1992). These attempts failed because, while the concept was good, computer hardware and storage space had yet to catch up. The first practical virtual outcrops came in the early 2000's with the work of Carlos Aiken et al. at UT Dallas (Xu et al., 2000). A robotic Total Station was used to record the location of a few tens of points on a cliff face. This provided a framework onto which photogrammetry was used to produce a photorealistic model of the outcrop. Whilst this work was pioneering, it did not receive the attention that it deserved at the time.

Figure 1. Lulworth Cove, UK. A. Typical sketch with annotations that a geologist would create from field observations. B. 3D View of a virtual outcrop of the same outcrop in the field sketch.

Stage 3 – LIDAR

Soon after Aiken et al. were building their models, terrestrial LIDAR appeared on the scene. Designed for architectural scanning, their first application in Geology was by Jerry Bellian and Dave Jeanette at the Bureau of Economic Geology (Bellian et al. 2005). A LIDAR system records the time of flight of a rapidly pulsed laser beam shot at cliff faces (several tens of thousands points per second – up to a million today) and calculates a spot position. This produces a point cloud of millions of georeferenced points that accurately recorded the shape of the outcrop. The subsequent addition of a digital camera meant the point cloud could be coloured to produce a highly accurate but lowish resolution 3D image. The 3D image is significantly improved when the point cloud is triangulated and meshed to create a solid surface onto which the photographs could be draped. The virtual outcrop as we know it today was born (Fig. 1B).

Stage 4 - Beyond basic LIDAR

Helimap, a Swiss company, borrowed an inertial navigation system from a Cruise Missile and developed a method of mounting the LIDAR scanner into a helicopter (Vallet and Skaloud, 2004). The creation of heli-lidar increased the practical size of virtual outcrops from less than 1km to 10's of kms. Suddenly, huge datasets could be collected from seismic-scale outcrop sections such as the Book Cliffs in Utah, the Karoo in South Africa and large arctic outcrops in Greenland and Svalbard (Buckley et al., 2008). A second advance that occurred in 2006 was the co-registration of hyper-spectral imagery of the cliff sections. Using long range infrared sensors, similar to those used for satellite remote sensing (1100 – 2500 nm), it was possible to automatically map lithology and mineralogy from cliff sections and drape classified images directly onto the virtual outcrop (Kurz et al., 2012). These advances, and the large datasets that were collected, required software to visualise and interpret the data. While some existing software was modified to handle the 3D data, the key step came when two software packages were developed in parallel, VRGS at the University of Manchester (Hodgetts et al., 2015) and LIME at Uni Research in Bergen (Buckley et al., 2019). Both packages were specifically designed to deal with virtual outcrop data with a suite of interpretation tools, and they ran well on standard desktop PCs or even laptops. Virtual Outcrops had arrived!

Stage 5 – Drones and Photogrammetry: The democratisation of virtual outcrops

By 2010 a number of different groups were collecting, processing and using virtual outcrops. However due to the cost of the hardware (a typical LIDAR was in excess of £100,000) and the time-consuming nature of acquisition and processing, it remained a specialist tool. This changed with the advent of two parallel but unrelated advances. The first of these was the resurgence of photogrammetry and the release of a new set of algorithms called Structure from Motion (SfM). Photogrammetry is the concept of picking corresponding points on a series of pictures of an object, taken from different locations, and using this to reconstruct the scene in 3D. While the concept has been around for almost as long as photographs, it wasn't until the advent of SfM in the mid 2000's, coupled with advances in computer processing power, that it became a practical method for building large 3D models of outcrops. The advent of SfM also coincided with the emergence of cheap consumer UAVs (drones), with high quality cameras that could take hundreds of photos of outcrops from optimal angles (Fig. 2). Drones, combined with SfM, meant that suddenly anyone could build 3D virtual outcrops – and they did. By 2018, virtual outcrops had become commonplace and almost anyone working on outcrop geology was collecting and utilising them. A drone has become a standard piece of field kit and data from a 20-minute flight are processed in a few hours to produce an accurate, 3D photorealistic model of a cliff section of interest, that can be interpreted on a laptop. For the first time in 200 years, we are no longer reliant on recording geological information on 2D maps using coloured pencils. The Virtual Geoscience Revolution has arrived.

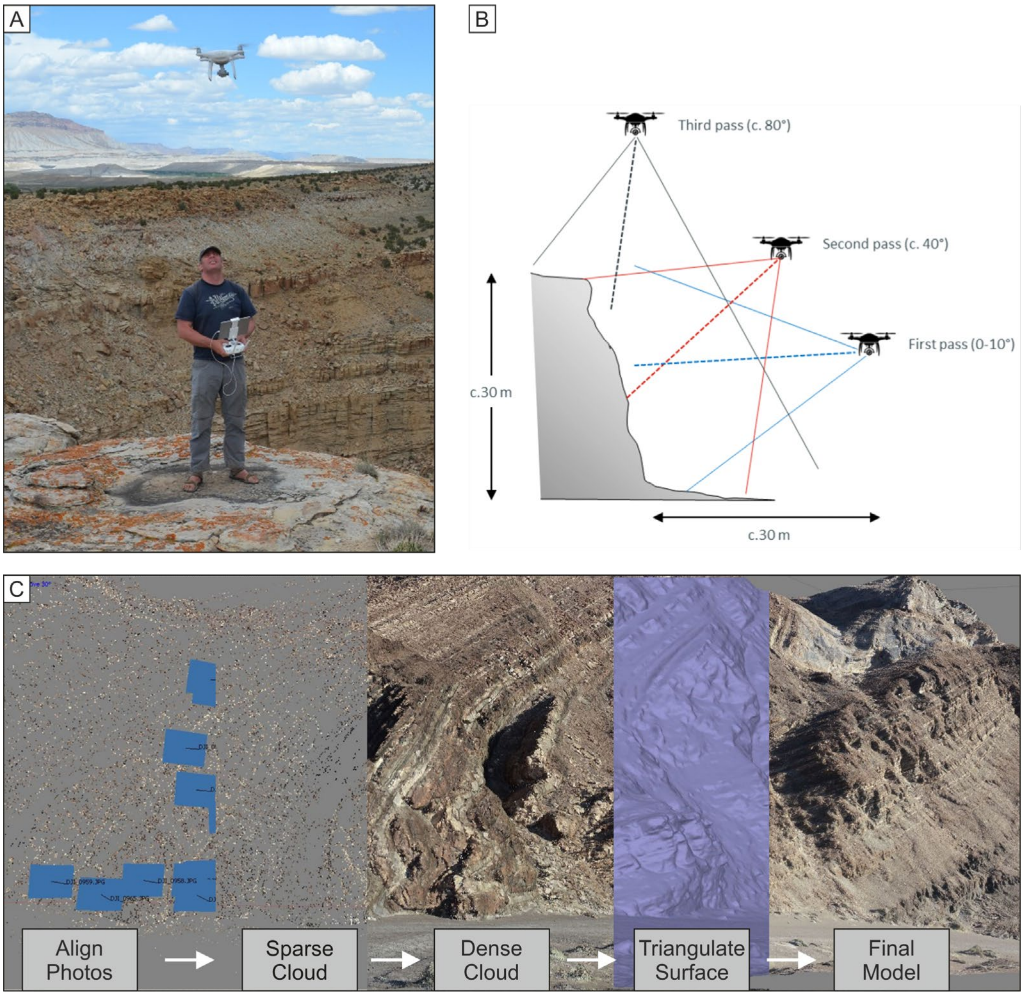

Figure 2. Data acquisition and processing using a UAV and SfM. A. Operator flies the drone along the outcrop. B. A series of overlapping photographs are taken from a variety of angles to ensure good coverage of the outcrop. C. Processing in Agisoft Metashapes software. The photos are loaded and aligned; this is aided by the internal GPS positioning of the camera. A series of common points are selected to create a "sparse point cloud. This is then used to create the "dense" point cloud which is then triangulated to create a meshed surface. Finally, a texture from the original images is created and draped to create the virtual outcrop.

The Future

Virtual Geoscience is in its early days; as more people adopt the technologies, significant advances will come. During the 2020/21 Covid pandemic, Virtual Field Trips based upon virtual outcrops became a key part of geoscience teaching. Virtual Reality (VR) (Fig. 3A), Machine Learning and automated interpretation using Artificial Intelligent systems on vast datasets (Big Data) are coming. V3Geo.com, the first public cloud-based repository specifically developed for virtual outcrops, was launched in 2020, and more are coming. Virtual outcrop technologies are fundamentally changing how we do field geology; the future (Fig. 3B) is once again very exciting!

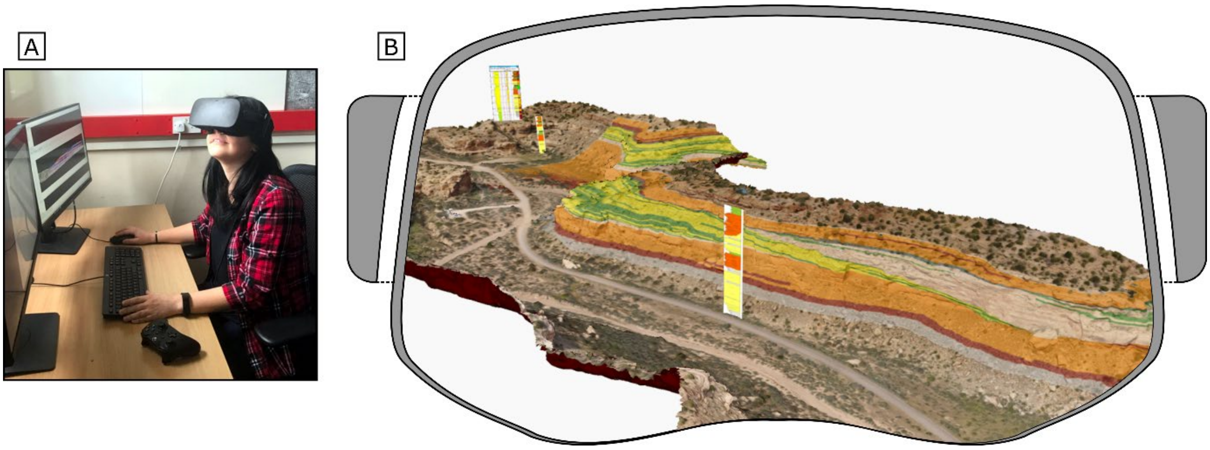

Figure 3. Virtual Reality of outcrop models. A. Geologist using a VR headset to view a virtual outcrop in an immersive 3D environment. B. Approximate user's view of a virtual outcrop in VR.

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