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Virtual Fieldtrips: construction, delivery, and implications for future geological fieldtrips

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Abstract

Virtual geological fieldtrips have become increasingly popular over the last decade, with the advent of remote piloted vehicles (RPVs; drones) leading to progressively sophisticated photorealistic virtual outcrops (VOs). As the COVID-19 pandemic led to widespread international travel restrictions, virtual fieldtrips (VFTs) became practical, and necessary substitutes for traditional fieldtrips. This contribution explores two VFTs delivered to a master's level Petroleum Geoscience course at the University of Aberdeen, normally run as traditional fieldtrips to the Spanish Pyrenees and Utah. The paper describes the delivery of these VFTs and examines student perception, gauged primarily through questionnaires. The VFTs were run in LIME, a software specifically designed for the interpretation of 3D models and the delivery of VFTs. Overall, the student questionnaires reflect the satisfaction of group with the teaching method and feedback was more positive for the virtual fieldtrips than the equivalent real-world fieldtrips in earlier years. Our findings also highlight several notable advantages associated with VFTs, including the ability to examine geology data at a range of scales, financial and access inclusivity, and reduced environmental impact. Several disadvantages with VFTs were also highlighted, including a reduction in social cohesion, and missing out on the experience of travelling and being outdoors. Our findings highlight implications for future application of VFTs and the opportunity to utilise both traditional fieldtrips and VFTs within a blended learning approach.

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 relevant professional body (The Geological Society of London) it had to contain 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 here Virtual Fieldtrips (VFTs). The use of VFTs also has significant advantages such as cost, safety and environmental impact; however, there has been significant reservation with regard to their use and value in teaching geosciences. To date there has been little systematic evaluation comparing virtual 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 in March 2020 forced the implementation of VFTs. Lockdowns imposed stringent restrictions on travel and social interaction, which had an inevitable knock-on effect for geological fieldwork (Scerri et al., 2020; Arthurs, 2021; Rotzein et al., 2021). As traditional fieldtrips were unable to run, universities and companies sought to rapidly find virtual substitutes for courses at all levels from undergraduate to postgraduate and CPD (continued professional development).

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 (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 (Enge et al., 2010; Rittersbacher et al., 2015, Eide et al., 2015 and many others). In recent years, virtual outcrops have started to be used in virtual fieldtrips (VFTs) (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 often only used to provide supplementary material. Even during the COVID-19 pandemic the VFTs run by many groups did not contain VOs, habitually being run using traditional teaching methods or in some cases using Google Earth and/or GIS tools (Bosch, 2021; Whitmeyer and Dordevic, 2020) for more regional scale VFTs.

The global pandemic and associated lockdowns forced the uptake of VFTs, in a range of different formats. However, there has been very limited research to examine their effectiveness or how they compare to each other or to traditional fieldtrips. Within this contribution we provide a detailed overview of the VFT creation workflow and teaching methods used at the University of Aberdeen. We also 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. These VFTs were based on 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. Enge et al., 2010; Rittersbacher et al., 2015; 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 learning objectives expected from a 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 traditional fieldtrips.

https://doi.org/10.5194/gc-2021-37
Preprint. Discussion started: 1 November 2021

The term virtual fieldtrip 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 VR experience. The form of immersive technology can also vary from desktop to VR headsets (Kippel et al., 2020) with augmented reality also starting to appear. VFTs can also be subdivided into location based or thematic trip (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 will visit a series of localities with a common theme such as a specific depositional environment. Thematic VFTs enable world-class examples to be visited across the globe without being limited by the logistic of travel.

Another classification is based upon the degree of tutor involvement at the time of delivery (figure 1 b). Again, 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. Different trip types are more suited to different topics, different learning outcomes and different levels of student experience. The pros and cons of the different VFT immersive technologies, geographical type, and delivery mechanisms are beyond the scope of this study. All the VFTs presented here were run in real-time, were fully tutor-led and locality based.

2 Learning Objectives and Planning

2.1 Initial Learning objectives

Prior to global lockdown, the two fieldtrips (Utah and Pyrenees) were run to provide field experience covering a wide range of the 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 systems. The Utah trip covers extensional tectonics, rift basins, salt tectonics, fluvial, aeolian and shallow marine depositional systems and igneous rocks in petroleum systems. 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 and present results back to the course tutors and the rest of the class. The goal of the VFTs was to recreate the learning outcomes and format of the traditional trips.

2.2 Pyrenees VFT Learning Objectives

The first VFT in the academic year was based on data from the Spanish Pyrenees. The VFT was a direct, real-time replacement for the traditional trip. The trip was run by three members of staff and two demonstrators. The trip ran in real-time over five days between 9am-5pm mimicking the traditional trip it was replacing. The main aims of the trip were as follows:

1. To study structural geology of a collisional mountain belt and associated foreland basins
2. To study the interaction of sedimentation and tectonics
3. To study deep water clastic depositional systems

https://doi.org/10.5194/gc-2021-37
Preprint. Discussion started: 1 November 2021

4. To study carbonate depositional systems
5. To start to build an atlas of sedimentary systems for reservoir modelling, which was continued during the Utah VFTs

The main assessment for the trip is a hydrocarbon play-fairway mapping exercise for the Pyrenean foreland basin, run as a group exercise, and the "facies atlas", which is an individual endeavour.

2.3 Utah VFTs Learning Objective

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. Like the Pyrenees, it ran in real-time and broadly followed the traditional trip. The trip was run by four members of staff and three demonstrators and lasted for 11 days. Unlike the traditional trip it did not run over the weekends. The main aims of the trip were as follows:

1. To study extensional tectonic and associated arid rift basins with a major rift basin exploration exercise
2. To study shallow marine systems and develop understand of sequence stratigraphy
3. To study distributive fluvial systems (DFS) and the implications on exploration and production
4. To study the impact that igneous activity has within basins and petroleum implications
5. To study salt tectonics and impact of halokinetics on sedimentation
6. To study analogue examples to develop understanding of exploration process and field development
7. To complete an atlas of sedimentary systems for reservoir modelling

The virtual fieldtrip ran in September 2020 and again in August 2021, with minor modifications and improvements made in the second year based on after action review and student feedback. The main assessments were a rift basin exploration exercise and a field development exercise, both assessed as group presentations. There was also a requirement to complete the second half of the facies atlas, which was individual work.

2.3 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., this volume, in review) and proprietary (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 the scope and desired learning outcomes of the fieldtrip. Trips can be topic based, such as examining a specific geological phenomenon from outcrops across the world or, location based, visiting a specific geographicarea. 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 and what data are required. Data include virtual outcrops, sub-regional DEMs, figures, traditional field data, subsurface data, photos, satellite images, video clips, 360° panorama

https://doi.org/10.5194/gc-2021-37
Preprint. Discussion started: 1 November 2021

photos 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. The data were then compiled, internal resources sorted into folders or uploaded online to reduce file size, such as videos. The URL of external resources such as Google Earth Engine was added to a spreadsheet, or saved using the web browser, for future reference. Ensure that coordinate systems are unified 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 1.
5. Distribute the LIME files and supporting material. Supporting materials include 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 – perform after action review, 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, so Google Earth was used instead of LIME. Building the VFTs took almost two months for the longer Utah trip and about a month for the Pyrenees VFT.

Demographic and setting

A total of 53 individual students participated across the three virtual fieldtrips. Of those 30 attended Utah 2020 (class of 2019-2020), and 23 (class 2020-2021) attended the Pyrenees 2020 and Utah 2021 VFTs. All students were enrolled on the GL5013 course, Professional Skills incorporating International Field Trip, of the Integrated Petroleum Geoscience (IPG) MSc.

3.1 Class 2019-20, Utah 2020 VFT

Prior to the COVID-19 pandemic this class attended the Pyrenees as a traditional field trip. However, as a direct result of the COVID-19 pandemic many students returned home. By the time of the Utah 2020 VFT most students were still based in the UK, however, a small proportion were located globally in countries including Malaysia and Tanzania. Gender distribution across the trip was 62.5% identifying as male and 37.5% as female.

Due to COVID-19 related restrictions during September 2020 students attended the VFT remotely off-campus, as a result, all participant (staff and student) interactions were conducted in the online environment. The University of Aberdeen provided a Virtual Desktop Infrastructure (VDI) for each student, to allow those with limited computing capabilities to run the required software. 56.5% of students utilised the VDI, and the remaining 43.5% used their personal laptops/PC with LIME installed locally. WIFI/ethernet download speeds varied from as low as 5Mbps to as high as 200Mbps. WIFI/ethernet speed quality was classified based on download speeds required to access the material within the VFT, 4.5% of student had poor download speeds of ≤5Mbps and were unable to access the material; 45.5% had adequate download speeds of 6-25Mbps and 50% had good download speeds of ≥ 36Mbps. Students that had poor internet were offered a free wireless internet dongle for the duration of the VFT, however, no participants accepted the offer.

https://doi.org/10.5194/gc-2021-37
Preprint. Discussion started: 1 November 2021

Table 1. 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

https://doi.org/10.5194/gc-2021-37
Preprint. Discussion started: 1 November 2021

3.2 Class 2020/21, Pyrenees 2020 and Utah 2021 VFTs

The majority (59.5%) of students of the 2020-21 class stated their nationality as British, with the remaining spread between Chinese 9%, Malaysian 4.5%, Kenyan 4.5%, Nigerian 4.5%, Portuguese/Angolan 4.5%, Cypriot 4.5%, Turkish 4.5%, Greek 4.5%. Gender distribution across the class was 57% of individuals identifying as male and 43% as female.

As a result of relaxation in COVID-19 related restrictions students attending Pyrenees 2020 were able to access on-campus computer rooms. 35.2% of students elected to use these rooms under the social distancing conditions of November 2020 (2 m distancing and facemasks). Of the remaining students 33.4% accessed the software through the VDI and 31.4% used their personal laptops/PC. Again, there was a large range in WiFi/ethernet download speeds from as low as 12.8Mbps (off-campus user), to as high as 806.86Mbps (on-campus user). WiFi/ethernet quality on this VFT increased with 76% of the class experiencing good Wifi/ethernet whereas 24% had adequate.

As the Utah 2021 VFT ran in August 2021 only certain university-outlined COVID-19 restrictions existed (e.g. mask wearing), which enabled all willing students to access the on-campus computer rooms. 57.9% students elected to use the on-campus facilities; of the off-campus participants, 26% employed the VDI to access the VFT software and 15.8% used their personal laptops/PC. As expected, WiFi/ethernet speeds were wide-ranging across the students from a low 4Mbps (off-campus) to over 500Mbps (on-campus). Three participants were affected by unexpected WiFi/ethernet network impairments and on occasions had download speeds <5Mbps. During this trip 81.6% experienced good Wifi/ethernet, 2.6% adequate, 15.7% poor (individuals with unexpected connection issue). Across the three VFT's a general trend of improved average internet speeds was observed.

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). The LIME 2.2.2 version of the software was used for all VFTs, chosen as it was the newest version at the time of VFTs. LIME is a high performance, lightweight 3D software for visualising, interpreting, and presenting 3D models and associated data (Buckley *et al.*,2019). 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 objects include:

- *3D Models:* these include virtual outcrops and other 3D models such as DEMs, hand samples and models commonly used as scales.
- *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, 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 with chosen material displayed (models, lines, panels, points and planes) to be stored and accessed in order. The VFT Storyline works as a guide for both staff and student 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 10 – 15 virtual outcrops and could easily require 10GB 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. this volume). The cloud storage solutions include V3Geo (V3Geo.com), a public repository of virtual outcrops (Buckley et al. this volume) and Safari (safaridb.com) a proprietary database using a similar 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; Bond et al., this volume, in review). 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, either as a stand-alone or as a supplement to a LIME project. On virtual field days where large regional areas were studied, including the first day of Utah which provides a regional overview and task set around Salt Lake (covering an area of >20,000km^2), Google Earth Pro was implemented. As Google Earth provides high-resolution satellite imagery draped onto a digital elevation model (DEM) it was particularly useful for these 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. This is partially mitigated where Google has integrated additional data in the form of "3D buildings". This data layer, which must be manually toggled on, 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. The 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 practicals within the 'Virtual Classroom'. The virtual classroom also provided a record function which enabled all days to be recorded for inclusivity of students with poor internet, or temporary absence. 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. For these reasons in addition to all students and staff had access and familiarity with Blackboard Learn 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, it is not possible to assume that all the students will have access to such. 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

https://doi.org/10.5194/gc-2021-37
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machine and the student's computer acts as a terminal. This allows students with low grade computers or 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.

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 resolve by a member of staff. Ahead of assessments, which were all groupwork-based, students were allocated groups and group list uploaded to Blackboard Learn.

5.1 Utah VFT: Outline

This direct replacement of a traditional trip lasted 11 days (2020) and 10 days (2021). A separate LIME project was built for most of the days. The data used for Utah 2020 is outlined in Table 1(a), with minor improvements made to most days on the Utah 2021 VFT based on the after-action review and student feedback. The days which changed significantly between 2020 and 2021 are outlined in Table 1(b). Over the Utah trips an average total of 30 virtual outcrops, 16 DEMs, 318 photos, 101 logs/wells and many other data were used (see table 10). 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; Somme 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 Cliff 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). This exercise culminated in a major student exercise dealing with exploration in salt basins. The final day (Day 11) 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 Related 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 combining outcrops with some 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 10c). 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). In the afternoon of Day two we moved laterally to Arguis and Pico de Aguillar discussing lateral changes along the thrust front and the role of salt with the detachment.

On Day three we moved into the Ebro Basin and studied the distributive fluvial deposits of the Huesca DFS (Nichols and Hirst, 1988). After day three we headed east into the Ainsa Basin for the last two days. Day four studied in deep water deposits of the Ainsa basin incorporating the behind outcrop wells and cores that have been collected over the years, (Falivene et al., 2006). The final day of this VFT, day five, was an assessed group exercise, reviewing the perspectivity 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 presentations.

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Preprint. Discussion started: 1 November 2021

6 Methodology for Evaluation

6.1 Student Experience

Student experience was evaluated through two different questionnaires. The university provides a standard form (Course Evaluation Form) that is filled in 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 qualitive 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 trip 1 there was a questionnaire response of 88% (24 out of 27), trip 2 it was 100% (23 out of 23) and trip 3 it was 90% (19 out of 21). Students that were unable to attend the full field trip due other commitments did not answer the questionnaire; this included five in trip 1 and two in trip 2. A total of 66 questionnaire responses were collected.

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 a COVID-19 incident in the classroom.

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. 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.

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Preprint. Discussion started: 1 November 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 info. Duration analysis was evaluated, and averaged.

7.1 Course Evaluation Form

The course evaluation forms provided a valuable comparison between student feedback for pre- and syn- the COVID-19 pandemic. The two course evaluation forms from 2016-2017 and 2017-2018 are the result of 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.

7.2 Learning Outcomes

The questionnaire results for learning outcomes are presented in Figure 8 (a-b). Across all three field trips an average of 94% 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 8d) 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 8e). Both the Utah VFTs were 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 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. With groupwork tasks (23%), LIME guided VFT (21%), independent work in LIME (8%), and discussions (7%) forming a large portion of the work activities during the VFT. A very small portion of the VFT was spend 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 8f). 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, with 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 8g) 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 therefore predominately disagreed, with 52.6% of individuals disagreeing with the statement. Scores were consistent for the statement *I understand how to use Google Earth Pro for geology* (figure 8h), with over 80% agreeing across all VFTs.

As a *tool LIME* was scored positively as *a good tool for VFTs* across all three VFTs (figure 8i). 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 with known Wifi issues 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. 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 8k).

7.4 Virtual Fieldtrips vs Traditional Fieldtrips

VFTs were broadly diverse when scoring if they *had learnt things during the VFT that they would not have learnt on a normal fieldtrip*. 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* as well as 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 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.

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Preprint. Discussion started: 1 November 2021

8 Discussion and Conclusions

8.1 Interpretation of Evaluation

8.1.1 Student Course Evaluation

The improved results in course evaluation forms from pre- to syn COVID-19 are attributed to the students' knowledge of the relative quality and extent of the VFTs. Based on the free text it was clear students were impressed with the VFT quality and appreciated the effort involved in constructing such VFTs. Students were clearly satisfied with the content of the VFTs and felt they provided an effective teaching experience, which they enjoyed.

8.1.2 Questionnaire

As the VFTs were a direct replacement of traditional trips, the learning outcomes remained the same as previous years. Utah Questionnaire results illustrate student attitude was largely positive towards the learning outcomes, broadly agreeing that they had learnt during the VFT and a better understanding of exploration processes. Analysis of the individual learning outcomes of both VFTs was beyond the scope of this contribution, however, again they were largely positive, providing satisfaction that the students had learnt the desired material.

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. 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. In informal discussion students the majority of students would state that they would have preferred a traditional fieldtrip, a viewpoint not as strongly represented in the student course evaluation forms. This is attributed to the simple fact the majority of people like travelling to new places and enjoy being outdoors.

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. Pyrenees VFT ran during the first term of the programme, and due to COVID-19 the students had little peer-to-peer social interaction prior to the VFT and had likely never used LIME before. Two possible influences on the lower scoring of days 1-2 of Pyrenees.

https://doi.org/10.5194/gc-2021-37
Preprint. Discussion started: 1 November 2021

8.2 Advantages of VFT

The VFTs presented within this contribution illustrate some clear advantages compared to the traditional fieldtrip, which are applicable to VFTs in general. (1) VFTs enable more data to be examined at a greater range of scales, from thin sections to global tectonics (pore to plate). (2) VFTs are logistically easier to plan and deliver. There are many factors which must be assessed when planning a traditional fieldtrip such as weather, accommodation and safety which are not part of VFT planning. (3) VFTs are typically significantly cheaper than traditional fieldtrips, making them financially inclusive. (4) The lack of travel also saves time, VFTs are time effective, covering more material than a traditional fieldtrip in a shorter space of time. (5) Moreover, without the need to fly or drive VFTs also have less environment impact. (6) VFTs are more inclusive for those who are unable or restricted to attend traditional fieldtrips due to mobility issues. (7) VFTs also provide flexibility, recordings enable those with other time commitments (e.g. caring responsibilities) to participate, (8) VFTs allow individuals to work at their own pace, inclusive of all learning speeds. (9) VFT can serve to prepare/orientate a class for a physical fieldtrip. (10) VFTs can be geographically independent, thematic VFT can visit world-class geological features from across the world.

8.3 Disadvantages of VFT

While there are many advantages to VFTs there are also disadvantages that were documented during the VFTs within this contribution. (1) Students expressed a loss in social cohesion, which improved for those who were able to access on campus facilities. The split of class between on-campus and off-campus led to unforeseen issues in minor social divides between the two working locations, which was partially mitigated by some groupwork being split into groups based on working location (on- vs. off-campus). (2) Students also stated they would have preferred a traditional trip, mainly for loss in experience of travel and outdoors, as well as loss of traditional field training. (3) IT issues are an expected part of online VFTs, particularly those using a virtual platform to operate, such as Blackboard Learn, Teams and Zoom. Questionnaire feedback illustrates IT issues were not a significant problem within the VFTs presented here.

8.4 Implications for Future Geological Fieldtrips

The COVID-19 global pandemic has significantly increased the demand and interest in VFTs. This demand has led to rapid developments within the field and the creation of virtual trips to a host of locations globally by various authors. While traditional fieldtrips remain the foundation of many geology degrees, we argue there is a key role for VFTs beyond COVID-19. It is noted that many of the negative aspects of VFTs have the potential to be significantly lessened by running VFTs in person within a classroom environment, with the whole class and staff located on-campus. Integration with some traditional fieldwork, would potentially further reduce the disadvantages of VFTs. An assessment of blended learning was out of the scope of this contribution, however, 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 illustrates the potential scope for future implementation of VFTs

https://doi.org/10.5194/gc-2021-37
Preprint. Discussion started: 1 November 2021

particularly during the potential digital alteration in the global working structure, with the many corporations and businesses encouraging at-home working into the future.

9. Conclusions

This contribution illustrates experience gained and the value of VFTs as a replacement for traditional fieldtrips and excursions during a time when travel and social integration was restricted due to the COVID-19 pandemic. We argue VFTs have a key role in the geological curriculum beyond COVID-19 for the following reasons:

1. VFTs enable a larger volume of data at varying scales to be intergrated and developed.
2. VFTs are logistically easier to plan and deliver.
3. VFTs are financially inclusive
4. VFTs are time efficient
5. VFTs have a lower carbon emission
6. VFTs are inclusive to those with restricted physical access
7. VFTs are flexible, inclusive to those with other time commitments
8. VFTs allow individuals to work at their own speed
9. VFT can serve to prepare/orientate a class for a real excursion
10. VFTs can be geographically independent

- While we establish some disadvantages to VFTs it is suggested many would be mitigated through blended learning.

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.

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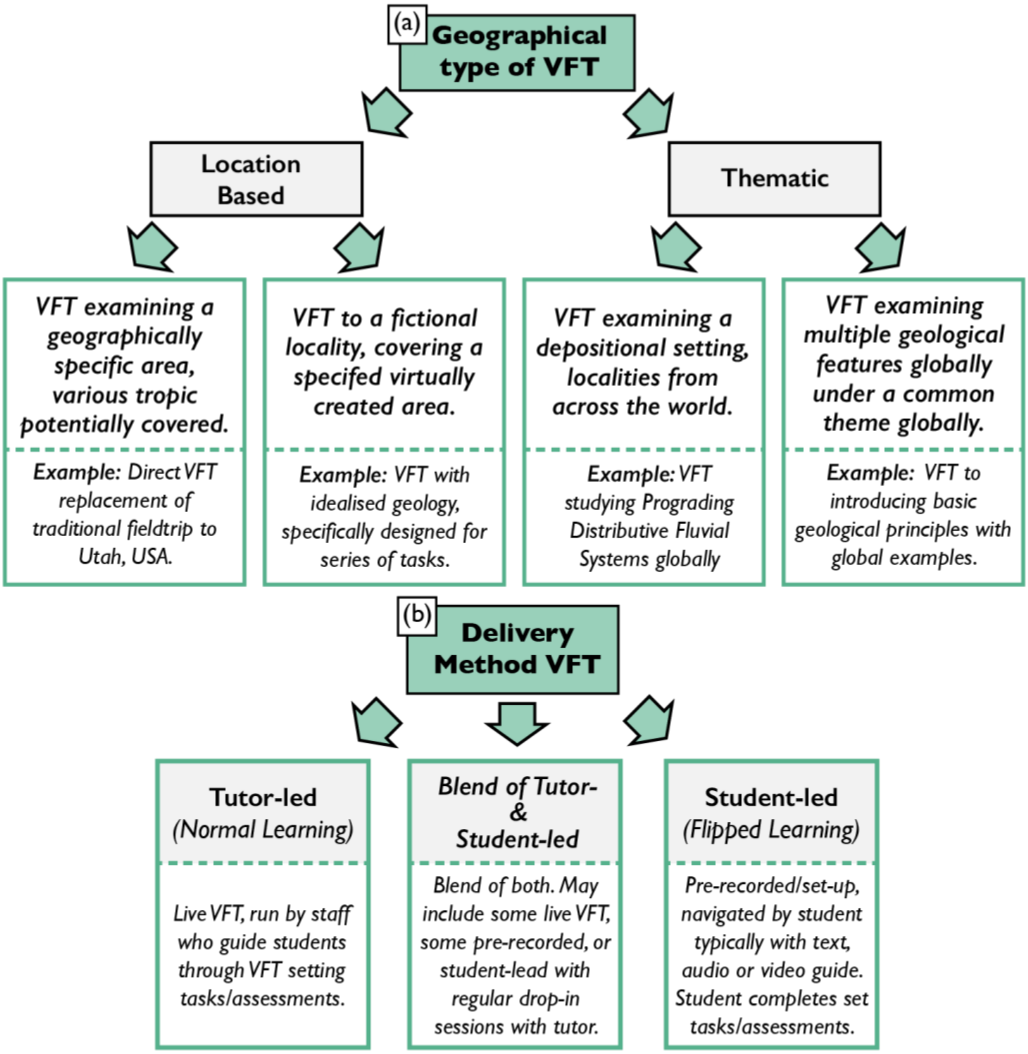

670 **Figure 1. Outline of types and delivery methods of VFT. (a) Types of VFT separated between location-based trips to a specific locality, and thematic trips spanning global localities with a common theme. Examples given. (b) Delivery method of VFT divided between tutor-led VFTs and student-led VFTs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

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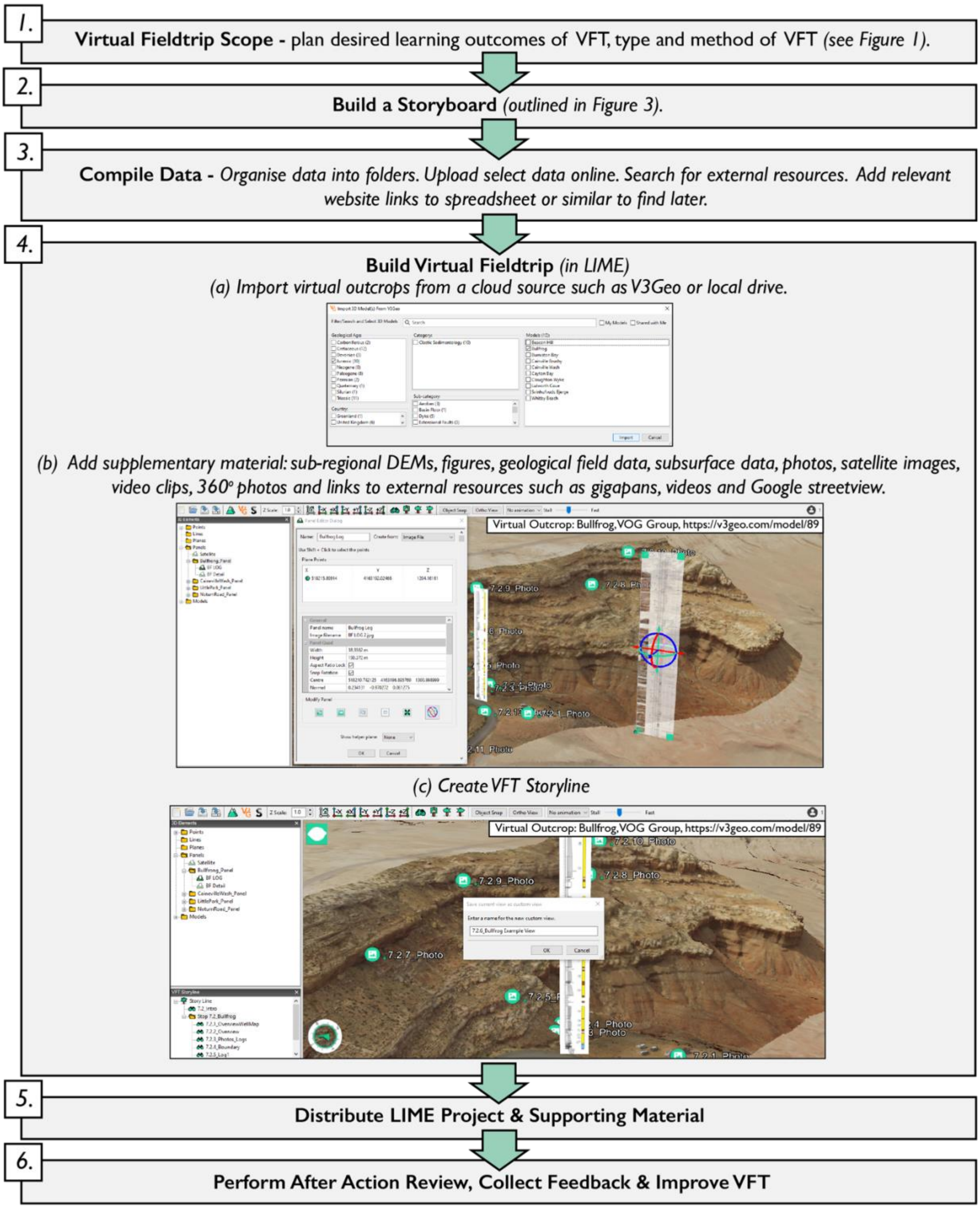

Figure 2. Proposed workflow for building and running VFTs, this workflow was followed for every VFT within this contribution.

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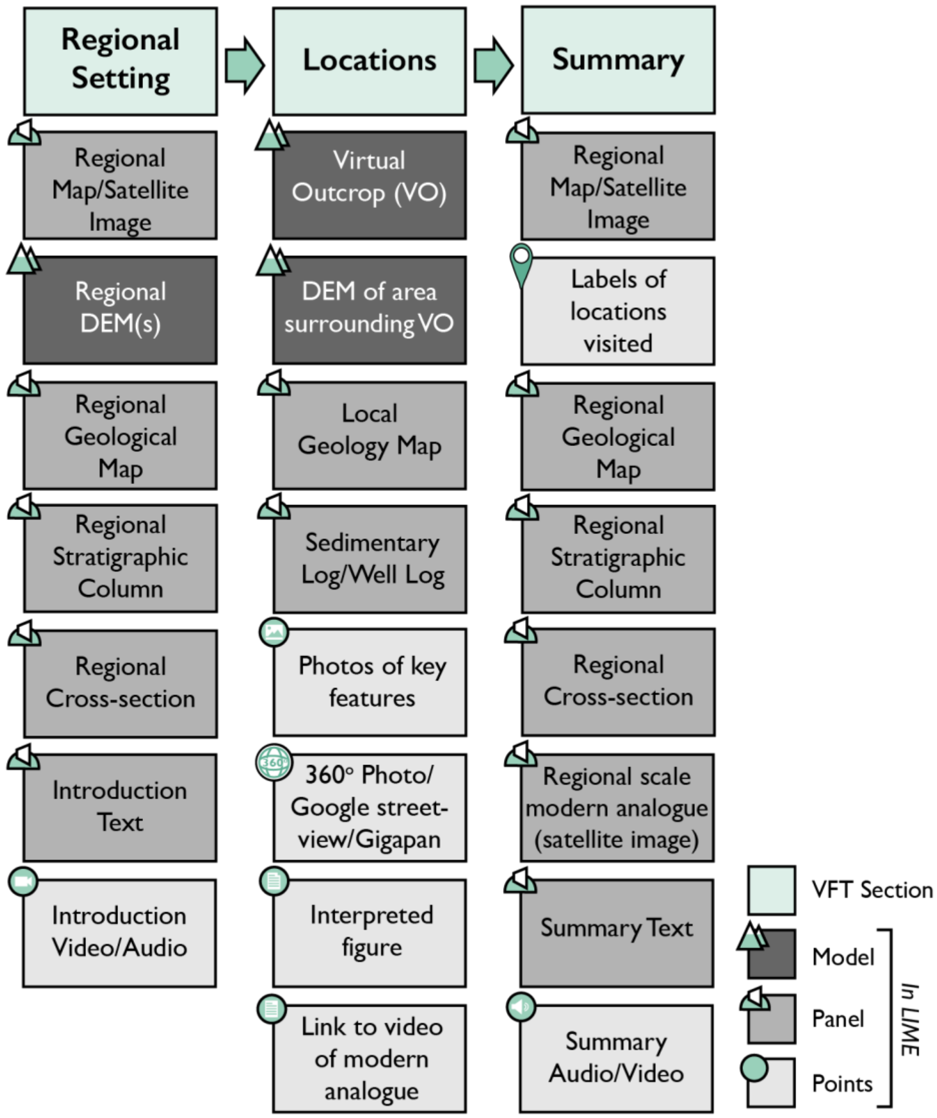

Figure 3. Template storyboard for designing a VFT. Data input within LIME indicated. Locations varied across each day of each trip, from as few as three locations to as many as eight depending on the days aims. Typically, a new location was created for each new virtual outcrop.

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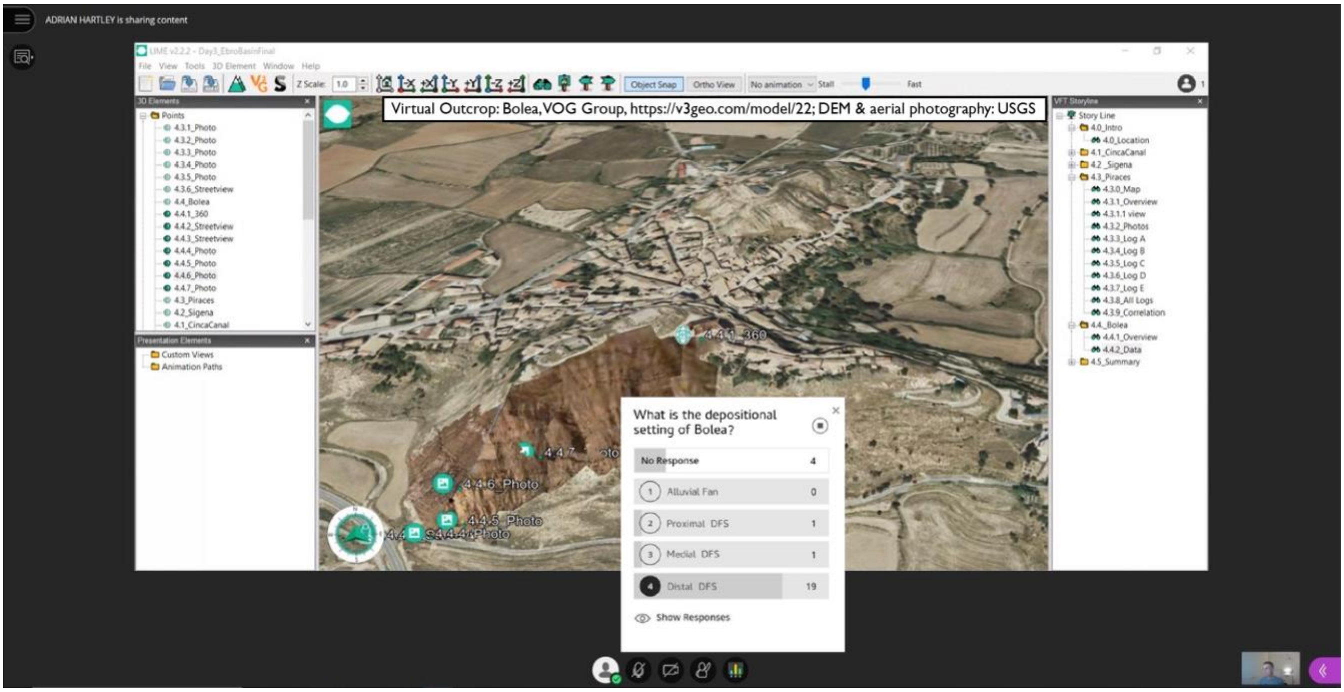

Figure 4. Bolea, Aragon, Spain, example Poll within Blackboard Learn Virtual Classroom, students asked to identify the depositional setting of locality. Virtual outcrop: Bolea, VOG Group, https://v3geo.com/model/22; Aerial Photography on DEM, USGS EROS Archive; DEM, USGS 3D Elevation Program.

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Preprint. Discussion started: 1 November 2021

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 panorama images (in this example from ©Google Maps). Aerial Photography on DEM, USGS EROS Archive; DEM, USGS 3D Elevation Program.

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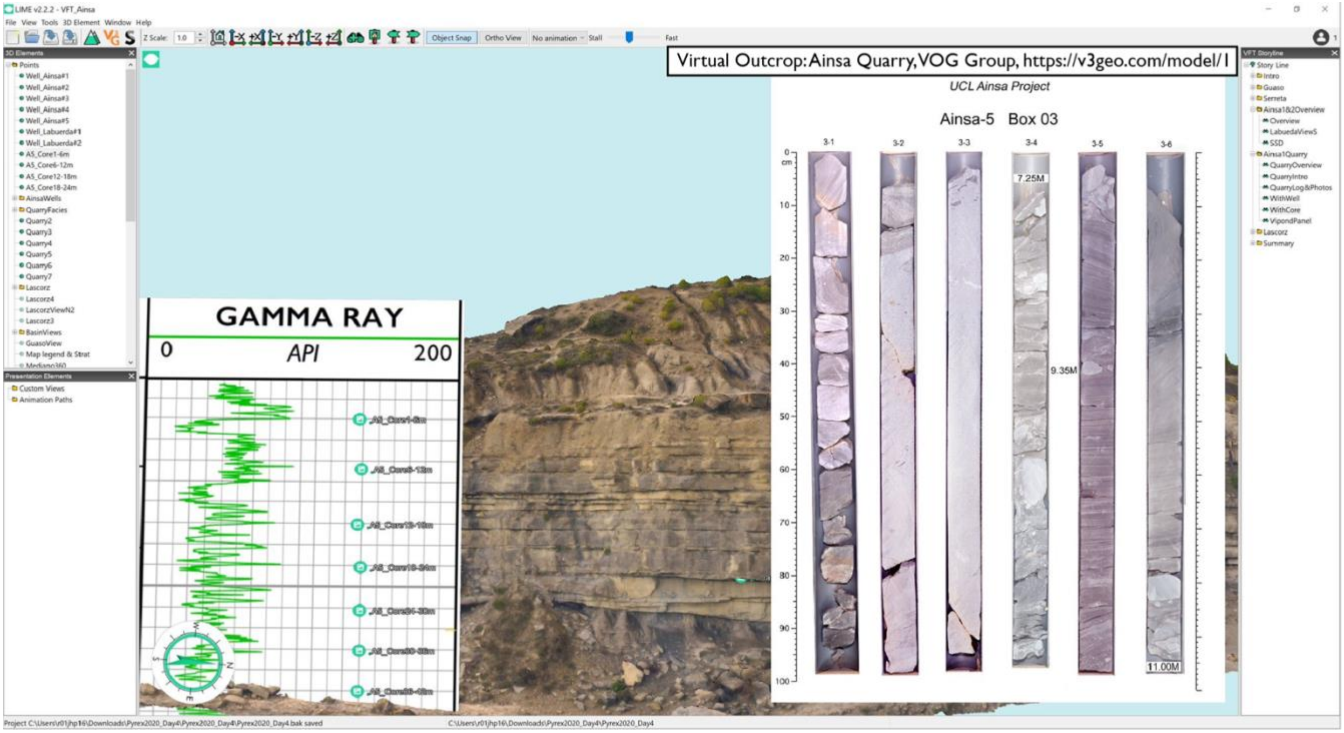
690 

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.

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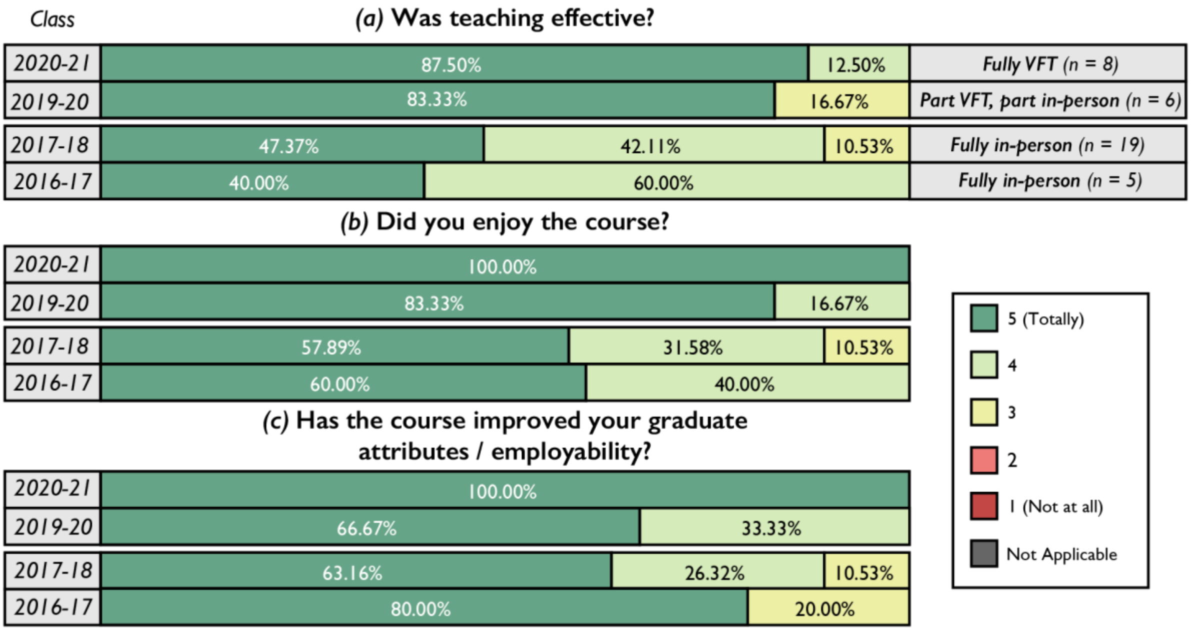

695 **Figure 7. Course elaluation reports for the IPG course including two fieldtrips. 2016-2018 data collected prior to COVID-19; trips were traditional fieldtrips. 2019-2020 Pyrenees was a traditional fieldtrip, whereas Utah was a VFT. 2020-21 both trips were run as VFTs.**

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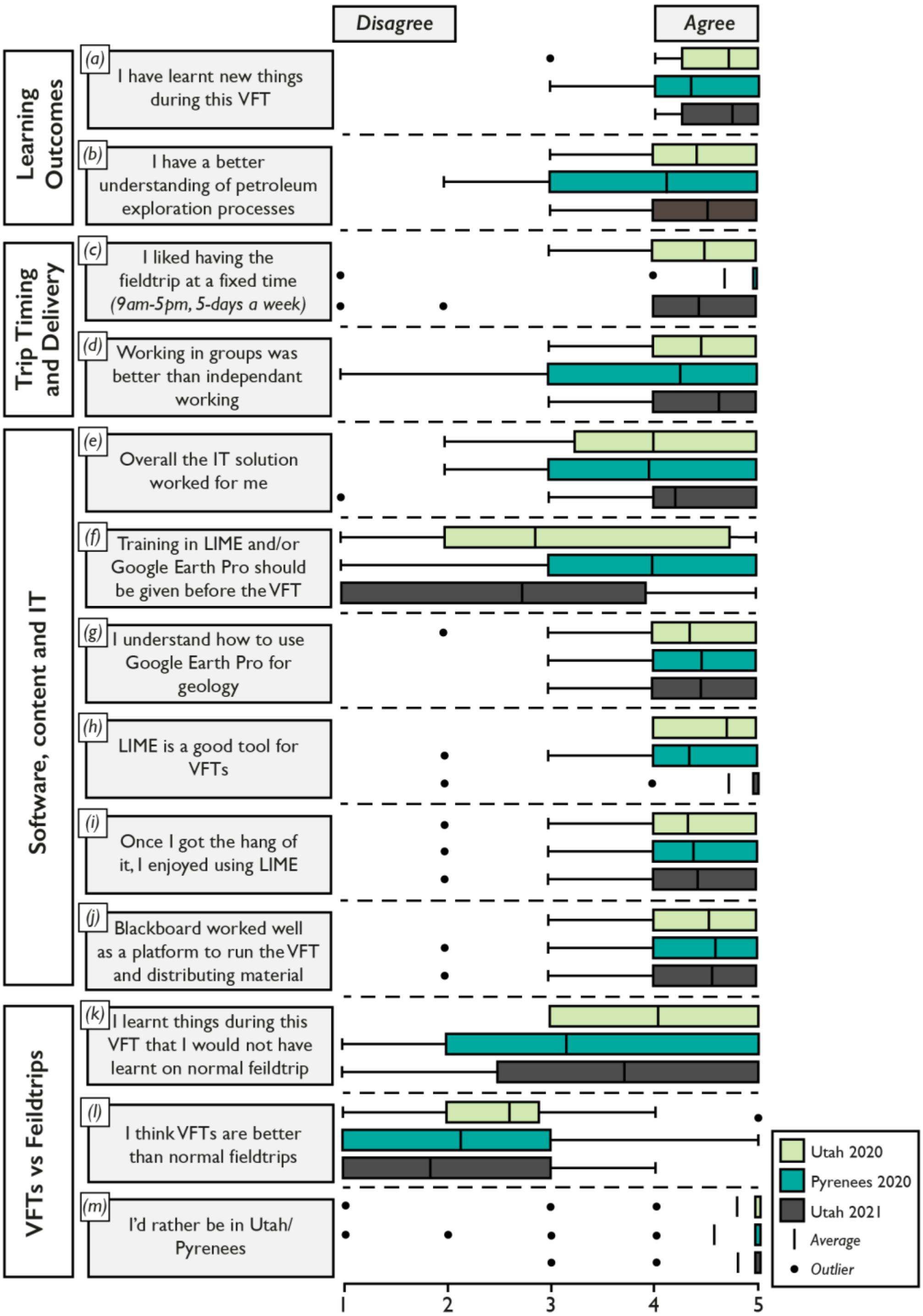

700 **Figure 8. Quantitative responses to questionnaires for all three VFTs presented as Box and whisker plots. a) and b) summarises learning outcomes, e) to j) summaries software, content and IT, and k) to m) summaries comparative statements between VFTs and traditional fieldtrips. Responses are collated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

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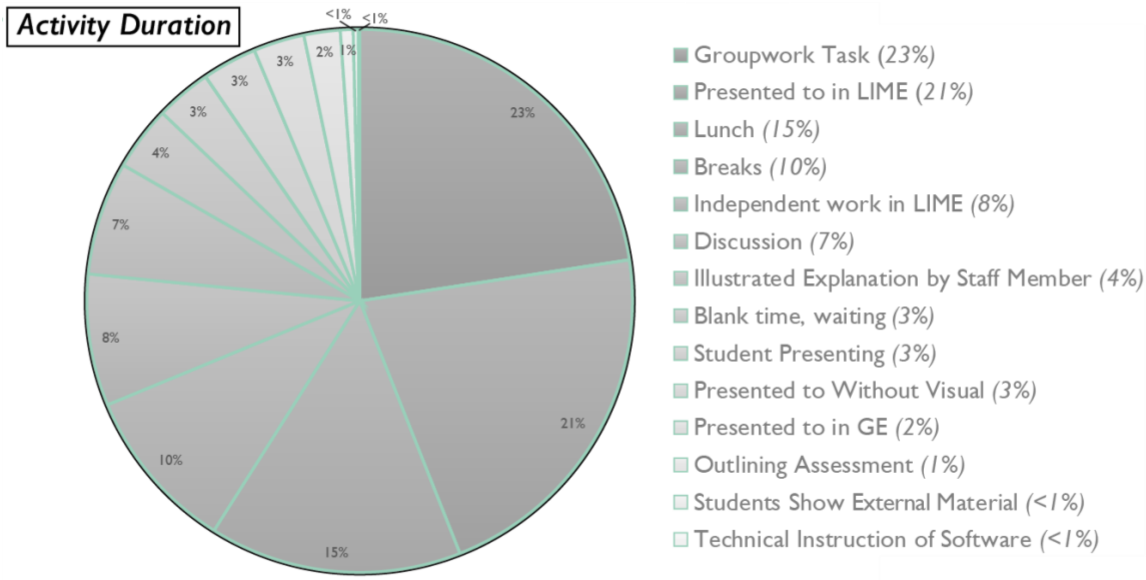

Figure 9. Duration analysis of activities across the Utah 2021 VFT, average of time spent each day on identified activities listed in the key.

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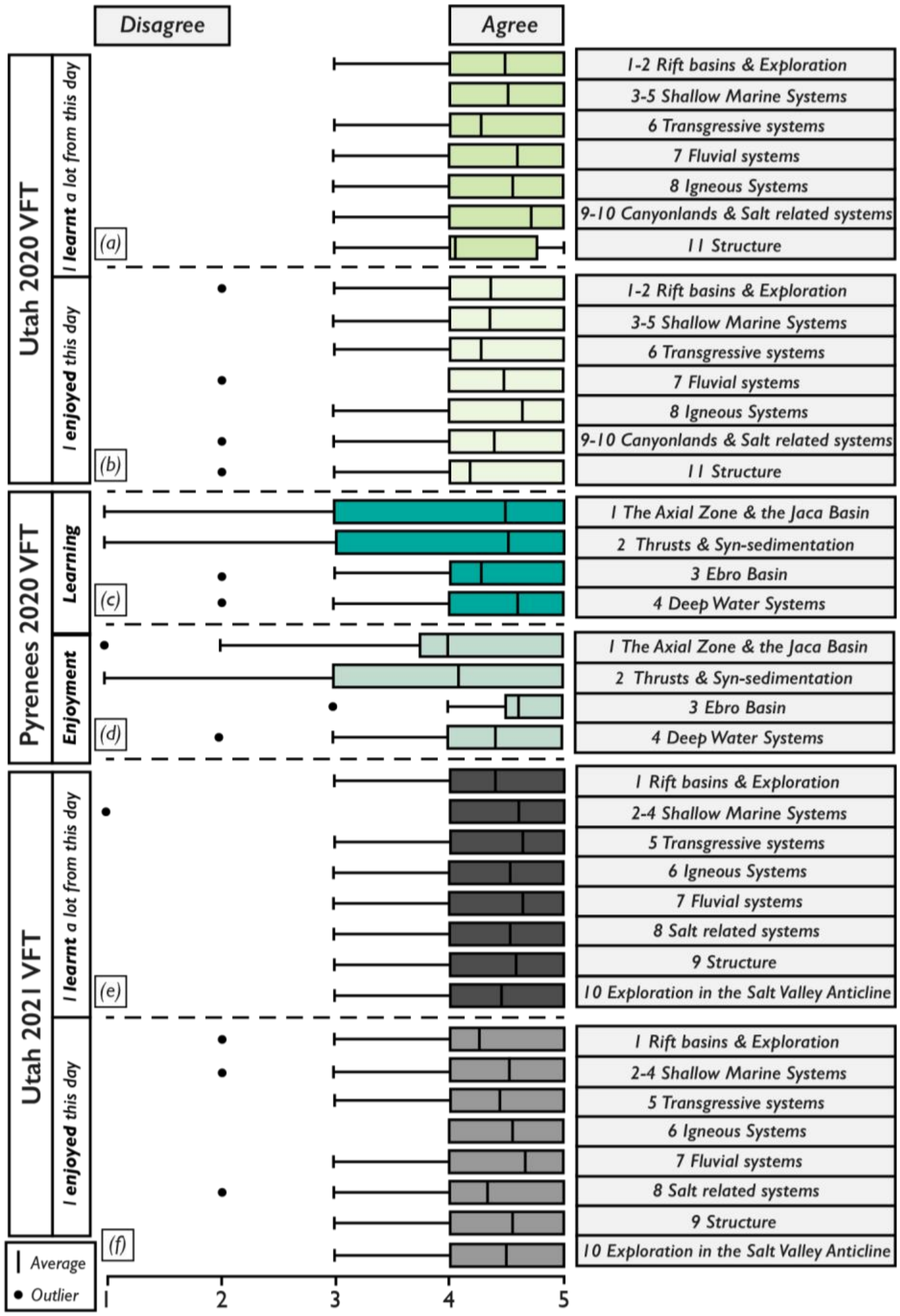

705 **Figure 10. Quantitative responses to day learning and enjoyment for all three VFTs presented as Box and whisker plots. a) and b) The responses to the 11 days of fieldtrip, c) and d) summarises software, content and IT, and k) to m) summaries comparative statements between VFTs and traditional fieldtrips.**