Virtual Fieldtrips Utilising Virtual Outcrop: Construction, Delivery, and Implications for the Future

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Abstract

The advent of photorealistic, 3D computer models of cliff sections (virtual outcrops) has significantly improved the immersive nature of virtual geological fieldtrips. As the COVID-19 pandemic led to widespread national and international travel restrictions, virtual fieldtrips (VFTs) became a practical, and essential substitutes for traditional fieldtrips and accelerated the development of VFTs based on virtual outcrop data. This contribution explores two such VFTs delivered to a master's level Petroleum Geoscience course at the University of Aberdeen. These VFTS are based up traditional fieldtrips that are normally run fieldtrips to the Spanish Pyrenees and Utah (USA). The paper summarizes the delivery mechanism for VFTs based on virtual outcrops and examines student perception, gauged primarily through questionnaires and learning outcomes. The VFTs were run in LIME, a software specifically designed for the interpretation of 3D models and the delivery of VFTs. Overall, the student perception was very positive and comparable to satisfaction with the conventional trips. Staff feedback and student assessments suggest that the learning outcomes were satisfied and highlights the value of this method of teaching for students who are unable to attend the field and as an additional component for those that can.

1 Introduction

Fieldtrips are a fundamental component of most geoscience degrees. Prior to COVID-19, in the UK, for a geology degree to be accredited by the Geological Society of London there was a required 60-days of fieldwork. Similar requirements exist in other countries. Significant emphasis is placed on the skills that are acquired through time spent in the field, observing rocks and structures in their natural habitat. In recent years there has been increasing recognition that, for a variety of reasons, fieldwork is not equally accessible to all students (Giles et al., 2020) and there have been increased efforts to provide digital alternatives, termed Virtual Fieldtrips (VFTs).

The term VFT has a broad range of implications and interpretations. VFTs can range from a slide-show to a Google Earth tour of localities, to a full immersive experience using 3D virtual outcrop models. The form of immersive technology can vary from desktop to VR headsets (e.g. Kippel et al., 2020) with augmented reality also emerging (e.g. Gazcón et al., 2018). Virtual fieldtrips can also be subdivided into location based or thematic trips (figure 1a). Location based trips are the most comparable to traditional fieldtrips and are based around the geology of a specific geographic area. Thematic or geographically unconfined VFTs follow a specific topic and visit outcrop examples from several distinct locations. These are more similar to traditional classroom taught course but are augmented with outcrop examples from across the World .

Virtual fieldtrips can be further subdivided based upon the degree of tutor involvement at the time of delivery (figure 1 b).There is a spectrum of trip types which range from real-time tutor-led through to releasing students into an immersive space and allowing them to explore for themselves, in their own time. The different trip types may be more suited to specific topics, particular learning outcomes and the level of student experience.

A virtual outcrop (VO), sometimes called digital outcrop model or virtual outcrop model, is a photorealistic model of a geological outcrop. Virtual outcrops first appeared in the late 1990s (Xu et al., 2000) and became more popular with the advent of LiDAR (Light Detection and Ranging) (Bellian et al., 2005; Pringle et al., 2006; Buckley et al., 2008; 2013). Over the last eight years there has been a proliferation of virtual outcrops due to the dual emergence of remote piloted vehicles (RPVs, commonly termed drones) and structure from motion (SfM) photogrammetry (Buckley et al., 2016; Harrald et al., 2021; Howell et al., 2021). Together these two technologies have made virtual outcrops widely available across the geosciences.

Virtual outcrops have traditionally been used for research purposes (e.g. Enge et al., 2010; Rittersbacher et al., 2015, and many others). In recent years, virtual outcrops have started to be used in virtual fieldtrips (VFTs) (e.g. Argles et al., 2015; Tibaldi et al., 2020; Bond and Cawood, 2021; Gregory et al., 2021) although their acceptance has yet to become widespread, and they are typically used to provide supplementary material. Even during the COVID-19 pandemic the VFTs run by many groups did not contain VOs, instead others employed conventional teaching methods (slides, powerpoint etc) or Google Earth and/or GIS tools (e.g. Whitmeyer and Dordevic, 2020; Bosch, 2021; Barth et al., 2022).

To date there has been little systematic evaluation comparing virtual outcrop based VFTs and real-world fieldtrips with similar conditions, primarily because of the logistical challenges of running parallel trips under controlled experimental setups. The onset of the COVID-19 global pandemic and associated lockdowns from March 2020 forced the implementation of VFTs on a far broader scale and created the opportunity for such studies. Within this contribution we examine the outcomes of two VFTs that were run as replacements for traditional field courses on the Integrated Petroleum Geoscience (IPG) MSc classes of 2020 and 2021. The VFTs ran in real-time over eleven days (Utah) and five days (Pyrenees). They were based on well-established traditional trips to Utah and the Spanish Pyrenees. The Utah course has run for over 25 years and the Pyrenees trip has run in various forms since 2010. The VFTs were built on an extensive set of VOs and other data collected by the authors for research purposes over the last 15 years (e.g. Eide et al., 2015; Howell et al., 2014; Phillips et al., 2021). The Utah VFT was run twice (Sept 2020 and August 2021) and the Pyrenees VFT was run in October 2020.

The aim of this contribution is to summarise the learnings from these VFTs to help ensure that future VFTs are more effective at achieving the similar learning outcomes to traditional fieldtrip. The specific objectives are: (1) to present the workflow for building and running VFTs developed by our research group over the past 5 years; (2) assess the effectiveness of VFTs through student interaction; and (3) review student perception of VFT and how this compared to the traditional fieldtrips.

2 Previous work on VFTs

The concept of teaching geological field skills in a virtual environment is not new (Hurst, 1998; Stainfield et al., 2000), however, over the past decade VFTs have become increasingly popular reaching a pinnacle during the COVID-19 pandemic. The advantages and disadvantages of traditional VFTs are well established, with numerous studies discussing the benefits and challenges of their delivery and reception. However, the developments in virtual outcrops and associated platforms (e.g., LIME, Buckley et al. 2019)) and cloud hosted web viewers (e.g. V3Geo, Buckley et al 2022), and the advent of immersive reality and VR headsets, illustrate that this field is advancing rapidly.

2.1 Advantages of VFTs

VFTs enable a larger volume of data to be presented at varying scales from the small (e.g. scanning electron microscope (SEM) images, thin sections and hand samples) to the large scale (e.g. virtual outcrops, DEMs and maps) (Hurst, 1998; Arrowsmith et al., 2005; Atchison and Feig, 2011; Çaliskan, 2011; Bailey et al., 2012). This range of data is linked to enhancements in 3D understanding (Hurst, 1998; Bond and Cawood, 2021), a key skill within geoscience. VFTs also have the capacity to be geographically independent (based on a common theme) and permit a higher number of individuals to join (Stainfield et al., 2000; Dolphin et al., 2019). They are also financially inclusive as they reduce the financial burden associated with travel (Stainfield et al., 2000; Fletcher et al., 2002; Ramasundaram et al. 2005; Jacobson et al., 2009; Litherland and Stott, 2012; Dolphin et al., 2019). They are weather independent (Dolphin et al., 2019), resulting in them being logistically easier to plan, deliver and timetable (Hurst, 1998; Peat et al., 2005; Butler, 2008), as well as being associated with lower carbon emissions (Schott, 2017). Largely owing to the absence of travel time, VFTs are also typically time efficient (Ramasundaram, et al., 2005).

VFTs offer inclusivity not only to individuals with restricted physical access (Stainfield et al., 2000; Atchison and Feig, 2011; Çaliskan, 2011; Dolphin et al., 2019), but also for students who require increased time flexibility, owing to learning difficulties or mental health (Fletcher et al., 2002; Arrowsmith et al., 2005; Kingsbury et al., 2020). VFTs also cater for those with other time commitments such as part-time work or childcare, as well as allowing individuals to revisit localities to cement learnings (Hurst, 1998).

2.2 Disadvantages of VFTs

Several disadvantages are routinely recited including a loss in social cohesion (Butler, 2008; Dunphy and Spellman, 2009), as individuals are typically unable to interact with peers and staff in an informal and flexible manner (Hurst, 1998). Within a virtual context the experience of travel, outdoors and nature is lost (Bellan and Scheurman, 1998) and sensations such as sound and smell are absent (Hurst, 1998). Embodiment is key within fieldwork (Clark, 2011; Hutchins and Renner, 2012; Mogk and Goodwin, 2012), which may be difficult to achieve within a VFT as an individual may not relate the scale of the landscape to their own body (Hurst, 1998), however, this can be improved with 360 photo spheres and immersive headsets (Klippel et al., 2019). Certain aspects of traditional field training are difficult to replicate (Hurst, 1998; Arrowsmith et al., 2005) such as use of a compass clinometer. As VFTs are typically computer based, IT issues can be a concern to many who may have unequal access to computers and the internet (Cliffe, 2017). Furthermore, the increased cognitive load associated with learning new software during a VFT has the potential to detract from the desired learning outcomes (Petersen et al., 2020).

Ultimately, there are numerous reservations about the ability of VFTs to replicate the cognitive, affective, and psychomotor skills acquired during traditional fieldwork (Bloom, 1965; Krathwohl et al., 1973; Mogk and Goodwin, 2012 Arrowsmith et al., 2005).

3 Learning Objectives and Planning

3.1 Initial Learning objectives

Prior to travel restrictions in response to the COVID-19 pandemic, the two fieldtrips in this study were run to provide field experience covering a wide range of geological aspects required for a broad training in Petroleum Geoscience. The trips were designed to complement each other and "bookend" the one-year MSc programme. In a typical year the Pyrenees trip ran near the start of the academic year (October) and Utah came at the end of the taught component of the MSc course in April. The Pyrenees trip deals with compressional tectonics, foreland basins, carbonate sedimentology, and deep-water clastic depositional systems. The Utah trip covers extensional tectonics, rift basins, salt tectonics, fluvial, aeolian and shallow marine depositional systems and igneous rocks in a petroleum context. Both courses use a series of exercises that draw on the observations in the field to simulate petroleum exploration and production scenarios. Students typically work in groups (4-6 individuals) and present results back to the course tutors and the rest of the class. The importance of teamwork was emphasised to the students, as recommended by VFT literature (e.g. Arrowsmith et al., 2005; Dolphin et al., 2019). The goals of the VFTs were to recreate the format of the traditional trips and to achieve the same learning outcomes.

3.2 Student learning outcomes and assessment deliverables- Pyrenees Fieldtrip and VFT

The first trip in the academic year was based on data from the Spanish Pyrenees. The VFT was a direct, real-time replacement for the traditional trip, with the same student learning outcomes. On completion of the fieldtrip or VFT students should be able to understand

1. the fundamentals of compressional tectonics and how the relate to the formation of foreland basins.
2. the formation of traps.
3. depositional models for deep water slope turbidite systems and how they impact heterogeneity in reservoirs.

4. depositional models for carbonate systems within a tectonically active foreland basin.
5. the interaction of tectonics and sedimentation in a compressional setting.
6. the formation and fill of structurally controlled mini basins and the 3D variability of basin fill.
7. petroleum system and play mapping.
8. the structural and stratigraphic evolution of the south Pyrenean foreland basin.

Deliverables:

- A group presentation detailing the petroleum perspectivity of the study area, including common risk segment maps for a variety of play types.
- A recommendation for future exploration activity.
- A compilation (Facies Atlas) of sedimentary geobodies that could form potential hydrocarbon reservoirs (for example mouthbar; channel fill; aeolian dune), that summarises their diagnostic criteria, sedimentary structures, dimensions, petrophysical properties and relationship to surrounding deposits.

3.3 Student learning outcomes - Utah Fieldtrip and VFT

The second trip of the academic year is Utah. The virtual version of the trip ran twice because lockdown occurred mid-way through the year learning outcomes and deliverables include ~~, again, with~~ the same student learning outcomes as the traditional trip. On completion of the VFT students will be proficiently in understand

1. depositional systems in rift basins with special reference to the key elements of petroleum systems.
2. sequence stratigraphy of shallow marine and paralic depositional systems, including understanding the importance of depositional process in controlling reservoir architecture and distribution.
3. field development planning in a shoreface/estuarine depositional system.
4. the DFS model as a predictive exploration tool in fluvial systems.
5. how to identify and the significance of large sandstone-dominated meanderbelt systems.
6. how intrusive igneous can effect petreoleum systems, with analogues for the West of Shetland area and the Norwegian Atlantic margin.
7. salt-related fluvial systems and the interplay of depositional systems and changes in accommodation ~~creation.~~
8. extensional tectonics and relationships between zones of fault interaction and their reservoir impacts.
9. the geological evolution of central Utah from the Permian to the present day.

Deliverables:

- An exploration play summary exercise, including group presentations on the plays and perspectivity of the Salt Lake Basin.
- A field development plan for an estuarine and shoreface reservoir system.

- Prospect evaluation exercise for the salt related fluvial systems in the Chinle Formation.
- An evaluation of the key exploration plays in the Salt Valley Anticline area, including integrating seismic, well and outcrop data, in order to produce a full economic evaluation and recommendation for drilling wells.
- Continued work on the Facies Atlas of sedimentary geobodies started in the Pyrenees.

3.4 VFT Planning

After the cancellation of the Utah 2020 April fieldtrip, the members of staff responsible for the course met to discuss alternatives. Given the prior experience in virtual outcrop geology and the access to public (V3Geo.com; Buckley et al., 2022) and proprietary (www.safaridb.com) datasets of virtual outcrops, both of which link to the LIME software (LIME, Buckley et al., 2019) it was a natural decision to run a VFT using virtual outcrops.

The process of building a VFT is summarised in Figure 2 and can be broken down into the following stages:

1. VFT Scope – decide on desired learning outcomes of the fieldtrip. VFTs can be thematic, such as examining a specific geological phenomenon from outcrops across the world or, location based, visiting a specific geographic area. The VFTs described within this study are all based directly on previous fieldtrips and are therefore, location based.
2. Build a story board – decide on the narrative of the trip using the learning outcomes. Agree on the type and rough volume of data required. Data include virtual outcrops, sub-regional DEMs, figures, traditional field data, subsurface data, photos, satellite images, video clips, 360º photo spheres and links to external resources such as gigapans, videos and Google Street View. An example template of a storyboard is shown in Figure 3.
3. Compile Data – sort internal resources into folders or upload online to reduce file size, such as videos. Compile Uniform Resource Locators (URL) of external resources such as Google Earth Engine in a database such as a spreadsheet, or saved web browser, for future reference. Unify coordinate systems for the spatial/georeferenced data.
4. Build the VFT – in this case we used LIME (Buckley et al. 2019). Separate projects were compiled for each day. A summary of the data used is provided in Table 2.
5. Distribute the LIME files and supporting material. Supporting materials include the field guide, work sheets and maps. In this case files were uploaded the day before each day of the trip within Blackboard Learn (blackboard.com).
6. Assess the effectiveness of VFT – assess effectiveness throughout VFT with regular end-of-day discussions, perform after action review at end of VFT, run questionnaires for student feedback. Using the acquired assessment, student feedback and staff experience, improve the VFT.

Across both VFTs, there were two days were there was insufficient virtual outcrop data at a large enough regional scale to meet the Learning Outcomes, so Google Earth was used instead of LIME. Building the VFTs took a total amount of time of two months for the Utah trip and about a month for the Pyrenees VFT, four staff members divided the workload.

3.5 Demographic and setting

All students were enrolled on the GL5013 course, Professional Skills incorporating International Field Trip, of the Integrated Petroleum Geoscience (IPG) MSc. Table 1 outlines the demographic and setting of students that attended the VFTs. Prior to the COVID-19 pandemic the 2019-20 class attended the Pyrenees as a traditional fieldtrip. However, as a direct result of the COVID-19 pandemic many students returned home and the whole class joined the VFT remotely in September 2020. By October 2020 and August 2021, the relaxations in COVID-19 related restrictions allowed students to attend the Pyrenees 2020 and Utah 2021 from on-campus computer rooms. Across the three VFT's a general trend of improved average WiFi speeds was observed. WiFi speeds were monitored by staff through blackboard learn, and students that had poor internet were offered a free wireless internet dongle for the duration of the VFT, however, no participants accepted the offer. Generally, there were few internet related issues.

Table 1: Demographic and setting information across the VFT's.

	Class 2019 -20	Class 2020/21	
	Utah 2020	*Pyrenees 2020*	*Utah 2021*
Student Participants	30	23	
Female Students	37.5%	43%	
Male Students	62.5%	57%	
Working remotely*	100%	64.8%	42.1%
Working on Campus*: Using University PC	0%	35.2%	57.9%
Remote working: Using VDI	56.5%	33.4%	26%
Remote working: Using students PC/laptop	43.5%	31.4%	15.8%
Poor WiFi (≤5Mbps)	4.5%	0%	15.8%
Adequate WiFi (6-35Mbps)	45.5	24%	2.6%
Good WiFi (≥ 36Mbps)	50%	76%	81.6%

4 Fieldtrip Software and Applications Overview

4.1 3D Software: LIME

The main software that was used for building and delivering virtual fieldtrips was LIME (Buckley et al. 2019). LIME is a high performance, lightweight 3D software for visualising, interpreting, and presenting 3D models and associated data (Buckley et al., 2019). The LIME 2.2.2 version of the software was used for all VFTs, it was the newest version at the time of VFTs. LIME was originally created as a simple-to-use software for geoscience application primarily for navigating, measuring and interpretating large LiDAR derived virtual outcrops (Buckley et al., 2019). The rapid expansion of virtual outcrop geology amplified demand for 3D software tailored to geoscience (Buckley et al., 2019), and over the past decade LIME has advanced to facilitate co-visualization of a wide range of data types in addition to virtual outcrop. Such supplementary spatial and non-spatial data include:

- *3D Models:* these include virtual outcrops and other 3D models such as DEMs, hand samples and models commonly used as scales (e.g. Car, Human or 10 m Measuring Pole).
- *Lines:* for interpretation lines, mapping contacts and measuring distances.
- *Planes:* for correlation and extrapolation of surfaces away from the virtual outcrops and for measuring strike and dip
- *Panels:* Panels are 2D planes in 3D space onto which image files can be draped. They serve as "billboards" in the virtual space. They can be used for maps, cross sections, subsurface data, satellite images, explanatory figures, and a host of other uses in the VFT.
- *Points:* are 1D pins in 3D space. They can be used as place markers, and they can also be used as hotlinks to launch other material. That material can be internal data such as photos, figures, videos, audio that are stored locally within the project, and external data such as Gigapan, 360° photos spheres, Google Earth Engine, Google Street View, YouTube etc. that are accessed via weblinks from the internet.

LIME allows users to store "custom views" and compile them into a storyline, which allows the course leader to build a narrative through the VFT. The VFT Storyline functionality, used extensively in this contribution, enabled pre-assigned views and animation paths. The views enabled the display of chosen material (models, lines, panels, points and planes) to be stored and accessed in order. The VFT Storyline works as a guide for both staff and students when presenting or exploring within LIME. Students navigate between views, ensuring a consistent and streamlined learning experience, through the display of specified material. Each view is created prior to the VFT with chosen models and supplementary material, providing participants a virtual replacement of locality stops, as well as regional context of those stops.

A typical virtual outcrop will contain around 0.5 – 1 GB of data and a typical one-day virtual fieldtrip may contain 5 or more virtual outcrops and could easily require 10 GB of diskspace. This is prohibitively large for downloading and storing for most students (and users in general). To reduce file- and transfer-size all virtual outcrops were first converted to multi-resolution tiled models and stored in the cloud. When building the virtual fieldtrip they are imported into LIME via the 'Import From Cloud Source' function. This ensures that only the data that are required for a specific view are downloaded and this happens in real time, whilst viewing (Buckley et al. 2019; Buckley et al., 2022). The cloud storage solutions include V3Geo (V3Geo.com), a public repository of virtual outcrops (Buckley et al., 2022) and Safari (safaridb.com) a proprietary database using a similar application programming interface (API). Students were given access to both databases of outcrop analogue data (Howell et al., 2014). The result is that the LIME project folder that is distributed to the students only contains the "other data" (points, lines and images) and is typically a few tens of megabits in size which is manageable for the students to download and store.

4.2 Additional Software: Google Earth Pro

Since the launch of Google Earth in 2005, it has been regarded as a powerful geological resource for teaching and research (Lisle, 2006) and has been used within the curriculum of many universities (e.g. Whitmeyer et al., 2009; Monet and Greene, 2012; Giorgis, 2015; Rotzien et al., 2021). Google Earth Pro, the desktop version, allows users to run the application from their own computer, provided they have the minimum system requirement of 2GB (RAM). Given the integral role Google Earth and Google Earth Pro play within many Geoscience degrees, the onset of the COVID-19 pandemic led many universities to partially or fully replace their field trips with Google Earth-based alternatives (e.g. Evelpidou et al, 2021; Bosch, 2021).

The VFTs presented here included virtual field days run within Google Earth Pro. On virtual field days where large regional areas were studied, including the first day of Utah, Google Earth Pro provided a regional overview to tasks set around Salt Lake (covering an area of >20,000km^2). As Google Earth provides high-resolution satellite imagery draped onto a digital elevation model (DEM) it was particularly useful for regional geology days. Additionally, certain tools within Google Earth Pro were used, including the 'Show Elevation Profile' on a delineated path, offering a cross sectional profile of the topography. This tool provided an immediate foundation to cross-section construction or discussion.

A limitation of Google Earth is that most of the imagery is nadir (taken from overhead looking vertically down) and is draped onto a DEM of varying resolution. This results in cliff lines and outcrops being poorly rendered and smeared (Yu and Gong, 2012). This is partially mitigated where Google has integrated additional data in the form of "3D buildings". This data layer has been gradually implemented since 2012 and uses data from low angle aerial photogrammetry to provide additional detail of vertical features. It is primarily applied to cities but is increasingly being implemented in areas of "public interest" such as national parks (Google 2021), therefore, coverage of geological interest areas is typically limited. Despite this, image quality and 3D rendering are very good and the layer provides an excellent alternative to virtual outcrops if they are not available.

4.3 Delivery Platform: Blackboard Learn

For the past 12 years, Blackboard has been employed as the digital learning platform at the University of Aberdeen. Pre-COVID-19, Blackboard Learn was primarily used for file sharing and assessment submission; however, in March 2020 it became the primary platform to run live lectures and practical's within the 'Virtual Classroom'. The virtual classroom also provided a record function, which enabled all days to be recorded for inclusivity of students. Blackboard Learn offers a host of teaching tools including Breakout Groups for participant interaction, polling to enhance engagement (see Figure 4), file sharing, and a whiteboard for annotated sketches and discussions. Blackboard also rates the WiFi quality of attendees, providing a visual and numerical indication of individuals who may be experiencing poor connection. All students and staff had access and familiarity with Blackboard Learn and therefore it was selected as a platform to run the VFTs.

4.4 Virtual Desktop Infrastructure

LIME, and to a lesser extent Google Earth, require PCs with a moderate to good processing power and moderate graphics capabilities. Whilst these are typically available for industrial/commercial consumers of VFTs, this is often not the case for all students. The University of Aberdeen runs a Virtual Desk Infrastructure (VDI) which allows students and staff to remotely log-in to a virtual computer in the University. That way the processing is handled on the virtual machine and the student's computer acts as a terminal. This allows students with low grade computers or computers that do not support the software (e.g. Macs) to run all the required software. With a reasonable internet speed (>6 Mbps) there is only a short lag time and the system worked well.

Table 2. Material displaying the breakdown of individual components for all 3 VFTs 2020

(a)

VFT Day Utah 2020	LIME or Google Earth	Models	DEMs	Photos	360° photos /Gigapan	Logs/ Wells	Satellite Images	Maps	Cross-sections	Other Figures	VFT Storyline Views
1-2. Rift basins & Exploration	GE	0	-	34	1	0	-	13	0	3	-
3. Northern Book Cliffs	LIME	3	0	43	3	13	1	1	1	7	50
4. Woodside	LIME	4	1	37	1	6	1	2	4	2	34
5. Southern Book Cliffs	LIME	5	4	28	4	12	1	3	7	2	49
6. Transgressive systems	LIME	4	1	38	2	14	4	3	2	4	28
7. Fluvial systems	LIME	5	2	45	10	14	2	2	0	2	19
8. Igneous Systems	Both	3	2	19	0	2	0	6	1	6	30
9. Canyonlands	LIME	1	-	15	3	4	-	3	1	2	-
10. Salt related systems	Both	1	2	16	2	26	0	6	8	2	-
11. Structure	Both	4	4	47	3	2	1	1	3	7	43
Total in VFT	-	30	16	322	29	93	10	40	9	37	253

(b)

Utah 2021: Days changed from 2020.	LIME or Google Earth	Models	DEMs	Photos	360° photos /Gigapan	Logs/ Wells	Satellite Images	Maps	Cross-sections	Other Figures	VFT Storyline Views
8. Salt Related systems	LIME	1	7	15	2	26	1	6	5	6	23
10. Exploration in the Salt Valley	LIME	1	0	12	10	8	3	7	0	16	74
Total in VFT	-	30	23	313	45	112	15	44	27	37	297

(c)

VFT Day Pyrenees 2020	LIME or Google Earth	Models	DEMs	Photos	360° photos /Gigapan	Logs/ Wells	Satellite Images	Maps	Cross-sections	Other Figures	VFT Storyline Views
1. Structural Transect	GE	0	-	13	5	1	-	7	1	3	-
2. Thrusts & Syn-sedimentation	LIME	3	3	32	11	9	3	9	5	3	43
3. Ebro Basin	LIME	3	4	26	2	9	2	3	1	7	39
4. Deep Water Systems	LIME	4	4	21	4	10	1	1	2	7	18
Total in VFT	-	9	11	92	22	29	6	20	9	20	100

5 Fieldtrip Design and Delivery

Prior to the running of each trip a document detailing how to operate the software used within the VFTs was digitally distributed to the participants (Supplement 1) along with a digital version of the field guide. Material for each day of the trip was typically made available around 6pm the evening before. Students were advised to download the files prior to the start of the VFT to prevent Blackboard connection issues and to ensure they wouldn't be negatively affected by slow download speeds. At the start of each day a poll was conducted to gauge whether all students had been able to download and open the material of that day. Any software issues were addressed with the aim to be resolved by a staff member ahead of assessments. All assessments were groupwork-based, students were allocated groups via a group list uploaded to Blackboard Learn. Groups were allocated by the same process as traditional fieldtrips, at random with some minor modifications to ensure equal ability and diversity.

5.1 Utah VFT: Outline

Direct replacement of a traditional trip lasted eleven days (2020) and ten days (2021). A separate LIME project was built for most of the days. The Utah 2020 data is outlined in Table 2 (a), with minor improvements made to most days on the Utah 2021 VFT based on the after-action review and student feedback. The days that changed significantly between 2020 and 2021 are outlined in Table 2 (b). Over the Utah VFTs, an average of 30 virtual outcrops, 16 DEMs, 318 photos, 101 logs/wells and many other data were used (see table 2). The volume of material provided to the students was well received and staff were confident that most students utilised the material to emulate the practices undertaken on traditional fieldwork. Supplement 2 provides a list of publicly accessible V3Geo virtual outcrops used during both VFTs.

The first two days of the Utah VFT examined modern basin and range tectonics around the Great Salt Lake, which were run from Google Earth Pro and culminated in an exploration play mapping exercise. Day three centred around the northern Book Cliffs and focused on shallow marine sedimentology (shorefaces and river-dominated deltas) and sequence stratigraphy (Howell and Flint, 2003; Enge et al., 2010; Enge and Howell, 2010). Day four was focused further south in the Book Cliffs, in Woodside Canyon and examined a tidal estuarine package interpreted as an incised valley complex (Howell and Flint, 2003; Sømme et al., 2008; Howell et al., 2018). The VFT continued south in the Book Cliffs for day five, focussing on sequence stratigraphy and correlation in shoreface parasequences within the section directly north of the town of Green River in the morning (Pattison, 1995; Eide et al., 2015; Jackson et al., 2009). The afternoon of Day 5 was spent at Thompson Canyon (Van Wagoner 1995) where the students completed a field development exercise. All Book Cliffs days used a series of large scale (kms) virtual outcrops and were run within LIME.

For day six, the field trip looked at older Cretaceous stratigraphy along the western side of the San Rafael Swell, including the transgressive deposits of the Dakota/Naturita system (Phillips et al., 2020) and the growth faulted, fluvial dominated deltas of the Ferron Sandstone (Bhattachraya and Davies, 2001; Enge et al., 2010; Braathen et al., 2017). Day seven compared the fluvial architecture of the incised Shinarump Sandstone at Capitol Reef with the distributive fluvial deposits of the Salt Wash Member of the Morrison (Owen et al., 2015). Special reference was made to the recognition of sand-dominated meandering systems, such as the large meander belt exposed at Caineville Wash and the Notom Road localities (Hartley et al., 2015).

Day eight discussed igneous-sedimentary interactions of the Caineville and Henry Mountain area (Horsman et al., 2005). Day nine included a traverse through Canyonlands, reviewing the stratigraphy and comparing different types of arid continental reservoirs. Day ten was a detailed study of the interaction between the Paradox salt and sedimentation within the Chinle Formation fluvial deposits (Mathews et al., 2004; Hartley and Evenstar, 2018). Day ten culminated in a major student exercise dealing with exploration in salt basins. The final day, day eleven, focused on extensional tectonics around Moab and within Arches National Park. The students visited a series of localities along the Moab Fault (Foxford et al., 1998) and at the Delicate Arch Relay Ramp (Rotevatn et al., 2009)

Utah 2021 followed a similar outline with minor changes to most days and slight changes to the running order. Three days changed considerably. Days one and two, the Rift Basins and Exploration around Salt Lake, were combined into a single day, covering the same volume of material. The Salt-elated systems day, was moved into LIME rather than using Google Earth Pro because LIME enabled better presentation of the additional data such as the sedimentary logs. The final day was a new assessed exploration exercise, which combined outcrops with seismic and well data from the Salt Valley anticline. This replaced the Canyonlands day. This exercise used LIME to combine the subsurface data with the outcrops.

5.2 Pyrenees VFT: Outline

This five-day long VFT included 30 virtual outcrops, 20 DEMs, 92 photos, 20 logs/wells and other data (see table 2c). Again, the amount of material provided to the students was well received and the extensive dataset allowed students to explore the area and apply their geological understanding to a similar extent as a traditional fieldtrip. Day one provided a regional geological overview and introduction to the structure of the Pyrenees with a transect from the axial zone to the Jaca Basin along the Hecho Valley. Google Earth Pro was implemented due to the large geographical scale of the day. Day two continued the transect south, crossing from the Jaca Basin, through the External Sierras to the Ebro Basin, along the Gallego Gorge. Here, thrust tectonics were combined with an examination of the syntectonic alluvial fans in Riglos and Aguero (Nichols, 1987). The afternoon of day two, moved to Arguis and Pico de Aguillar, where lateral changes along the thrust front and the role of salt with the detachment were discussed.

Day three considered the distributive fluvial system deposits of the Huesca DFS (Nichols and Hirst, 1988) of the Ebro Basin. Day four studied in deep water deposits of the Ainsa Basin incorporating behind outcrop wells and cores (Pickering and Corregidor, 2005; Falivene et al., 2006). The final day of this VFT, day five, was an assessed group exercise, reviewing the prospectivity of the south Pyrenean Foreland Basin and required the students to revisit all the stops we had visited previously. A summary of the VFT was presented to the students within LIME after the student group presentations on basin evaluation.

6 Methodology for Evaluation

6.1 Student Experience

Student experience was evaluated through two different questionnaires. Ethics approval was granted for all questionnaires by the University of Aberdeen. The university provides a standard form (Course Evaluation Form) that is completed after every course. These were used as they provide a benchmark to compare the VFT with the physical course over the previous five years. In addition, a specific questionnaire was conducted to provide a more detailed, day-by-day insight into the VFTs. In these, questionnaire participation was voluntary and anonymised, under university guidelines. Individuals were asked to answer a series of questions rating their experience between 1 (disagree) to 5 (agree) and provided with the opportunity to give qualitative statements to provide further information to their answers within an open text box. Supplement 3 is an example of one of these, the same format was used for all three VFTs. On the Utah 2020 VFT there was a questionnaire response of 88% (24 out of 27), Pyrenees 2020 it was 100% (23 out of 23) and Utah 2021 it was 90% (19 out of 21). Students were asked to fill out the questionnaire on the final day of each VFT, with extra time allocated to a break, individuals who wished to respond after the VFT were asked to do so within 2 weeks. Individuals that were unable to attend the full field trip due to other commitments did not answer the questionnaire; this included five in Utah 202 and two in Pyrenees 2020. A total of 66 questionnaire responses were collected.

Standardised course evaluations and questionnaires are routinely used across the academic curriculum to gauge student perception. Nonetheless, the authors acknowledge there is an issue of self-reporting (Spooren et al., 2013; Boring and Ottoboni, 2016; Esarey and Valdes, 2020). Students can only draw on their own experience and are unable to truly compare between a traditional fieldtrip and a VFT if they do not attend both. Furthermore, the notion of understanding is not a true measure of understanding, as an individual cannot evaluate the true extent of what they understand (Kuorikoski and Ylikoski, 2015). However, all students had attended a traditional fieldtrip at some point in their education, therefore each had field experience to base their opinions on. As there is not a way to truly standardise the data, the questionnaires presented are used to gauge general opinions and suggested improvements.

6.2 Activity/Attendance

Within Blackboard Learn, auto-generated reports are accessible through the *Evaluation* and *Course Reports* function. These reports provide insights into usage and student activity across Blackboard Learn. This data includes the overall time an individual spent within the course as well as information about their activity within the content area, from time to number of accesses. Each day of the VFT was also allocated its own virtual classroom, allowing reports to be run for every day assessing student attendance across the VFT. These reports were accessible to staff as an excel file or exported to CSV and the relevant data extracted.

6.3 Duration Analysis

Over the Utah 2021 VFT, activities in each day were divided into categories and timed using a digital stopwatch. The total active time within nine days was 43 hours, 40 minutes, and 8 seconds, with an additional 14 hours, 22 minutes and 11 seconds of allocated breaks (e.g. lunch), day ten was not timed due to change in plans related to COVID-19 precautions.

6.4 After Action Review

On completion of a VFT, the staff and demonstrators discussed what they felt had worked and what could be improved across the VFTs. After-action reviews took place at the end of most days and at the end of each fieldtrip. Suggestions from this after-action review and free text were noted for the Utah 2020 VFT, and where appropriate, enhancements were implemented prior to Utah 2021.

7 Evaluation Results

Questionnaires were compiled, free text comments were added to a master word document and numerical answers summed in a master excel spreadsheets. Later trips were added to the same master documents facilitating direct comparisons to be made. Numerical responses across the 3 trips were plotted and compared through box and whisker plots giving the range in responses for each trip. Blackboard Learn evaluations and course reports were compiled selecting relevant information. Duration analysis was evaluated, and averaged.

7.1 Course Evaluation Form

The course evaluation forms provided a valuable comparison between student feedback for before and during the COVID-19 pandemic. The two course evaluation forms from 2016-2017 and 2017-2018 are when both trips were traditional fieldtrips. The 2018-2019 results were unfortunately not available for analysis due to controls outside this study. The 2019-20 form evaluates the year when the Pyrenees trip ran as a traditional fieldtrip, whereas Utah ran as a VFT due to the onset of the COVID-19 pandemic. The form from 2020-21 represents the year which both trips ran as VFTs due to the COVID-19 pandemic.

Across the three questions within the course evaluation forms, a notable improvement in results is observed between the oldest (2016-17) and most recent (2020-21). With 100% of 2020-21 students totally agreeing that they enjoyed (Figure 7 b) the course, and it improved their graduate attributes/employability (Figure 7 c). 2020-21 students also all agreed that the teaching was effective with 87.5% (Figure 7a, the highest of all 4 years) totally agreeing and the remaining 12.5% agreeing. Again, while standardised course evaluations can be regarded as unreliable (Boring and Ottoboni, 2016; Esarey and Valdes, 2020; Spooren et al., 2013), this does not undermine the overwhelming positive perceptions of the students attending the VFTs. Although no precise comparisons can be made between the traditional fieldtrips and VFTs due to a change in student cohorts, the data illustrates students appear satisfied with the VFTs.

7.2 General Learning Outcomes

The questionnaire results for general learning outcomes are presented in Figure 8 (a-b). Across all three field trips an average of 94.3% of students agreed that they *had learnt new things during the VFTs*, with the remaining 5.7% scoring neutral, no student disagreed, and interquartile ranges (IQRs) all plotted between 4-5. The overarching learning outcome statement of *I have a better understanding of exploration processes* was rated mostly positive for the Utah VFTs with IQRs between 4 and 5, for Utah 2020 91.7% of students agreed and for Utah 2021 it was 89.5%. The Pyrenees IQR had a wider range from 3-5, with an average of 73.9% of students agreeing.

7.2 Trip Timing and Delivery

The statement *I liked having the fieldtrip at a fixed time* (figure 8c) scored positively across all three trips, with the Pyrenees VFT participants responding particularly positively (95.7%), with an IQR of 5. For the Pyrenees 2020 VFT there was one individual who responded negatively and the Utah 2021 VFT had two individuals who disagreed. Students across all three VFTs mostly agreed that *working in groups was better than independent working* (figure 8d). Both the Utah VFTs received particularly positive responses, with the 2020 VFT scoring 83.3% and the 2021 VFT scoring 94.7%, and remaining scores on both VFTs were neutral. The Pyrenees 2020 VFT, in contrast, exhibits a broader IQR between 3 and 5, with 4.3% disagreeing, 26.1% scoring neutral, and 69.6% positive.

The daily average time students spent within the virtual classroom across the Utah 2020 VFT was 5 hours and 49 minutes, for the Pyrenees it was 6 hours and 22 minutes for Utah 2021 it was 6 hours and 48 minutes. A breakdown of average time spent doing activities is illustrated in figure 9. Groupwork tasks (23%), LIME guided VFT (21%), independent work in LIME exploring the virtual outcrop and supplementary data (8%), and discussions (7%) formed a large portion of the work activities during the VFT and emulated similar activities of traditional fieldwork. A very small portion of the VFT was spent providing technical instruction of software, outlining assessment and presentation of external material, such as Google Earth Engine. Time spent waiting, which includes waiting for students to re-join after lunch, share screen and resolve technical issue also formed a very small proportion of the trip at an average of 3% of each day.

7.3 Software, Content, and IT

IT solutions worked for most participants across all VFTs (figure 8e). The Utah 2020 VFT had a 75% positive response (IQR between 3.25 and 5), Pyrenees 2020 69.6% were positive (IQR between 3 and 5), and Utah 2021 a higher 84.2% responded positively (IQR between 4 and 5). There were occasions where IT solutions did not work for individuals, such as for Utah 2021, an individual scored 1, however, their WiFi was negatively impacted by unexpected local issues and beyond the control of staff.

The statement *Training in Lime and /or Google Earth pro should be given before to the VFT (would require an extra day)* (figure 8f) was met with a full range of responses and wide variations in IQRs. The two VFTs (Utah 2020 and Pyrenees

2020) where most students had the highest agreeing response, with 37.5% of Utah 2020 and ~~a high~~ 65.2% of Pyrenees 2020 participants indicating they would have preferred a day of software training prior to the VFT. Whereas the Utah 2021 VFT, individuals had already attended the Pyrenees 2020 VFT, and 52.6% of individuals disagreed with the statement. Scores were consistent for the statement *I understand how to use Google Earth Pro for geology* (figure 8g), with over 80% agreeing across all VFTs.

LIME was scored positively as *a good tool for VFTs* across all three VFTs (figure 8h). 100% of the Utah 2020 VFT agreed, as did 78.3% of the Pyrenees 2020 VFT and 94.7% of the Utah 2021 VFT. Two individuals across the three VFTs disagreed, in both cases they were individuals who reported lower WiFi speeds, ~~that~~ were unable to be resolved in the VFT timeframe. The same year group who joined the Pyrenees 2020 and Utah 2021 VFT displayed a positive shift in perceptions between the two VFTs in the view of LIME as a VFT tool. The statement regarding individuals who enjoyed LIME after they became more familiar with the platform (polled as "*Once they got the hang of it*"), was also met with a mostly positive and markedly consistent response across all three VFTs. Interquartile ranges (IQRs) were consistent falling between 4 and 5, with an average of 86.5% agreeing, 5.8% neutral and 3.2% disagreeing. As a *platform to run the VFT* most agreed *Blackboard worked well* and with a consistent response across all VFTs which presented IQRs spanning 4-5 (figure 8j).

7.4 Virtual Fieldtrips vs Traditional Fieldtrips

Responses for the statement "*I learnt things during the VFT that I would not have learnt on a normal fieldtrip"* were diverse. The Utah 2020 VFT perceptions were predominately positive with 66.7% of students scoring between 4 and 5, and 33.3% were neutral, with no students disagreeing. The Pyrenees 2020 VFT presented a larger IQR range of 2-5, 34.8% of students agreed, 30.4% were neutral, and 34.8% of students disagreed. The Utah 2021 VFT also offered a large IQR range of 2.5 to 5, 57.9% of students agreed, 15.8% were neutral, and 26.3% of students disagreed.

With the statement "*I think VFTs are better than normal fieldtrips"* (figure 8l) there was a broad, predominately negative response with IQRs spanning 2-3 and 1-3, most did not agree that VFTs were better. When asked if they would rather be in Utah/Pyrenees all IQRs fell at 5 (figure 8m), with medians falling between 4.6-4.8. An average of 92.4% of students would rather be in the field, although there were some outliers. Within the free text individuals who preferred the VFT stated cost of fieldwork and accessibility as the main reasons for their scores.

7.5 Individual Days

Each VFT day was listed across all three VFTs and students were asked to score the statements *I learnt a lot from this day,* and *I enjoyed this day*. For assessed days they were asked if the *exercise worked well.*

7.5.1 Results for Utah 2020 VFT

Both for learning and enjoyment this VFT was scored positively and consistently by participants (figure 10 a and b). Ten of the days IQRs fell between 4-5 for learning, with day 11 as the exception with an IQR between 4-4.75. Enjoyment IQRs were a consistent 4-5. The average positive response across all days of this VFT was a 94.6% for learning and 90.3% for enjoyment.

7.5.2 Results for Pyrenees 2020 VFT

This VFT presented a higher range and day-to-day variation. Days 1-2 IQRs sit between 3-5 for learning, with the full range of scores represented (figure 10c). For enjoyment, day 1 scored higher than learning (figure 10d) with an IQR of 3.75-5, whereas day 2 was consistent with the learning IQR. Students were more positive about day 3-4 with IQRs for both increasing to 4-5 for learning. Enjoyment peaked on day 3 with an IQR of 4.5-5. Overall, the average positive response for the Pyrenees VFT for learning was 79.35% and 80.29 for enjoyment.

7.5.3 Results for Utah 2021 VFT

This VFT scored remarkably consistent for both enjoyment and learning presenting IQR of 4-5 for all days (figure 10 e and f). The average positive response for the Utah 2021 VFT for learning was 90.2% and 87.9% for enjoyment, a notable increase from the previous Pyrenees VFT the class attended. This increase is largely attributed to over half the class (57.9%, table 1) located on campus, where they were able to interact in person (within social distancing guidelines).

8 Discussion and Conclusions

8.1 Interpretation of Evaluation

8.1.1 Student Course Evaluation

Within the student course evaluation improvements in the student perceptions are observed from pre-COVID to during pandemic learning. This is attributed to a couple variables: firstly, the VFTs ran during or around COVID-19 lockdowns, at a time were everything was run online. Student moral was lower than a traditional year, and the students verbally expressed low expectations ahead of the VFTs. The free text comments reflect how the students felt the VFT was better than they had anticipated, with individuals stating, "overall I thought it was much better than expected", "above my expectations" and "it was far more engaging than I thought it would be, and I am surprised by how interactive it was". Secondly, students also acknowledge the quality and extent of the VFTs, with free text comments including "on the whole the class felt very positive about the trip, we were all really impressed of the example that has been set for VTF's", and "I think as a replacement the VFT was fantastic, very engaging and an exemplary substitute for the field trip". Finally, students were clearly satisfied with the content of the VFTs and felt they provided an effective teaching experience, which they enjoyed with comments including: "I actually thought I learnt more on the virtual fieldtrip as it was easier to understand the context and get my bearings" and "very enjoyable and well organized trip".

However, it is noted that while the students were positive about their VFT experience, the majority still stated they would have preferred a traditional trip physically travelling to Utah and the Spanish Pyrenees. Many free text comments reflected this including: "although I would have preferred to have been in the Pyrenees, the virtual fieldtrip was still very beneficial"; "I think everyone would much rather be in Utah for the scenery and culture but I found it easier to focus and understand on the VFT than normal", and "I think the field trip had many benefits and I did feel like I learned a lot, but I would probably preferred being in Utah". Again, this highlights the issue with standardising the course evaluation forms, as the improvements in the VFT years compared to pre-COVID traditional fieldtrip, does not appear to relate directly to the VFT, instead context of COVID and low expectations of VFT.

8.1.2 Questionnaire

Utah Questionnaire results for general learning outcomes illustrate that student attitude was largely positive, students broadly agreed that they had learnt during the VFT and developed a better understanding of exploration processes. Staff were also largely satisfied that the more specific learning outcomes had been achieved.

The structure and duration of the course was specifically designed to emulate that of a traditional fieldtrip, which worked for most participants. Students agreed having a fixed time for the VFT worked, and for those who were absent for short sections, recordings were made available. The students also agreed working in groups was particularly helpful during online learning and eased the negative impact of those with IT issues due to the screenshare function. The importance of groupwork noted within this study is in line with others (e.g. Arrowsmith *et al.*, 2005; Stumpf et al., 2008; Atchison and Feig, 2011; Lukes, 2014).

Time spent during the VFTs was used efficiently, there was little wasted time on travel etc. In the previous, real-world Pyrenees trip, a diary of time spent illustrated that an average of 3.50 hours (max 5.1 and Min 2.2) was spent travelling by coach or walking to the outcrop. There is clearly a significant time saving and this time was used on study and exercises.

IT solutions worked for most students, with only a few, mainly related WiFi, issues encountered. An average of 44.8% of students felt there was need for some training within the VFT software prior to the running of the VFTs, indicating this may be a useful addition going forward. Students were largely positive about LIME as a tool for VFTs, with the Utah 2021 VFT being particularly positive, attributed to their developed skills in using LIME over two VFTs. The use of Google Earth and Blackboard Learn were also met with a positive response by the students, but neither showed the improved metrics of LIME.

The Utah days of the fieldtrips were rated particularly consistent across the two years of delivery. Pyrenees days showed a higher level of variation, however a general increase in metrics is observed over the duration of the VFT. The Pyrenees VFT ran during the first term of the masters programme. Due to COVID-19 the students had little peer-to-peer social interaction prior to the VFT and most had never used LIME before, both possible influences on the lower scoring of days 1-2 of Pyrenees.

Within the students qualitive free text comments a consistent theme of improved 3D visualisation and geospatial understanding was often stated for the VFT relative to a traditional fieldtrip. Student comments included “I thought the VFT was much better for the regional context as well as 3D thinking”, “being able to see things in 3D and from a bird's eye view was very useful”, and “the ability to maneuverer through different scales (quickly) and around the outcrop to different angles was excellent and not possible on a normal fieldtrip”. Students also self-reported that they believed the learning outcomes were met, with comments including “definitely think the learning outcomes were achieved” and “I don’t think there were many learning objectives that could be hit any better”. However, some students expressed that they believed they would have learnt more on traditional fieldwork, with comments including “VFTs cannot fully replace learnings from the field such as small sedimentary structures”. Generally, the free text comments reflected the students opinion that the VFT is not a better experience than a traditional field, which is in line with the quantitative results. However, many stated an integration of the two (VFT and tradition fieldtrip) would be beneficial to their learning.

8.2 Implications for Future Geological Fieldtrips

The COVID-19 global pandemic has significantly increased the demand and interest in VFTs, leading to rapid developments within the field and the creation of virtual trips to numerous locations globally by a myriad of authors. While traditional fieldtrips remain the foundation of many geology degrees, we argue there is a key role for VFTs beyond COVID-19 for several reasons. Firstly, students self-reported an increased 3D and geospatial understanding within the VFT, compared to their experience of traditional fieldwork. Secondly, it is noted that many of the negative aspects of VFTs have the potential to be significantly mitigated by running VFTs in person within a classroom environment. This is illustrated by the positive increase in learning and enjoyment expressed by the students of the Utah 2021 VFT, where over half the class was able to join on-campus from the course’s designated computer room. With the whole class and staff located on-campus we would anticipate further improvement in perceptions, facilitated by peer-to-peer and staff-student interactions taking place in person. Additional benefits would include an equal distribution of IT equipment and WiFi speeds, and easier detection of students who require further assistance.

Ultimately, a blend of traditional fieldwork with VFTs, specifically virtual outcrop, would further reduce the disadvantages of VFTs. Other studies have reported similar findings with VFTs implemented as a supplement to traditional fieldwork (Litherland and Stott, 2012; Peat and Taylor, 2005), including a preview or preparation to fieldwork, or a post fieldwork overview (Hesthammer et al., 2002; Çaliskan, 2011). Within this contribution an average of 53.1% of students agreed they learnt material during the VFT that they would likely have not during a traditional trip. This further illustrates the potential scope for future implementation of VFTs, particularly during the likely digital alteration in the global working structure, with the many corporations and businesses encouraging at-home working into the future.

9. Conclusions

The VFTs presented here provided students the opportunity to observe, interpret and apply their geological understanding to a series of localities using virtual outcrop. The VFTs delivered were a direct replacement ~~to~~ traditional fieldtrips that ran prior to COVID-19. This contribution illustrates experience gained and the value of VFTs as a total replacement for traditional fieldtrips and excursions during a time when travel and social integration was restricted due to the COVID-19 pandemic. A cohesive dataset consisting of multiple virtual outcrops, DEMs, field photos, 360° photo spheres, maps, cross sections and schematic diagrams enabled students to implement many of the same skills utilised during traditional fieldtrips. Through the interrogation of student quantitative questionnaire responses, as well as their qualitive free text comments, we demonstrate that the benefits of VFTs are far reaching, with many highlighted advantages mirroring other researchers' findings. Course evaluation *improvements* were observed during the VFT years, compared to pre-COVID traditional fieldtrips, albeit ~~within~~ the prism of COVID and lower expectations of the VFT. Students nevertheless enjoyed the VFT, and staff were satisfied that the learning outcomes were achieved.

This study ultimately demonstrates it is possible to ~~fully~~ replace a traditional fieldtrip with a VFT addressing the same learning outcomes. However, true emersion within the landscape, culture, and physical outdoor environment cannot be fully recreated. We therefore argue that VFTs, with a strong virtual outcrop component, can be integrated with traditional fieldwork to deliver a best-of-both-worlds approach for geological curricula, beyond COVID-19.

Data Availability

Many virtual outcrop models presented in this paper are available on V3Geo (V3Geo.com), linked within Supplement 2.

Author contributions

JAH, AH, NS and JHP developed the virtual fieldtrips. JAH and JHP designed and distributed the questionnaires. JHP and JAH wrote the main manuscript draft. GM and RB aided in the running of the VFTs. MC was responsible for processing most of the model data used across the VFTs. JAH, SJB, and NN conceptualised the VFT tools available in LIME, which were implemented by KR, JV and the LIME team. All authors read and gave input through multiple iterations of the manuscript draft.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

The authors would like to thank all IPG Masters participants for contributing their perceptions and thoughts on the VFTs. The VOG group is acknowledged for their extensive work on virtual outcrop, as is the LIME team for developing the software and providing support through all VFTs. V3Geo is also acknowledged as a useful cloud-based platform to host many of the 3D models used within the VFTs, and the SAFARI consortium (https://safaridb.com) for hosting the remaining virtual outcrops and the support. Finally, Harry Johnson, a demonstrator on the first Utah VFT is thanked for his participation in the course and assistance in questionnaire design.

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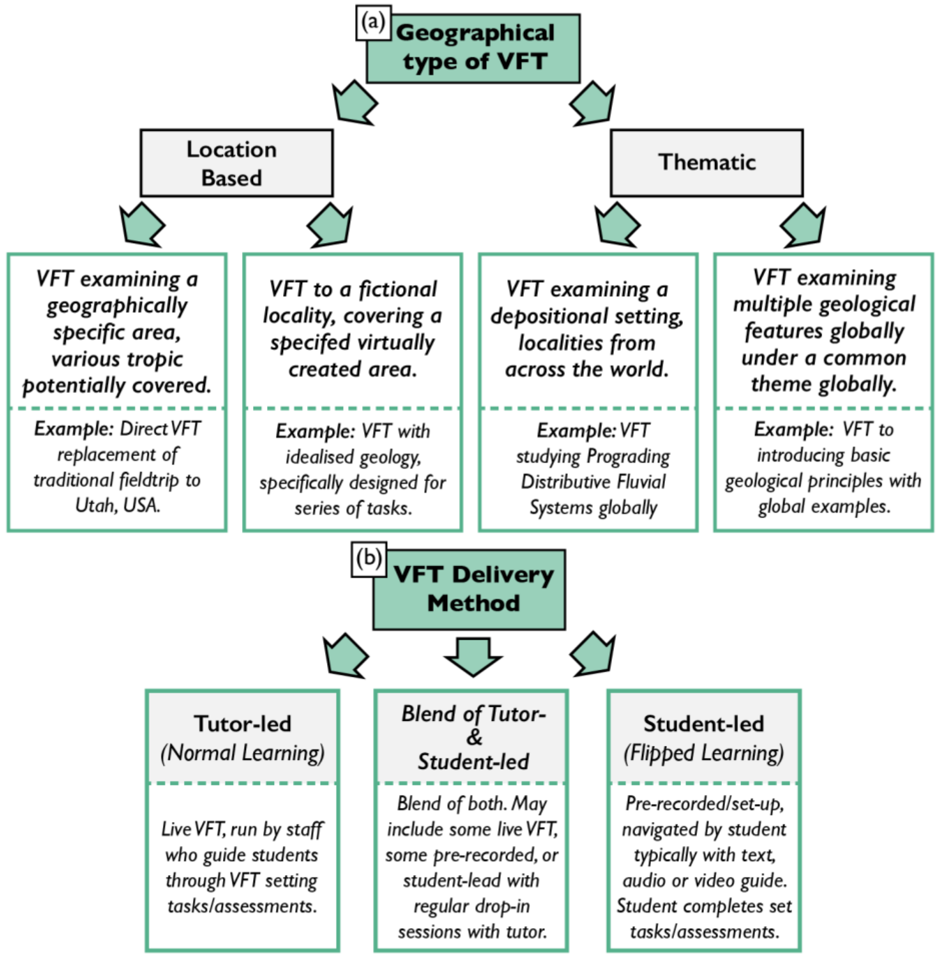


Figure 1. Outline of types and delivery methods of VFT. (a) Types of VFT separated between location-based trips to a specific locality, and thematic trips spanning global localities with a common theme. Examples given. (b) Delivery method of VFT divided between tutor-led VFTs and student-led VFTs and the blended spectrum between. Examples given.

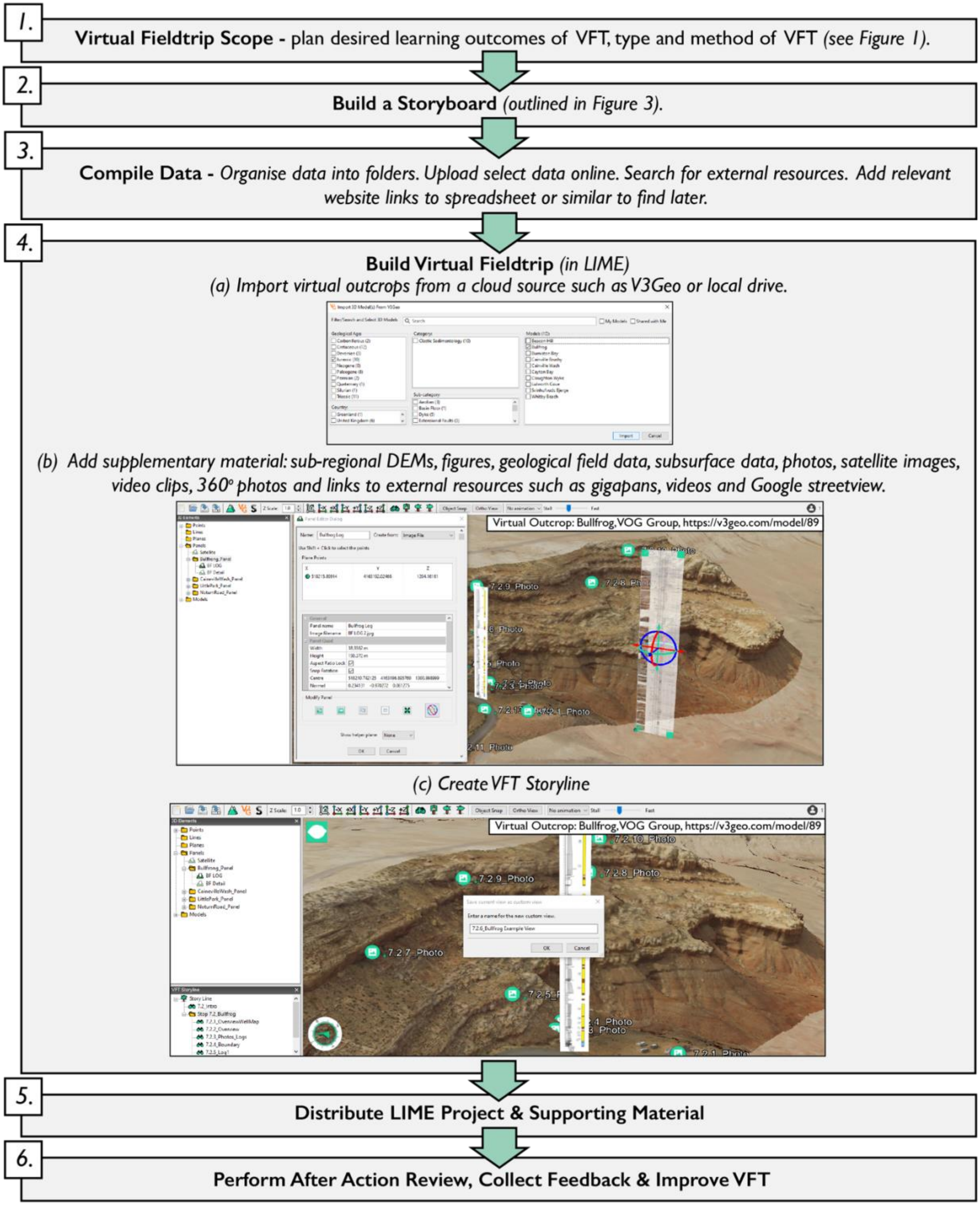


Figure 2. Proposed workflow for building and running VFTs, this workflow was followed for every VFT within this contribution.

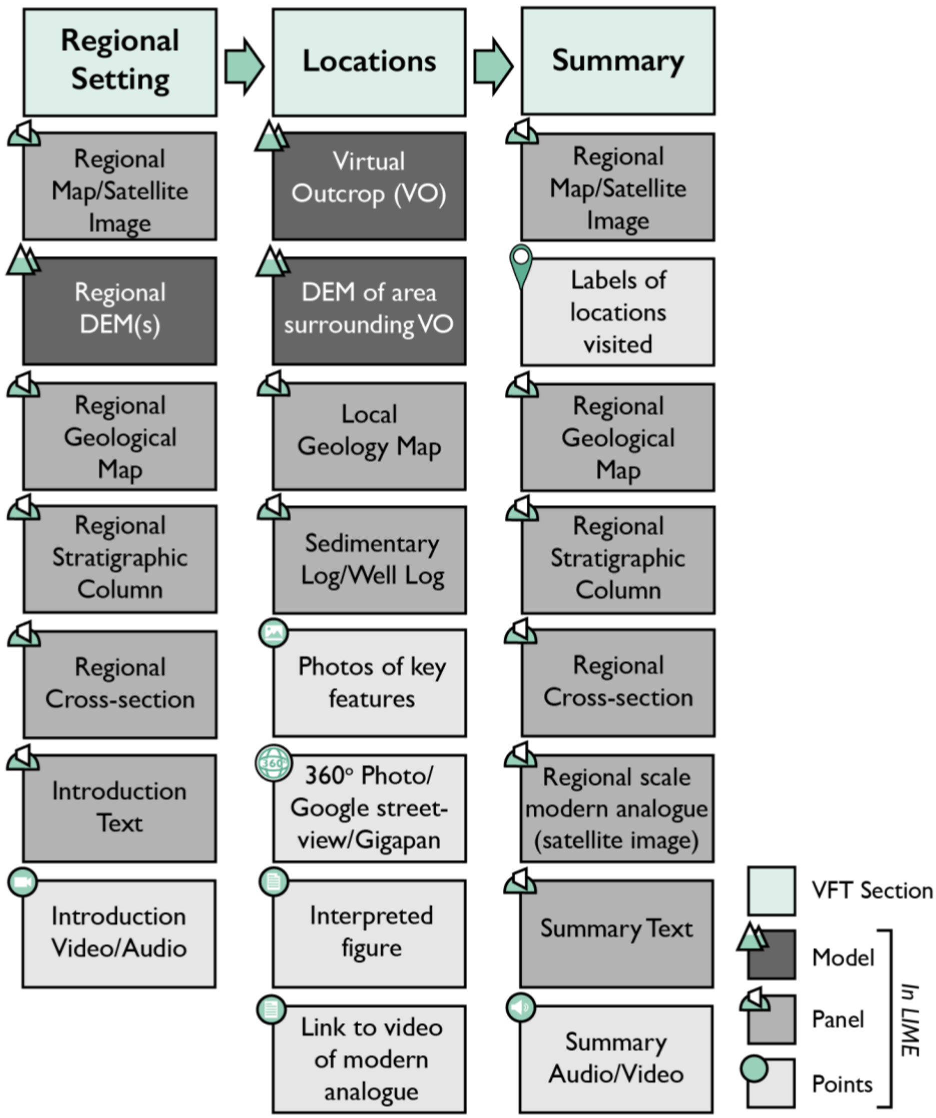


Figure 3. Template storyboard for designing a VFT. Data input within LIME indicated. Locations varied across each day of each trip, from as few as three locations to as many as eight depending on the days aims. Typically, a new location was created for each new virtual outcrop.

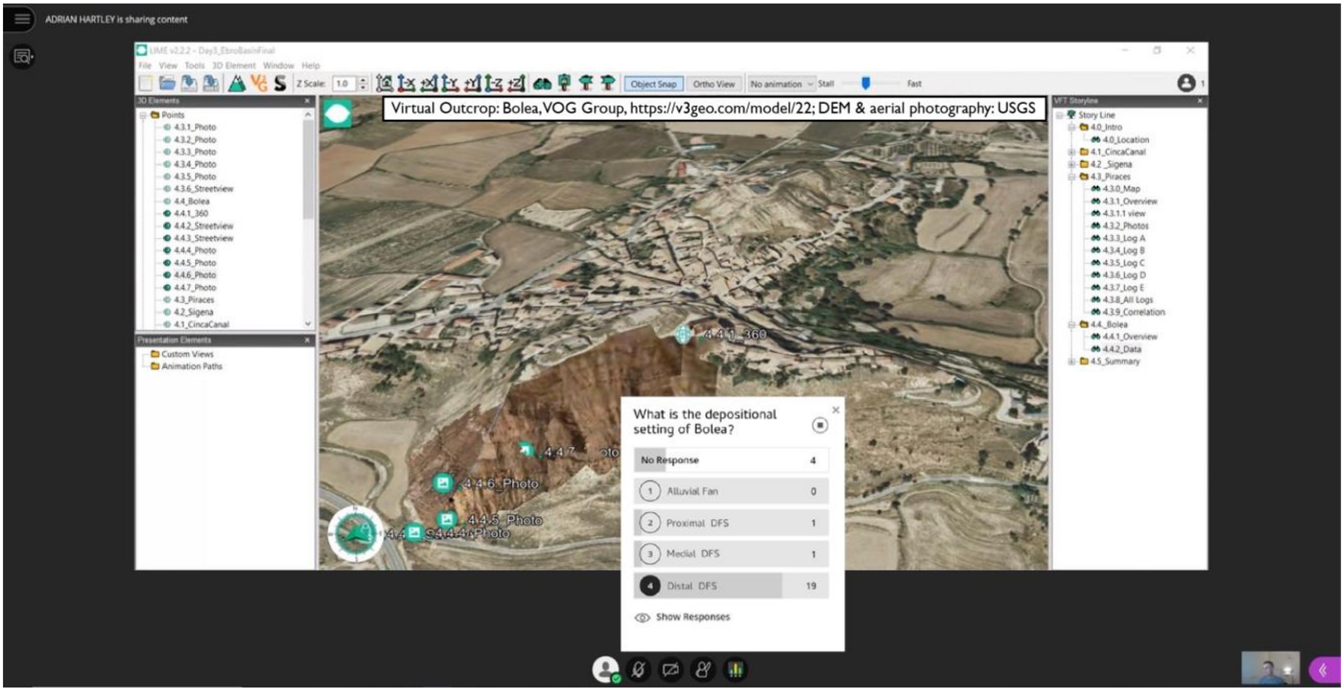


Figure 4. Bolea, Aragon, Spain, example Poll within Blackboard Learn Virtual Classroom, students asked to identify the depositional setting of locality. Virtual outcrop: Bolea, VOG Group, https://v3geo.com/model/22; Aerial Photography on DEM, USGS EROS Archive; DEM, USGS 3D Elevation Program.

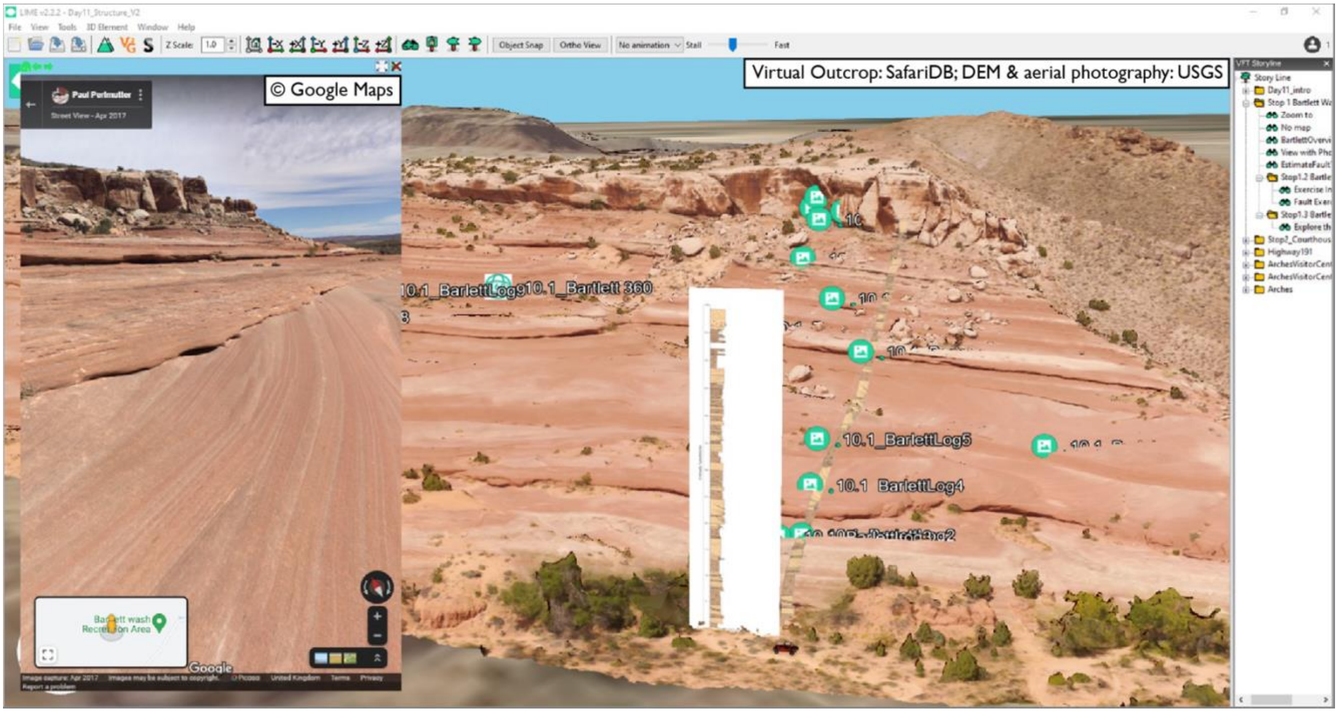


Figure 5. Bartlett Wash, Utah, USA, model available on SarafiDB. Locality task to calculate the impact of fractures on reservoir quality. Virtual outcrop from Safari and viewed in LIME with additional material including logs, photos, and 360 photo spheres (in this example from ©Google Maps). Aerial Photography on DEM, USGS EROS Archive; DEM, USGS 3D Elevation Program.

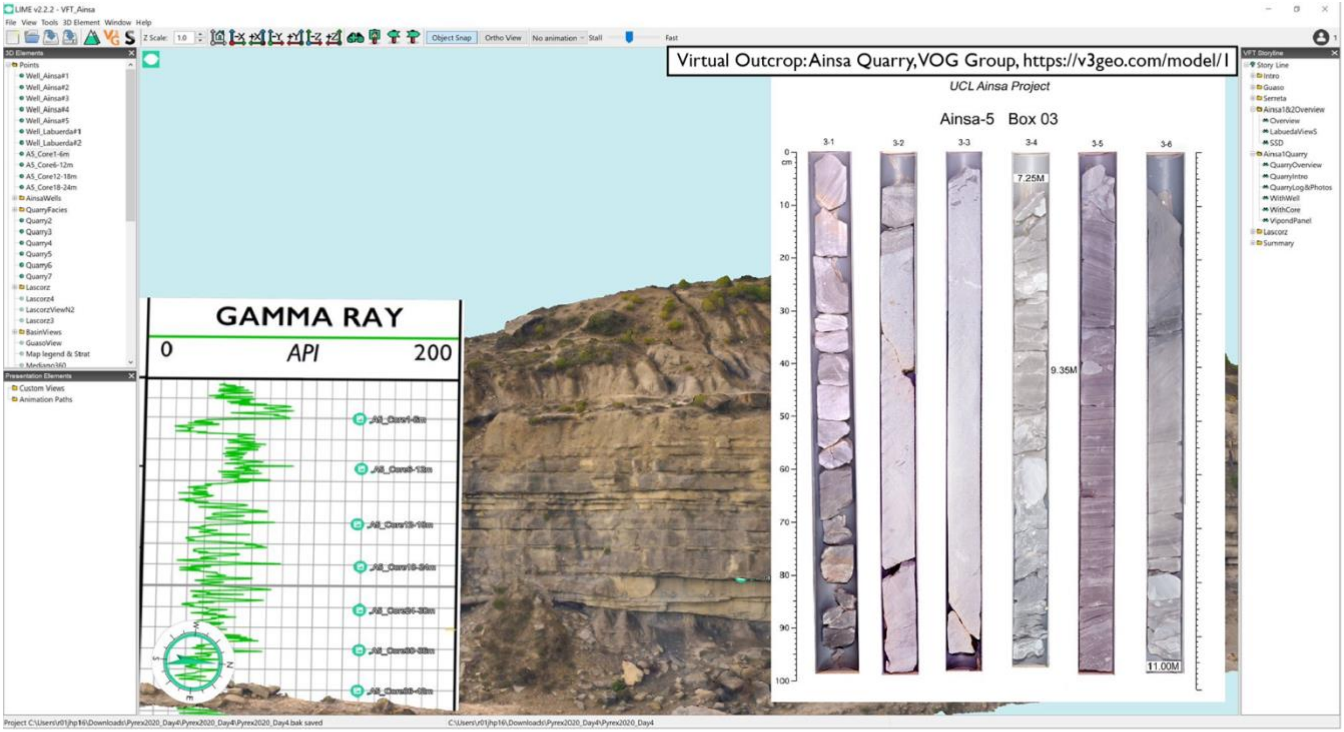


Figure 6. Ainsa Quarry, Spain, a view within the Pyrenees 2020 virtual fieldtrip. Virtual outcrop available at: Ainsa Quarry, VOG Group, https://v3geo.com/model/1, supplemented with additional material including well logs and core photos within LIME.

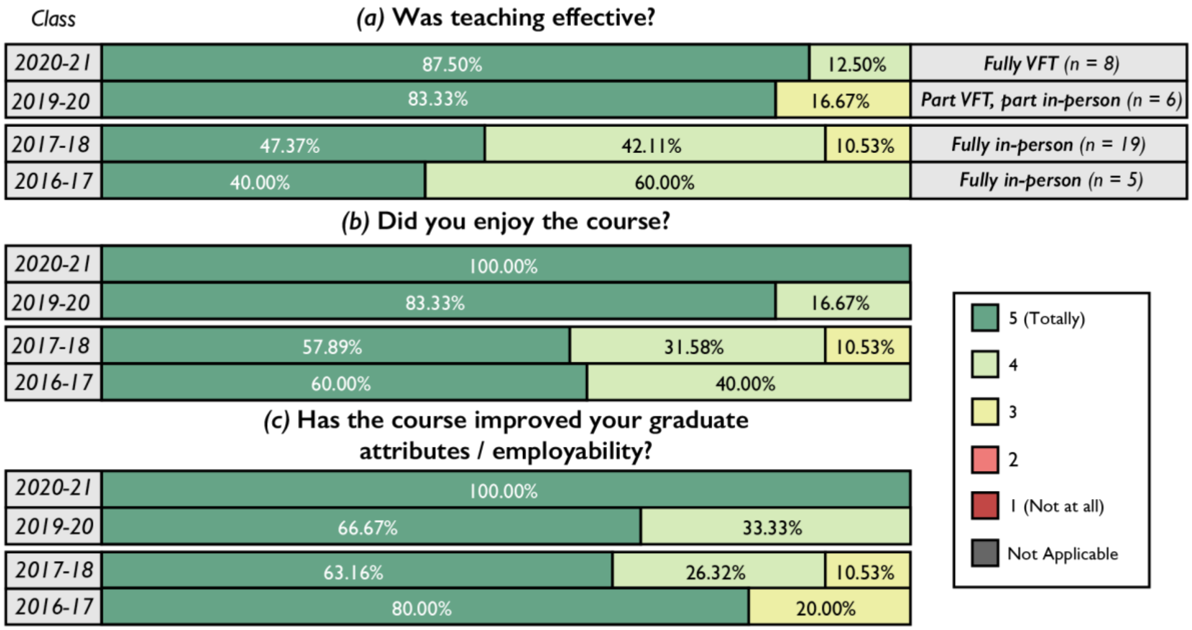
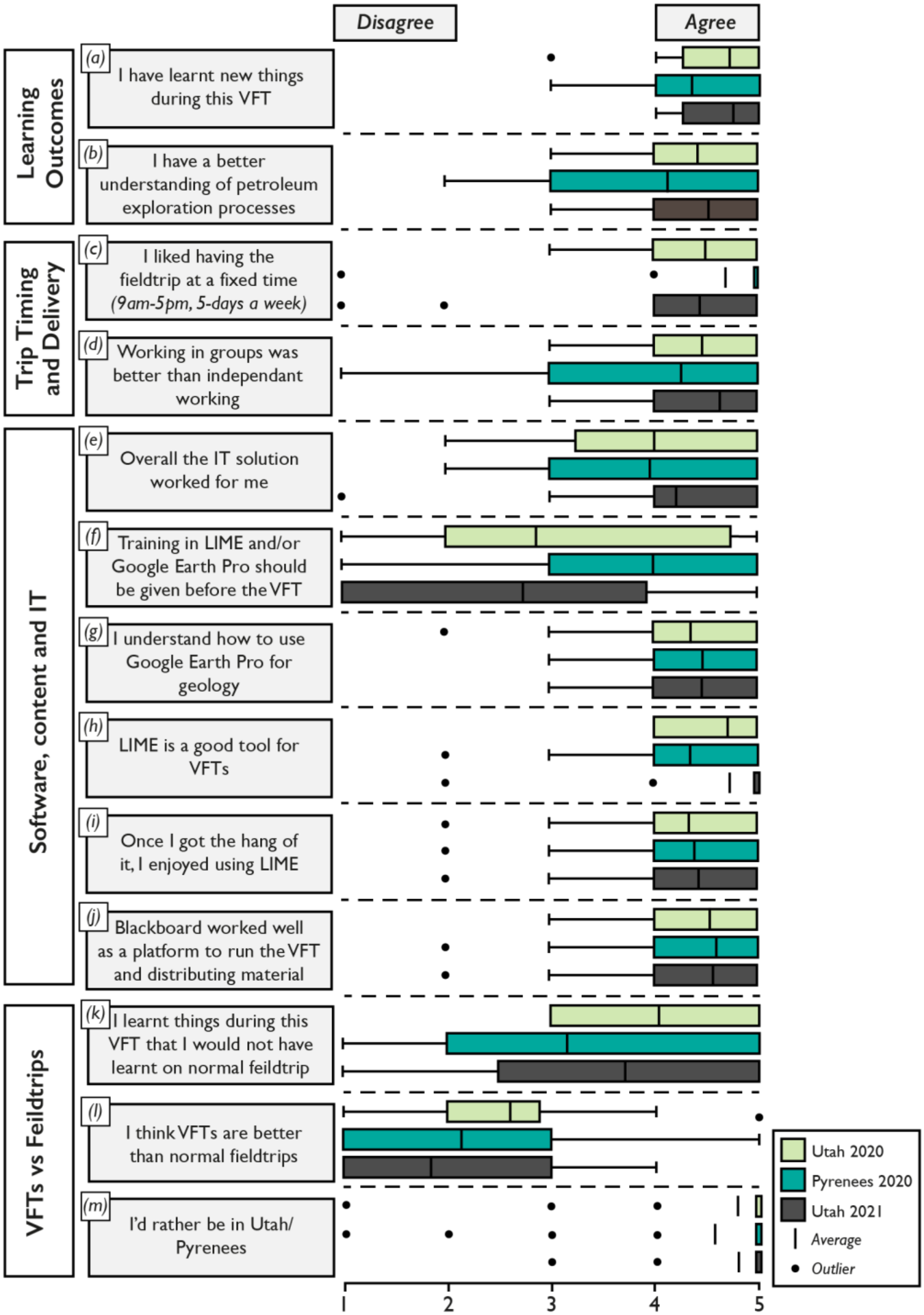


Figure 7. Course elaluation reports for the IPG course including two fieldtrips. 2016-2018 data collected prior to COVID-19; trips were traditional fieldtrips. 2019-2020 Pyrenees was a traditional fieldtrip, whereas Utah was a VFT. 2020-21 both trips were run as VFTs.



825 **Figure 8. Quantitative responses to questionnaires for all three VFTs presented as Box and whisker plots. a) and b) summarises learning outcomes, e) to j) summaries software, content and IT, and k) to m) summaries comparative statements between VFTs and traditional fieldtrips. Responses are collated for each trip presented for comparison.**

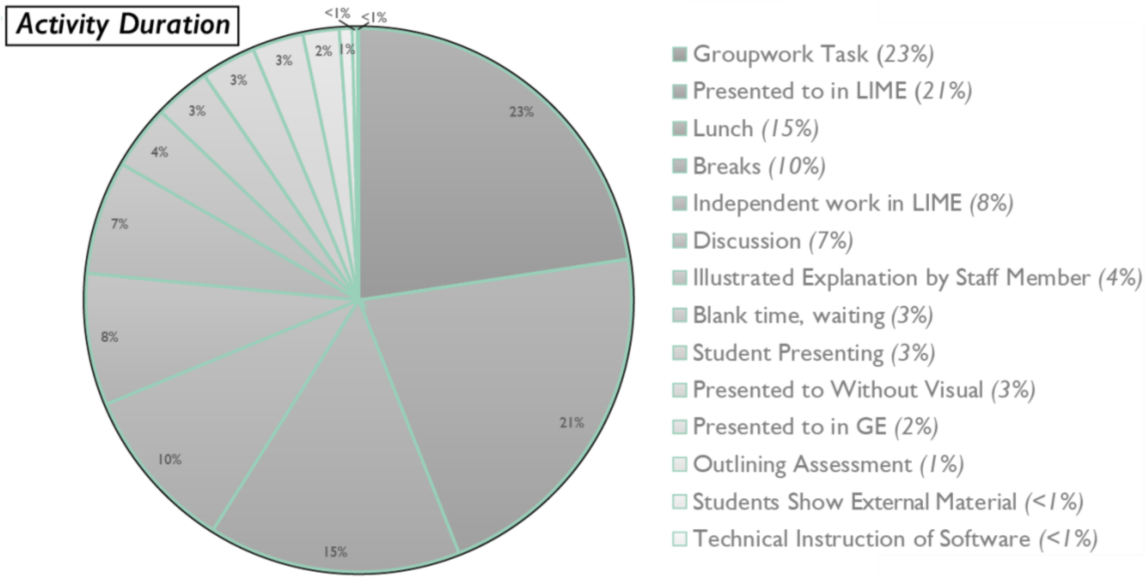


Figure 9. Duration analysis of activities across the Utah 2021 VFT, average of time spent each day on identified activities listed in the key.

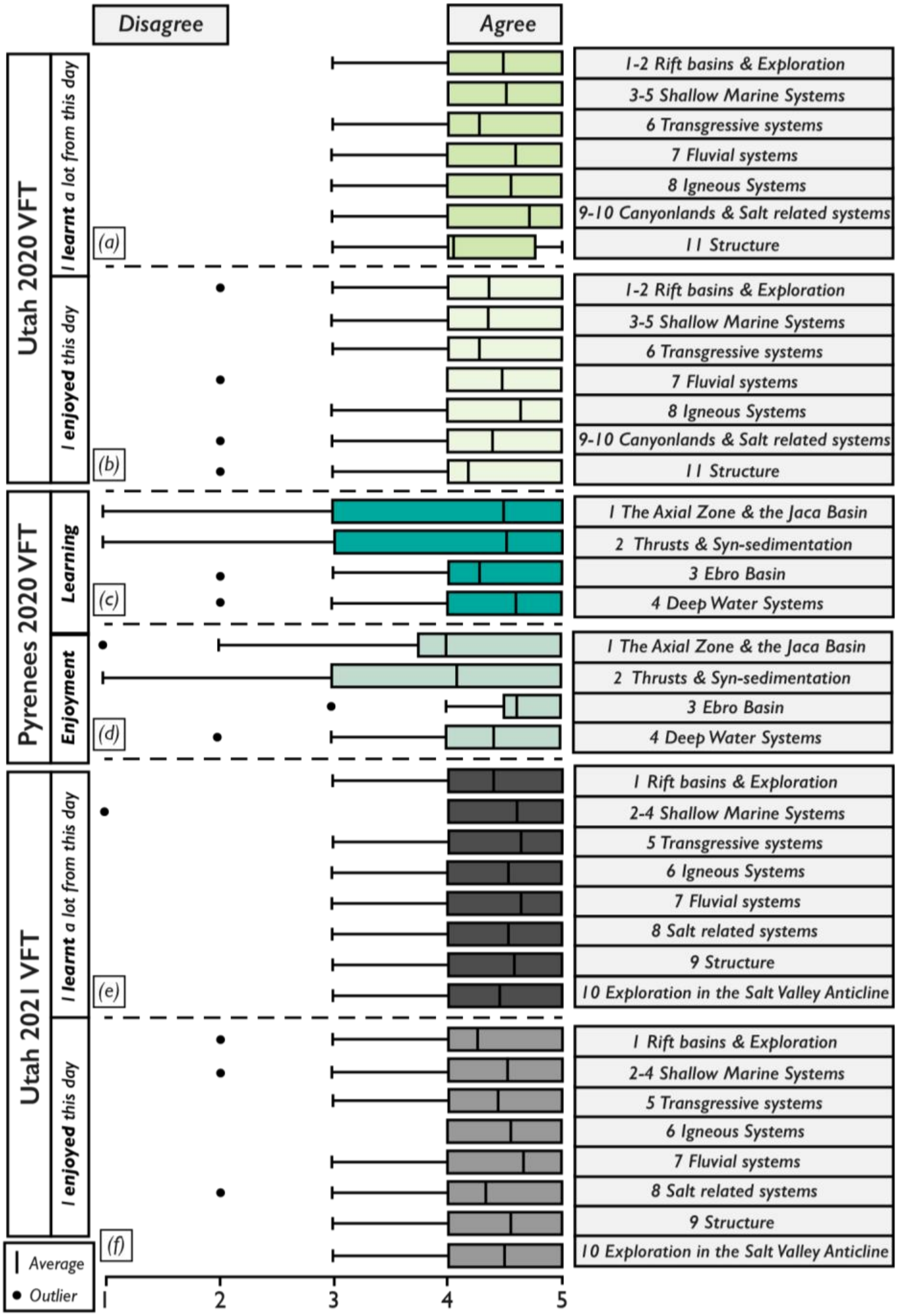


Figure 10. Quantitative responses to day learning and enjoyment for all three VFTs presented as Box and whisker plots. a) and b) The responses to the 11 days of fieldtrip, c) and d) summarises software, content and IT, and k) to m) summaries comparative statements between VFTs and traditional fieldtrips.

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