A role for Virtual Outcrop Models in Blended Learning: improved 3D thinking, positive perceptions of learning and the potential for greater equality, diversity and inclusivity in geoscience

Clare E. Bond[1], Adam J. Cawood[1,2]

5 [1] School of Geoscience, University of Aberdeen, Kings College, Aberdeen, AB24 3UE, UK.
[2] Southwest Research Institute, 6220 Culebra Rd, San Antonio, Texas, TX 78238, USA.

Correspondence to: Clare E. Bond (clare.bond@abdn.ac.uk)

Abstract

Virtual outcrop models are increasingly used in geoscience education to supplement field-based learning but their efficacy for
10 teaching key 3D spatial thinking skills has not been tested. With the rapid increase in online digital learning resources and blended learning, most recently because of the global COVID-19 pandemic, understanding the role of virtual field environments to support and develop skills conventionally taught through field-based teaching has never been more critical. Virtual outcrops and virtual field environments have not been evaluated for their effectiveness in teaching and learning in geoscience, however. Here we show the efficacy of virtual outcrop models in improving 3D spatial thinking and provide
15 evidence for positive perceptions amongst participants of using virtual outcrops in teaching and learning. Our results show that in a simple multiple choice scenario, participants were more likely to choose the 3D block diagram that best represents the structure when using a virtual outcrop (59%), compared to more traditional representations, a geological map (50%) and field photograph (40%). We add depth to these results by capturing the perceptions of a cohort of students, within our full participants set, on the use of virtual outcrops for teaching and learning, after accessing a virtual field site and outcrops to
20 which they had previously visited on a day's field teaching. We also asked all participants if and how virtual outcrops could be used effectively for teaching and training, recording 87% of positive responses. However, only 2% of participants felt that virtual outcrops could potentially replace in-field teaching. We note that these positive findings signal significant potential for effective use of virtual outcrops in a blended learning environment and for breaking barriers to ensure equality, diversity and inclusivity of geoscience field skills and teaching.

25 **1. Introduction**

1.1 The importance of, and barriers to, field teaching for 3D spatial thinking

Field-based learning is known to enhance geological understanding (McKenzie, 1986; Elkins & Elkins, 2007; Tretinjak & Rigg, 2008) and is highly desired by geoscience employers for its ability to enhance 3D spatial awareness and thinking (Butler,
30 2008). Field-based learning places rocks and concepts into a unique spatial context and provides a sense of the scale of geological processes. Fieldwork places interpretive 2D models such as cross sections and geological maps into context in the 3D environment. Through field-based mapping exercises, students make their own observations, generate working hypotheses and test these hypotheses in 3D by generating serial cross sections and geological maps. This process develops 3D spatial reasoning skills as students need to make interpretations and predictions based on what they see and measure in the field to
35 explain the geology of a 3D volume.

There are however barriers to field access, due to a range of logistical, financial and physical factors. Students with physical or other disabilities, for example, may find fieldwork difficult or impossible unless specific measures are put in place to enable access (e.g. Cooke et al. 1997, Gilley et al. 2015; Feig et al. 2019; Lang & Persico, 2019). Field-based training is expensive
40 and because students are increasingly expected to self-fund field trips at undergraduate level (Kent at al. 1997, Boyle et al. 2007, Giles et al. 2020), fieldwork may be prohibitively expensive for portions of the geoscience student population, or may simply discourage study from the outset.

Assuming the logistical, financial and physical barriers to fieldwork can be circumvented, there are several other issues which
45 may inhibit the effectiveness of field-based training. Students can find it difficult to keep up in group field activities when resources are limited, for example in 'back of the class' scenarios where students are only just arriving at the outcrop when the lecturer has finished the explanation, or weather conditions make it difficult to hear what is being said at the front, especially for those with hearing impairments. Students with little previous experience in the field or outdoors can be preoccupied and distracted by issues of safety, personal comfort, the physical demands of fieldwork and interactions with fellow students and
50 instructors (Nairn et al. 2000; Boyle et al. 2007). A lack of in-course outdoor training, and acknowledgement of the uncertainties faced by such students in fieldwork participation may also put such students off studying geoscience in the first place.

The recent Black in Geoscience movement, formed in the wake of Black Lives Matter, has also highlighted social and cultural
55 issues around fieldwork participation, notably that many individuals from BAME communities lack experience in field and outdoor activities[1]. Further issues include cultural norms in many western Universities in which the bar and evening drinking culture may exclude many on religious grounds, as well as others. Finally, safety concerns unrecognised by many organisers

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[1] Although we do not wish to stereotype, and recognise that many BAME individuals have experience; whilst also recognising that outdoor pursuits and field geology have been the preserve of the white male (in general).

in being black or brown in some areas and communities globally, or in being LGBTQ+ or female may hinder or exclude participation and breach human rights (Giles et al. 2020). Such safety concerns outweigh the potential benefits of fieldwork.

60 Finally, global public health concerns and safety in the light of the COVID-19 global pandemic adds a further challenge to delivering field teaching. Although acknowledged as an effective method for improving 3D thinking and spatial skills and a positive learning experience for many (Marques et al. 2003; Boyle et al. 2007), geological fieldwork may simply not be possible in the current situation and for a number of individuals may potentially negatively impact on their learning experience.

1.2 Classroom-based teaching of spatial skills and 3D thinking

65 Field-based training works to develop 3D thinking and spatial reasoning skills, yet most teaching of geological skills including spatial reasoning and 3D thinking happens in the classroom. This is partly because of the issues discussed, but mainly because of the practicalities of delivering undergraduate level University courses. Classroom based teaching also develops the skill of 'seeing' information in 2D (e.g. maps & cross-sections) or pseudo 3D (e.g. fence diagrams) and thinking in 3D. These 2D to 3D spatial skills underpin the concept of 3D thinking. 2D representations of our 3D world are common, not only in the

70 geoscience classroom (e.g. Newcombe and Shipley, 2015), but in everyday use e.g. walking maps and guidebooks. Despite an increasingly digital and virtual world, 2D paper solutions are predominantly used in the classroom, and in other aspects of life, to convey 3D relationships including those of geological geometries in the subsurface. Research has shown that students often have difficulty in visualizing 3D geometries from these 2D materials (Ormand et al. 2014). These difficulties can be because of several factors, including a lack of training (e.g. how to read a map properly) and inherent difficulties with spatial thinking

75 (e.g. Liben & Titus, 2012). Liben & Titus, 2012 suggest that *"Students arrive with underdeveloped spatial skills because there is inadequate attention to spatial thinking in both formal and informal education".* Yet spatial thinking has been identified as important for success in undergraduate STEM courses (Uttal and Cohen, 2012) as well as in geoscience (Riggs and Balliet, 2009, Titus and Horsman, 2009); yet evaluation of effective methods for teaching spatial skills and their development is limited to a few key investigations (Ormand et al. 2014; Gagnier et al. 2016; Ormand et al. 2017, Gold et al. 2018).

80 **1.3 Virtual outcrops for supplementing field and classroom-based training**

The rise in Virtual Worlds, including Google Earth and virtual gaming environments, and a parallel revolution in digital photogrammetric (structure from motion (SfM)) techniques has changed 3D digital teaching possibilities. Virtual outcrops and hand samples can now be rapidly generated at low cost and presented through online teaching platforms. COVID-19 and the cancellation of many field courses globally has resulted in the rapid development of many virtual field trips, virtual outcrops

85 and experiences in what had previously been an emergent area of expertise and teaching resources (e.g. Bond & Wightman, 2012; Whitmeyer, 2012; Granshaw & Duggan-Haas, 2012; Pringle, 2014; De Paor, 2016; Houghton et al. 2016; Carbonell et al. 2017; Cawood and Bond, 2019). Many newly developed fieldtrips and resources can be found online (e.g. NAGT website https://nagt.org), we do not review the efficacies of specific resources here, but acknowledge that studies have shown that

virtual field trips can improve learning outcomes and student experiences (e.g. Klippel et al. 2019) and gains in content
90   knowledge (e.g. Markowitz eta l. 2018; Mead et al., 2019). The Blended Learning Environment in which online material
including virtual field trips (e.g. Whitmeyer & Dordevic, *in press*), outcrops (e.g. Cawood & Bond, 2019) and thin sections
(e.g. Herodotou et al. 2018) that support traditional classroom learning is here.

In this new era of Blended Learning with virtual fieldwork and online material, fully understanding the efficacies and
95   limitations of these digital resources is increasingly important. The use of such digital resources is generally shown to have a
positive impact on the student experience and some studies have shown improved learning outcomes, but no known studies
have addressed the effectiveness of digital content for specifically teaching spatial awareness and 3D thinking in geoscience.
In this study we use web-based 3D virtual outcrop reconstructions, and block diagrams of structures to test whether these
virtual 3D models are more or less effective than traditional materials (photographs, geological maps and cross-sections) for
100   conveying 3D structural geology. We enhance our findings by asking several cohorts about their general perceptions of using
the 3D virtual outcrop reconstructions, including in what contexts they found them useful and whether they felt that virtual
outcrops should be included in curricula to improve learning, the learning environment and experience.

2. Methods

2.1 Questionnaires and online quizzes

105   An online set of quizzes and questionnaires were completed by two cohorts. Cohort 1 were final year undergraduate geology
students and comprised of 67 respondents who undertook an online class-based exercise. No data on student background or
expected degree grade was collected or considered in the analysis. Cohort 2 comprised of individuals enrolled on the
JISCMAIL Geotectonics list server. This cohort is considered as academic and industry structural and tectonic geology
specialists representing a range of experience and career levels. Cohort 2 consisted of 156 respondents, and data on age and
110   affiliation were collected to provide some context for analysis. The cohorts participated in three distinct elements that together
formed the set of online questions and quizzes, with Cohort 1 completing all the elements and Cohort 2 completing elements
1 and 3. The first element: 1) considered geospatial awareness using three different representations of the same geological
structure: a geological map, an oriented field photograph and a 3D virtual outcrop model. Participants looked at each
representation and were asked to choose one of four block diagrams that they thought best reflected the structure observed.
115   The second element: 2) focused on a virtual field site and outcrops created by SfM from a locality previously visited on a day
field trip by Cohort 1. For this cohort it allowed a direct comparison between their visit to the site in person and their viewing
of the field site and outcrops digitally. The final element, undertaken by both cohorts, 3) focused on the perceptions of the
participants in their use and experience of virtual outcrop models. The three elements are outlined in more detail below.

2.1.1 Geospatial Awareness

In an online quiz both cohorts were presented with a map, oriented field photograph and a 3D virtual outcrop model of the classic syncline structure in carbonates that forms a sea stack at Stackpole Quay, Pembrokeshire, SW Wales (see, Cawood et al. 2017 for further context and here for a link to the Virtual Outcrop model: www.e-rock.co.uk/stackpole). Each representation appeared in the sequence; map, field photograph and virtual outcrop model to participants, and associated with each representation were four block diagrams, from which participants were required to choose the one which was most representative of the syncline structure (Figure 1). The virtual outcrop could be zoomed and rotated and embedded into the virtual outcrop viewer were annotations denoting the orientation of the model (see www.e-rock.co.uk/stackpole). The four block diagrams were similar in appearance, with only small differences in, for example, which limb of the syncline is dipping more steeply, and the direction of plunge of the syncline (E or W).

2.1.2 Post-fieldtrip Virtual Outcrop

This element undertaken by the undergraduate cohort only (Cohort 1) built on an annual single day fieldtrip, for students in the third year of a four-year UK undergraduate course. This day trip takes students to investigate Dalradian metasediment exposure along the Moray Coast, Scotland near Macduff. The Dalradian metasediments are folded at a range of scales (from centimetres to hundreds of metres) in a series of upright folds. Sedimentary structures are retained in many units and a combination of way-up criteria and cleavage development in pelitic layers allows the large scale folding to be determined. Students are tasked in the field with building a cross-section using bedding and cleavage orientations together with the concept of vergence to build-up a picture of large-scale folding along the coastal section (Figure 2). Students generally find the exercise challenging as the coastal exposure has sections that are missing or inaccessible and therefore requires visualisation skills and the confidence to make predictions between isolated outcrops to create a complete cross section. It is also the first time the students actively use the concept of vergence in the field, taking a theoretical concept presented as 2D images and cartoons in the classroom into a 3D physical space. When surveyed, students cite difficulties in understanding bedding-cleavage relationships (42%) and internally visualizing the cross-section (41%) as the most challenging aspects of the exercise.

Four months after the day field trip we provided students with a link to the virtual field site and outcrops (www.e-rock.co.uk/tarlair). Embedded annotations, detailed virtual outcrops and photographs provide context and specific examples of cleavage-bedding relationships, particularly where model resolution does not allow these to be observed directly (Figure 3). The students were given computer laboratory time and access to complete the online exercise, but participation was voluntary and it was emphasised to the students that the work would be completed anonymously and would not be formally or informally assessed in the context of their degree study. We asked the participants to respond to eight online statements related to their

perceptions of the virtual outcrop model and how it impacted their understanding of structures at the site. The students responded to these statements by selecting their response from: Strongly Agree, Agree, Neutral, Disagree and Strongly Agree.

2.1.3 General perceptions

155 In the final element participants in Cohort 2 answered two questions about how the virtual outcrops had enhanced, or not, their understanding of the fold geometry and which visualisation: virtual outcrop, oriented field photograph and geological map combination, geological map, or oriented field photograph. Then participants in both cohorts answered three questions about how they perceived the use virtual outcrops models generally, and their use for teaching and research. Multiple answers could be chosen from a range of specified options, these are outlined in figures 6.

160 Note that for Cohort 1, each exercise was completed sequentially on campus in a computer laboratory space through an online quiz, and with access to the virtual outcrops and field sites. For Cohort 2 elements 1 and 3 were completed sequentially through a single online quiz.

3. Results

3.1 Geospatial awareness and choice of block diagrams

165 The geospatial awareness element was completed by both cohorts making it possible to amalgamate and compare the results across a range of career stages and affiliations. We divided the results into the following career stage/affiliation categories: 1) Undergraduate and Masters students (82 participants), PhD Students (26), Professional (28), Academic (70) and other (7). Combining data from Cohort 1 and 2; BSc and MSc students (e.g. Cohort 1 and those that identified themselves as this in Cohort 2) perform worse than other categories in identification of the most representative block diagram, whilst the self-

170 identified Professionals in Cohort 2 do the best. Overall participants found identifying the correct block diagram from the field photograph the most difficult with only a 40% success rate. Participants were better able to identify the most representative block diagram to match the virtual outcrop model and map. Overall, participants performed best when using the virtual outcrop model (59%), as compared to the map (50%) (Figure 4). The response data in Figure 4 is broken down into affiliation categories, these effectively show the difference between experience levels; there is a general increase in correct response rate

175 with increasing experience. We also note that in contrast to the overall results, both PhD students and academics were more likely, 65% and 74% respectively, to choose the correct block diagram after viewing the geological map.

3.2 Post-fieldwork virtual outcrop access perceptions

Cohort 1 generally responded positively to the eight statements about use of the virtual outcrop model to enhance their learning and understanding (Figure 5A). For six of the statements the majority of the participants, between 60-83%, answered Strongly

180   Agree or Agree. These statements focused on the visualisation of geometries, for example; the participants felt that the virtual outcrop model improved their understanding of structural geometries, with the majority of students (60%) selecting either Strongly Agree, or Agree from the response choices (Figure 5A). The two statements that were not answered so positively were: "*has changed my ideas about the structural geometries at MacDuff, since visiting the area last year*", to which the most chosen category was neutral (40%), with an approximately symmetrical split of answers around this majority neutral response.

185   The other statement that did not elicit a positive response was: *"allows me to differentiate between psammite and pelite more easily than in the field"*. We investigate the potential reasons for these responses in the discussion (Sect. 4.4).

3.3. General perceptions of virtual outcrop models

Having viewed the virtual outcrop model of the Stackpole syncline Cohort 2, similarly to Cohort 1, felt that the virtual outcrop enhanced understanding of the fold geometry, with 83% of participants Agreeing (54%) or Strongly Agreeing (29%) (Figure

190   5A). The majority of Cohort 2 participants also felt that the virtual outcrop provided the best appreciation of the fold geometry (62%) in comparison to the field photograph and geological map combined (20%), the geological map (15%) or the oriented field photograph (3%) (Figure 5A).

Both cohorts (1 & 2) answered questions about why they found the virtual outcrop useful, if they felt virtual outcrops could

195   be used as a teaching and training resource and finally if they felt they should be used. Figure 6 shows the responses to these questions as a percentage of participants in the whole cohort. The participants found the virtual outcrop useful mainly because they could rotate and view the structure from several angles (86%), with a further 53% indicating that they found the ability to zoom in and out to see different levels of detail useful. Only 3% of all 223 participants did not find the virtual outcrop useful. Cohort 1 also Agreed or Strongly Agreed (72%) with the statement that *'the virtual outcrop allows me time and space to*

200   *carefully think about structural geometries'*. 87% of participants felt that virtual outcrops had potential to teach geological concepts in the classroom, with 75% of participant Agreeing that they could be used to reinforce field-based training. In contrast only 1% of participants felt that virtual outcrops had no potential as a teaching or training resource. However, only 2% felt that virtual outcrops had potential to replace field-based teaching.

205   **4. Discussion and Conclusions**

In our experiment we found that a virtual outcrop model aided participants' ability to identify the block diagram that best represented the cropping out structure from a choice of four. In conjunction with these results we found that the participants perceived significant value in the use of virtual outcrops as a teaching and training resource. Here we discuss the limitations

210   of our spatial thinking experiment, the challenges in soliciting opinions and perceptions, the implications of our results for

spatial thinking and learning, the perceptions of participants and reasons behind these, with a view to inform spatial thinking and learning, and finally suggest how virtual outcrops might be used in a blended teaching environment for the benefit of all, but particularly to improve equality, diversity and inclusion in geoscience field work.

4.1 Experimental limitations

215 As is common to all experiments, our experimental methods likely impacted our findings to some degree, which we discuss here. The experiment was delivered online and the software we used for this online delivery did not allow randomisation of questions. Hence the sequential representations of the Stackpole syncline structure as a map, field photograph and virtual outcrop in the spatial thinking element were always presented to participants in the same order. This is likely to have resulted in some growing knowledge through the sequential exposure of these different representations. In order to help mitigate this

220 issue we changed the location of the 'correct' block diagram, in the set of four, so that participants had to critically investigate elements of the representation they were viewing to match against the details in the different block diagrams. Future studies that both engage a greater number of participants and that include randomisation of question order and visual representations would be useful to support or challenge the findings presented here on spatial thinking using virtual outcrops.

4.2 Challenges in soliciting and interpreting perceptions of participants

225 Spatial thinking experiments that show learning are hard to construct because of a series of confounding issues (Ormand et al. 2018), and like several other studies (e.g. Gold et al. 2018) we focus on the perceptions of participants to add value and depth to our results. In our interpretation of the perceptions of participants we acknowledge that the perception of value to learning for an individual may not correspond to actual impact on their learning, as noted by Oloruntegbe et al. (2010) and DiPiro (2010). However, we also note that perception of value and positive experiences aid learning (Lopez-Perez et al. 2011, Gillen

230 et al. 2011). In this context we interpret the perceptions of participants purely as positive, negative or neutral experiences without deriving any implication for affective improvements in learning or geological understanding, but as an indication of how to create positive learning experiences and environments.

Given the nature of the study and the form of questions in the experiment participants may have felt that in being asked about

235 their perceptions of virtual outcrop use the study was hypothesising or expecting positive responses. This may also be viewed as being reinforced by some of the statements provided. Such as is possible we attempted to mitigate these confounding elements by free and anonymous participation of individuals and opportunity to choose negative statements. In this respect we believe that we provided participants with free choice to respond negatively, neutrally or positively to how they found virtual outcrops and their potential use for teaching and training, and indeed some participants, albeit a small number, did choose

240 negative responses.

4.3 Spatial thinking

The results of the spatial thinking element of the exercise showed that participants performed better when using the virtual outcrop model (59%), as compared to the other representations. Although overall the virtual outcrop model proved to be the representation that resulted in the most correct block diagram choice responses, both PhD students and academics were more likely to choose the correct block diagram after viewing the geological map. We suggest that this may be due to familiarity with map-based problems, amongst PhD students and academics, rather than in working in a digital 3D environment, which may be more familiar to undergraduate and masters students through gaming and for industry professionals working in digital 3D interpretation software. These suggestions are suppositions and further research is needed from which to draw robust conclusions. Irrespective of the variance in response between affiliation categories, it is increasingly common for geoscientists to spend a significant proportion of their time at a computer and visualising geology digitally in 3D is common practice in industry. Virtual outcrops provide a clear opportunity to bridge the gap between 2D representations of 3D information, common in classrooms, and interpretation and analysis of geoscience data and information within a digital 3D environment in industrial applications.

The ability to work between 2D representations and 3D is identified as a specific and important skill for geoscientists (Ormand et al. 2017). Even in advanced professional geoscience software e.g. for seismic interpretation, the user is often working between 2D and 3D space because of the constraints of desk-top digital environments for fully immersive 3D interpretation and interaction. Building skills to manipulate and interrogate virtual outcrops and to go between 2D representations and views into 3D space in a digital environment, in the context of future working environments, would appear to be a good thing. It will build digital skills analogous to those used in software for subsurface datasets. The ability to think in 3D, as highlighted by employers as a key skill for geoscientists (e.g. Butler, 2008), is likely to be enhanced by working in 3D space (Woods et al. 2016, Carbonell et al. 2017). Given the need to work between 2D and 3D representations, development of virtual environments in which not only map view is possible but section views can be seen would likely aid such skill development. These types of section view are available in digital block model generators such as PyNoddy (e.g. Wellmann et al. 2016), and the ability to move between maps and sections, and draped realisations of these (e.g. Bond and Wightman, 2012), and other data e.g. synthetic seismic imagery (e.g. Anell et al. 2016) in a virtual field environment would likely add learning value.

4.4 Perceptions of virtual outcrop value for 3D spatial thinking and learning

Positive responses to statements were made by both cohorts about virtual outcrop use. These included: being able to rotate and view the structure from different angles (86%) and being able to zoom in and out to see different levels of detail (53%). Only 3% of the 223 participants across both cohorts responded that they didn't find the virtual outcrop useful.

With the students that formed Cohort 1, we were able to investigate their perceptions of access to virtual outcrops and a virtual field site model after visiting the site on a day field trip. Their responses to the virtual field environment were positive,

275   particularly for elements that involved 3D spatial understanding, the majority of participants Strongly Agreeing or Agreeing to statements such as: *allows me to better appreciate the 3D nature of the landscape* (83%), *allows me to better visualise the cross-section and where the fold hinges would be* (74%), and *allows me to better appreciate the spatial distribution of the outcrops and how they link to each other* (82%). Cohort 1, undergraduate students, perceived that access to the virtual outcrop and field site helped their 3D appreciation for the field site and structures.

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Two of the statements that Cohort 1 responded to focused less on 3D spatial understanding aspects, rather on over-arching understanding and rock identification; responses to these questions were less positive. The two statements that were responded to less positively were: "*has changed my ideas about the structural geometries at MacDuff, since visiting the area last year*", to which the most chosen category was neutral (40%), with an approximately symmetrical split of answers around this majority

285   neutral response. We interpret this as the virtual outcrop confirming existing opinions from the participants field experience rather than informing any radical re-interpretation. This response was expected given the virtual outcrop use in a context where students have previously developed a conceptual model in the field.

The other statement that did not elicit a positive response was: *"allows me to differentiate between psammite and pelite more*

290   *easily than in the field"*, with 46 % of participants Disagreeing or Strongly Disagreeing with this statement, we believe this highlights two things. Firstly, the importance of observing rocks and their textures in the field and that photography and virtual outcrop models, are not the same as viewing something in its physical reality in terms of detail. The ease of transition between scales in the field may also be critical to effective learning and assimilation of information. In the case of the virtual field site used here, a higher level of rock texture detail in the photogrammetric reconstruction may have improved the ability of

295   participants to distinguish between rock types in the virtual outcrop. Secondly, that for geological field observations a range in scale is often important. Virtual outcrops with tiled photographs allow observations at a range of scales. The resolution of UAV photography and UAV and SfM technology is improving at a significant rate, making higher resolution models at different scales increasingly possible, even with limited viewing hardware. The balance in the near term will be on rendering models with high enough resolution to be effective, whilst understanding the limitations of internet/cloud access to virtual

300   outcrop resources and the participants' own operating hardware. In terms of the range of possible scales virtual outcrops have the potential to provide a transition across multiple scales, from satellite imagery to hand lens view. With potential assimilation of thin section imagery and beyond into electron microscopy in an integrated environment they could surpass in-field possibilities, in terms of the range of observational scales available. Web-based viewers with 'seamless' transitions between views and across a range of scales at this level is not yet available, however.

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In the field participants are fully embedded in the 3D space. The scale of the landscape relative to the viewer is easily apparent. With the use of a map participants can take this 'in landscape' view point into a bird's eye view if they have accomplished 3D thinking and spatial skills. It is difficult for even the best virtual outcrops and virtual field sites to compete with the experience of being physically present in a landscape and the associated appreciation of relative scale. In terms of viewpoints the

310 participant in the field is limited by local topography in their ability to gain different viewpoints and perspectives. In a virtual outcrop or virtual field site effectively any view point is possible and the translation from within the model to a bird's eye (map) view is straightforward. Participants from both cohorts recognised being able to rotate and view the structure from different angles (86 %) as a key benefit of virtual outcrop models. Virtual reality environments also increasingly allow participants to be embedded in the scene, this we believe will become a significant area of development in virtual geoscience

315 field trip environments. In summary carefully built virtual environments have a lot to offer in terms of the range of scales of observation and view points, and in some areas offer more than the field experience. The value of these elements in terms of 3D spatial thinking is perceived positively by participants in our study using virtual outcrops.

4.5 A role for virtual outcrop models in blended learning

Perceptions across all participants on the potential for virtual outcrop use as a teaching or training resource was high, with 87

320 % of participants Agreeing with the statement that virtual outcrops have potential to teach geological concepts in the classroom, and to reinforce field teaching 75%. These positive responses to statements were backed up with a further 81% of all participants Strongly Agreeing or Agreeing to the statement that *'Virtual outcrops should be used for teaching geoscience undergraduates'*. Only 5% of all participants Disagreed or Strongly Disagreed with this statement, and only 1% indicated that virtual outcrops have little to no potential as a teaching or training resource. The potential role of virtual outcrop models for

325 teaching and positive perceptions of virtual outcrop use for teaching and learning across a range (age, career level) of geoscientists is clearly documented in our study.

Advantages and disadvantages outlined in our discussion on perceptions of the value of virtual outcrops for 3D spatial thinking and learning (Sect. 4.4) suggest that virtual outcrops and field experiences are not a replacement for fieldwork, but can

330 significantly enhance learning and can be used as part of a positive learning experience. Survey responses support this, with only 2% of participants Agreeing with the statement that virtual outcrop models have the potential to replace field-based training. The positive responses to how virtual outcrops may enhance learning and training opportunities do however call for them to have a place alongside field training in a blended learning environment. The pure educational benefits identified in this study, and the positive perceptions of learning experiences and benefits support this argument. But there are clearly other

335 advantages in terms of equality, diversity and inclusion in geoscience, as raised in the introduction, where virtual outcrop models and virtual field sites have several major advantages over in-field experience, such as: (1) Virtual access for those who can't get to the field because of disability, financial constraints etc., or who find it difficult to operate effectively in the field, (2) access to global locations and viewpoints to areas that are simply not accessible during traditional fieldwork, for anyone.

(3) The ability to go at your own pace, with less pressure, fewer distractions or concerns. To improve, equality, diversity and
340 inclusion in geoscience and field access virtual outcrops models and virtual field sites, we believe, have an indisputable role.

Blended learning, flipped learning and other models that integrate self-learning practices with taught elements, are growing with increasing access to education at a range of ages and career stages. e.g. the University of the 3rd age and online MOOCS. These have become possible in part through the growing digital revolution and an associated ease of accessibility. For
345 geoscience and for geological field work in particular, digital delivery has until COVID-19 been a slowly evolving field, which in 2020 has experienced significant acceleration in learning and practice. We argue that in a post-COVID-19 World virtual outcrops and field experiences have a key role to play in blended learning environments to improve 3D spatial thinking and learning, in creating positive learning experiences and to significantly improve equality, diversity and inclusion in geoscience field work.

350 **Author Contributions**

Clare Bond conceived the experiment; in collaboration with Adam Cawood together they determined the questions and designed the online questionnaire. Cawood built the online questionnaire and created an initial analysis of the results through creation of the main figures/tables in the paper. Together the authors discussed the results and a paper narrative which Cawood outlined based around the study results. Bond then wrote the manuscript which Cawood edited and commented on.

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Figures
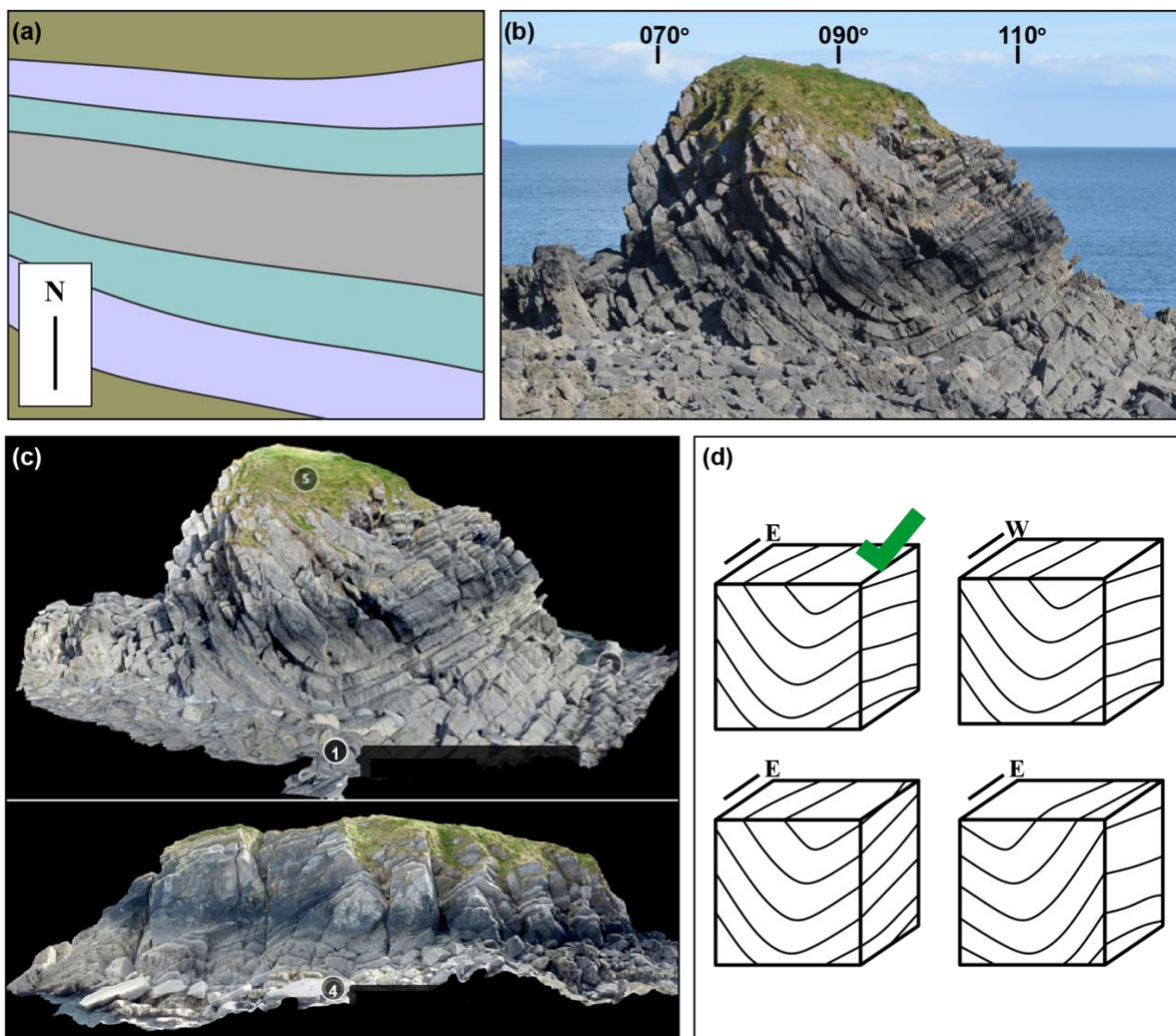
Figure 1. Representations of the Stackpole Syncline, Pembrokeshire. a) Map view, b) Field photograph, with marked orientation directions, c) Two views of the virtual outcrop, top view looking East, bottom view looking South. The numbered annotations seen on the virtual outcrop give the participants the directional information and are embedded into the viewer. D) The four block diagrams from which participants had to choose the most accurate representation. The most accurate representation is the top left block diagram noted by the green tick.
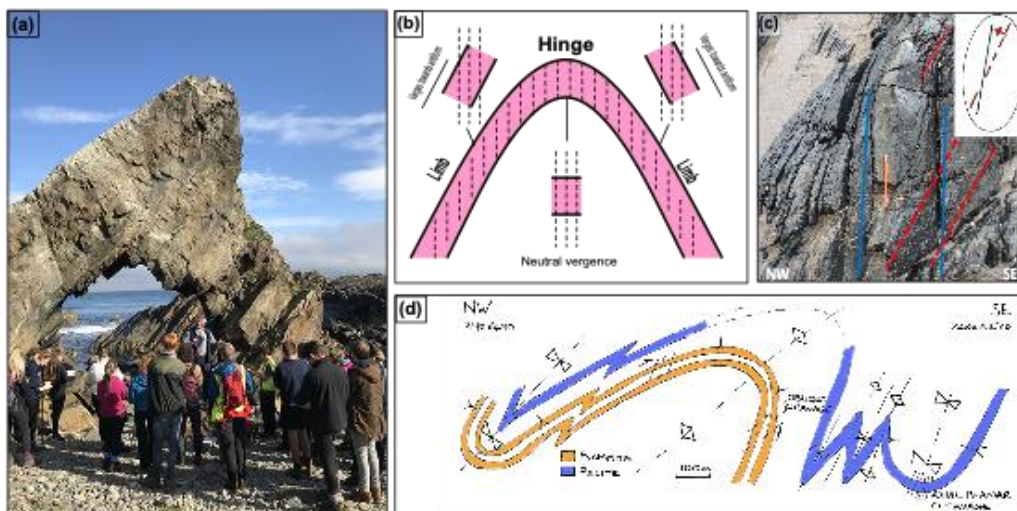
Figure 2. Summary images of a day field exercise to map folds in Dalradian metasediments and to use the concept of cleavage vergence to create a cross-section. a) Example student group being shown bedding-cleavage relationships in the field and how they can be used to predict an anticline of syncline along section. b) Class-room based course material showing cleavage-bedding relationships around a fold; the students employ this concept in the field to build a cross-section. c) Example from a field photograph of a bedding-cleavage relationship and interpretation, and d) worked solution cross-section. Note course material and worked solutions developed by Ian Alsop, Clare Bond and Rob Butler.
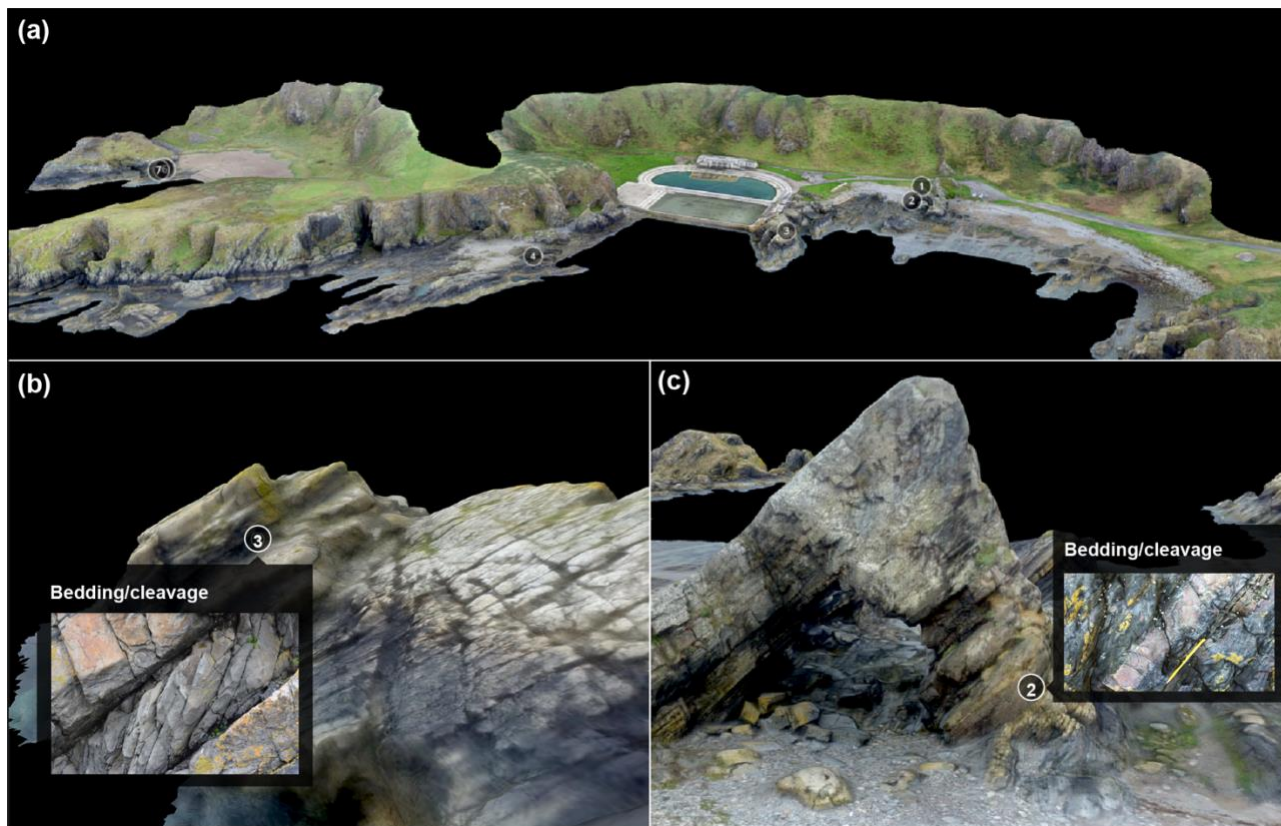
Figure 3. Virtual field site and outcrops. The panels show a) the whole field site, numbered annotations zoom the student into greater detail, as shown in b), with a higher resolution field photograph pop-up, and c) annotation 2, that links to detailed virtual outcrop model of the bedding-cleavage relationship.

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Block diagram quiz	Affiliation					
	BSc or MSc Student (82)*	PhD student (26)	Professional (38)	Academic (70)	Other (7)	All (223)
Geological Map	40	65	74	72	43	50
Field photograph	25	46	47	50	57	40
Virtual Outcrop	47	46	79	67	71	59

Figure 4. Responses to the geospatial awareness test in which participants had to identify the most representative block diagram given a: 1) geological map, 2) field photograph, 3) virtual outcrop model. Data from both Cohorts 1 are represented in the figure. The amalgamated data are split into five affiliation categories, actual numbers of participants in each affiliation category are given in parentheses after each category. Percentages are given for the correct response.

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(a)	Cohort 1 (n = 67)				
The virtual outcrop…	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
has improved my understanding of the structural geometries at Macduff	17	43	26	8	6
has changed my ideas about the structural geometries at Macduff, since visiting the area last year	11	20	40	23	6
allows me to better visualise the cross-section and where the fold hinges would be	19	55	19	3	4
allows me to better understand how bedding-cleavage relationships relate to folds	18	46	17	11	8
Allows me to better appreciate the spatial distribution of the outcrops and how they link to each other	28	54	12	1	5
allows me to better appreciate the 3D nature of the landscape	38	45	8	6	3
allows me time and space to carefully think about structural geometries	23	49	17	6	5
allows me to differentiate between psammite and pelite more easily than in the field	11	12	31	31	15
(b)	Cohort 2 (n = 156)				
The virtual outcrop has enhanced my understanding of the fold geometry*	29	54	14	3	0

Which visualization provides the best appreciation of the fold geometry?	The virtual outcrop 62%	Photo & map combination 20%	Geological map 15%	Oriented field photograph 3%

Figure 5. Responses by participants to questions on the value of virtual outcrops to enhance learning and understanding. a) responses by Cohort 1 to eight statements given in column 1. b) responses by Cohort 2 to a single question on enhancement of understanding, and to which of the representations gives the best visualisation of the fold geometry. Responses are given as percentages to the possible answers, see figure 4 for colour scale.

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I found the virtual outcrop useful because:	%
I was able to rotate the structure and view it from several angles	86
It allowed me to zoom in and out, and see different levels of detail	53
It provides me the time to consider the fold geometry carefully	48
I didn't find it very useful	3

Virtual outcrops have potential as a teaching/training resource	%
To teach geological concepts in the classroom	87
To reinforce field-based training	75
As a tool for comparing different sites and subsurface analogues	48
To replace field-based training	2
No, little potential	1

Virtual outcrops should be used for teaching geoscience undergraduates	%
Strongly agree	46
Agree	35
Neutral	14
Disagree	2
Strongly disagree	3

Figure 6. Responses, summarised as percentages, from both cohorts to question on virtual outcrop use and value for teaching.

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