Mobile 3D Visualization Techniques in Field Geology Education

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Abstract

Despite the fact that we are in the mobile computing age, student geologists still carry out geological fieldwork using centuries old tools and techniques. This thesis investigates the question "how can 3D visualization on smartphones and tablets help students learn during geological fieldwork?"

To answer this question, the thesis first reviews the types of difficulty encountered by novice geologists, narrowing it down to one particular issue: the extrapolation of 2D geological features into the 3D real world. The tasks carried out by novice geologists during introductory fieldwork were analysed systemically. This thesis then explored how apps from Android and iOS app stores may be used in the field to carry out such tasks. The overall finding is that there is limited work focused on novice geologists' difficulties during fieldwork, particularly 2D to 3D extrapolation. Then, using a perception test, the options of representing a single strike and dip measurement in a 3D environment is explored. The results of the test was that there were more accurate methods to represent a measurement than a traditional symbol (e.g. a T-shape). Then, a hypothesis was evaluated which states that instead of using 2D geological maps alone, a 3D visualization of strike and dip measurements plotted on them can assist students in understanding geological structures. The thesis then outlines functionality of a prototype that can be used by higher education institutions as a foundation for a novice geologists' field app.

Key findings of the present work are: there has been no apps developed with focus on issues faced by novice geologists doing fieldwork during the time of this study. There was only British Geological Survey's iGeology3D which was released at the time of the study which focused on 3D visualization of geological data to be used in the field. In a separate study an iPad2 was found to be accurate enough for taking strike and dip measurements. In a perception experiment a 3D visualization of strike and dip was deemed to be better for comprehending structural orientation of outcrops but found to be no better than other 2D shapes. Finally, an experiment comparing the use of 2D maps versus 2D maps overlaid with 3D visualization of structural data, the latter found to be more effective for structural interpretation by novice geologists.

Dedicated to

My family (Sakar and Ziney) and my bigger family (mum, dad, my brothers and my only sister)

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Declarations

The candidate confirms that the work submitted is his/her own, except where work which has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

(a) Chapters based on work from jointly authored publications:

  a. Chapter three

  b. Chapter four

(b) Publication list:

  a. Hama, L., Ruddle, R.A. & Paton, D., 2013. 3D Mobile Visualization Techniques in Field Geology Interpretation: Evaluation of Modern Tablet Applications. *Proceedings of AAPG Hedberg Research Conference: 3D Structural Geologic Interpretation: Earth, Mind and Machine*. Reno, NV, USA.

  b. Hama, L., Ruddle, R.A. & Paton, D., 2014. Geological Orientation Measurements using an iPad: Method Comparison. *Proceedings of Computer Graphics & Visual Computing (CGVC)* 2014. Leeds, UK.

(c) In the above (b) list of publications, L Hama was the author of the present work, who carried out the studies. The other two authors were Professor R. A. Ruddle (supervisor) and Dr D. Paton (co-supervisor) of the researcher.

(d) In the above (b) list of publications, the supervisor and co-supervisors lead L Hama through the study and publications.

Glossary

Computer Science

API: Application Programming Interface. A set of tools and instructions to help implement a particular application.

CPU: Central Processing Unit.

CAD: Computer-aided Design.

GL: Graphics Library. Any program that can render computer graphics.

GPU: Graphics Processing Unit. A unit dedicated to carry out graphics processing.

HCI: Human Computer Interaction, the branch of computer science dealing with user aspects of design.

iOS: Apple's proprietary OS running on Apple devices such as iPhones and iPads.

Metal: Apple's new GL for rendering on their iOS device.

OpenGL: Open Source Graphics Library by Khronos Group Inc.

OpenGL ES: OpenGL for Embedded Systems. A lighter version of the standard OpenGL library for mobile devices.

OS: Operating System. Any software that is responsible to manage hardware and software on a computer.

Tablet: Any tablet computer running either any smartphone OS such as Android and iOS.

VR: Virtual Reality, real world is simulated by computer generated graphics.

AR: Augmented Reality, real world scenes are augmented with computer generated graphics.

≡

Geology

AAPG: American Association of Petroleum Geologists.

ASTER: Advanced Space-borne Thermal Emission and Reflection Radiometer.

BGS: British Geological Survey

DEM: Digital Elevation Model, defined as “an ordered array of numbers that represents the spatial distribution of elevations above some arbitrary datum in a landscape” (Moore, Grayson et al. 1991).

DOM: Digital Outcrop Model. Any digital model of a field outcrop.

GIS: Geographic Information System.

Outcrop: defined by Cambridge dictionary as "a large rock or group of rocks that sticks out of the ground" (Cambridge 2015).

SEE: School of Earth and Environment, University of Leeds.

SRTM: Shuttle Radar Topography Mission. International research effort to for global DEM acquisition.

USGS: United States Geological Survey.

“Geological model” or “3D Model”: “Geomodeling consists of the set of all the mathematical methods allowing to model in an unified way the topology, the geometry and the physical properties of geological objects while taking into account any type of data related to these objects”(Mallet 2002), a classification is also given.

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Chapter one

1 Introduction

Gartner research (October 2014) numbers show that 71% of total mobile phones sold worldwide were smartphones in 2014 and that Android OS operated devices to be shipped in 2015 in emerging markets only will hit one billion (Gartner 2014). It is assumed that these devices should be able to assist novice geologists to carry out geological fieldwork more efficiently compared to use of traditional tools and techniques.

Students in Earth sciences often have difficulty comprehending 2D geologic maps and understanding how observations made in the field relate to the real 3D geology around/beneath them (Whitmeyer et al. 2009). Students are taught to do fieldwork using tools and techniques such as printed maps, notebooks and compass clinometers that are reliable and robust but have changed little over a century. An increasing number of higher education institutions worldwide are convinced that the use of Geographic Information Systems (GIS) and other technologies are fundamental to prepare students for their future careers (Schultz et al. 2008).

In the introduction to the Semiology of Graphics French Cartographer Jacques Bertin states *"Graphics can stimulate exceptional motivation, foster better questions, aid in constructing the written text and ...reveal the intelligence of so-called 'poor students'"* (Bertin 1983). Although the present work is about *visualization* of geological field data, or *geo-visualization* (MacEachren & Kraak 2001), visualization is also computer generated graphics. It is assume that novice geologists can be motivated and aided in constructing a 3D visualization of data that is traditionally recorded in text and numbers on modern smartphones and tablets.

This thesis starts by investigating generic issues that student geologists face during fieldwork using traditional tools and techniques. It also investigates the theoretical background of these difficulties. It then evaluates current smartphone and tablet apps and proposes 3D visualization techniques to assist students carrying out fieldwork using smart devices. It also proposes a novel 3D visualization of structural data that is believed to assist novice geologists understand better compared to the use of 2D maps (digital or printed). It ends with conclusions, limitations and future research directions.

1.1 Research objectives

This research is guided by an assumption that smartphones and tablets *should* be able to assist novice geologists comprehend geology *better* during fieldwork. That is such devices could be adopted in addition to traditional tools and techniques to assist novice geologists carry out challenging tasks. This assumption builds on the premise that the use of information technology in general in geological fieldwork has more benefits than possible downsides (Hesthammer et al. 2002). It is also assumed that using 3D visualization technology is a genuine need for teaching geology (Bullen, Morgan et al. 2011).

Based on the above assumption the present work has these objectives:

- Understanding the difficulties faced by novice geologists during fieldwork.
- Understanding the state of the art in using smart devices for use in the field by novice geologists.
- Proposing novel solutions for one or more of the difficulties.

1.2 Contributions

The objectives outlined were met in the present work resulting in the following contributions:

- Systematic analysis of the issues facing novice geologists in the field. First hand observations of students doing actual fieldwork as well as interviewing staff and students. The focus was on analytical issues and spatially challenging tasks not practical or technical difficulties from a novice geologist's perspective.
- Exploratory evaluation of available *apps* (Android and iOS) for use in geological fieldwork. The evaluation was carried out during real student fieldwork. The evaluation found that such apps were not tailored for fieldwork and spatially challenging tasks could not be supported using available functionality on current.
- The first published technical evaluation of an iPad2 for capturing geological data, namely strike and dip (Hama et al. 2014). The results were compared with measurements taken using a traditional tool. The results showed the iPad2 was accurate and consistent for dip angle measurement but not so for strike.
- User evaluation of four methods of representing strike and dip measurements in a 3D virtual environment. This was achieved by a perception experiment using a method known as "staircase" in psychophysics, and showed that use

of a traditional “T shape” had significantly worse performance. All of the new proposed models (disc, square and wedge) allowed more accurate judgements.

- User evaluation provides more evidence that the visualization using the results of the last contribution could assist comprehension of the geological structures compared to using just 2D maps.
- The design and implementation of a proof of concept for a novice geologist field app on an Apple iPad2.

1.3 Thesis overview

In the next seven chapters, each of the contributions outlined in the last section. Chapter two includes the required background reading and some important preliminary analysis. Followed by an exploratory field study in chapter three, which leads to an experiment on the accuracy of smart devices for data collection by novice geologists described in chapter four. Chapter five then outlines a novel perception test on the use of 3D visualization of field data. It follows by another experiment of using 3D shapes for structural geological analysis. The work in these chapters is then summarised as a proof of concept app for novice geologists to use in in the field in chapter seven. The last chapter contains conclusions, limitations and future directions of further research.

Chapter Two

2 Research background

2.1 Introduction

This chapter introduces the background research and concepts that are relevant to the work outlined in subsequent chapters. The nature of the work requires understanding and background research into various subjects and disciplines, whilst the focus of this work remains on visualization of geological data to aid comprehension during geological fieldwork by novice geologists. This chapter also includes original work which is presented in this chapter and constitute part of the contribution of the present work.

Researching 3D visualization techniques to assist novice geologists requires in depth understanding of certain topics. These include the issues and aspects related to field geology education, a theoretical background from cognitive science about the spatial abilities required to study geology in general, and scientific visualization as the launch ground for proposing suitable methods of visualizing geological structures in a mobile app.

That is why the chapter is structured as follows: introducing geological field work and related concepts such as mapping and map reading difficulties to start with. It then covers traditional tools which are related to the work carried out in the subsequent chapters. It then covers spatial cognition and relevant topics overlapping between psychology and earth sciences. It then moves onto a systematic analysis of the issues faced by novice geologists. The issues are researched using the literature and from work carried out for this research. This includes first hand observations, interview of staff and students at the School of Earth and Environment (SEE) at the University of Leeds. It finally covers the state of art in geological information systems ending with brief outline of modern app ecosystems.

Due to the scope of this thesis, this chapter does not cover literature related to human visual system. It also does not cover the role of scientific visualization in education or any pedagogy related topics. This thesis also does not cover in any detail the temporal nature of geological data.

Three factors are considered to be the rationale for an assumption that a mobile device taken to the field to analyse field data *should* be able to assist novice geologists. These are: the superiority of human visual system is "best" described by J Bertin (Bertin 1983, p.3), earth sciences is one of the most visual disciplines (Saini-

Eidukat et al. 2002) dealing with the structure and evolution of Earth and finally fieldwork is still regarded as one of the most important ways of teaching geology.

The subject of geoscience is both spatial and temporal (K. J. W. McCaffrey et al. 2005). All four dimensions: 1D (size and scale), 2D (shapes and maps), 3D (geological models) and 4D (geological models over time) play a role in learning and teaching geological sciences. For example role of 1D (size and scale) is reported to be important in geoscience cognition such as use of size of grains to determine a rock type (Delgado 2012). US K-12 students are reported to encounter difficulties with cognition of size and scale such as estimating the size of an atom, or the size of the Earth compared to the sun (Delgado 2009, p.6).

Geological structures are distributed on a large scale in 3D space and have a geological time dimension, so visualizing them is a challenging task for novice geologists. It has been almost a century since (Eckert & Joerg 1908) stated that it is impossible to represent 3D space on 2D paper, it is also reported (Barnes & Lisle 2004, chap.1) that S R Wallace famously argued in a lecture in 1975 that substitutes for 2D maps does not exist "*there never was and there never will be*".

Many earth sciences departments use modern desktop applications but rely on traditional tools and techniques for fieldwork (Jones et al. 2009; Whitmeyer et al. 2009; Whitmeyer et al. 2010), including School of Earth and Environment (SEE) at the University of Leeds. These are the tools and techniques that higher education students wish to put behind them (Murphy 2011). To address this, some UK universities have started using mobile devices in geological field trips since 2005 (FitzPatrick 2011).

One of the conventional and essential tools for teaching geological fieldwork is a printed map. Students have to learn to visualize the third dimension of geology they study from these maps, whether printed or in digital format (Rapp et al. 2007; Whitmeyer et al. 2009) to be able to develop the spatial awareness skills required in their discipline. This has been acknowledged as an "intellectual exercise"(Patnode & Hodgson 1964).

According to (Newcombe 2012), assisting students with their spatial difficulties may be divided into two categories: educating students in their spatial skills and *"improving the presentation of geoscience material"*. There is evidence that domain-specific spatial ability can be trained, for example, in the case of dental students spatial ability (Hegarty, Keehner et al. 2009), this research is dedicated to "improving the presentation of geoscience material". That is focusing on 3D visualization of geological data taken to or collected in the field by novice geologists.

Geological field trips are an essential part of teaching geology in higher education institutions. The tools and techniques for fieldwork have not changed for many years, and students often have difficulty *visualizing* geological structures using them (Whitmeyer et al. 2009). Therefore it is also necessary to outline the tools and techniques used to carry out fieldwork conventionally.

2.2 Geological fieldwork

A description for "geological field work" is given by Coe, Argles, Rothery, & Spicer, (2010 p1) as: "*Fieldwork involves making careful observations and measurements in the field, and collection and precise recording of the position of samples for laboratory analysis*". The role of fieldwork in the learning process is "*direct experience with concrete phenomena and materials*" (Orion 1993), and there is a substantial amount of research around the role of field work in geological fieldwork education as well as wider scientific field work. Geological field work is also a substantial part of the teaching process within the SEE at the University of Leeds.

The starting point for a mental model of the underlying geology of an area by a geologist is developing a spatial understanding of the *outcrops* (visible exposure of rocks). The finishing point is a 3D geological model of the field area, produced by a repeated process of extrapolating and interpreting observations and measurements. Altogether, this is part of what geologists call "thinking in 3D" and has been acknowledged as "*not necessarily easy come*" (Twiss & Moores 1992). This can be illustrated in Figure 1, where a geologist is able to explore and area equipped with tools and data in form of maps, he or she is then expected to form a 3D geological model of the field area or maybe even the wider region.

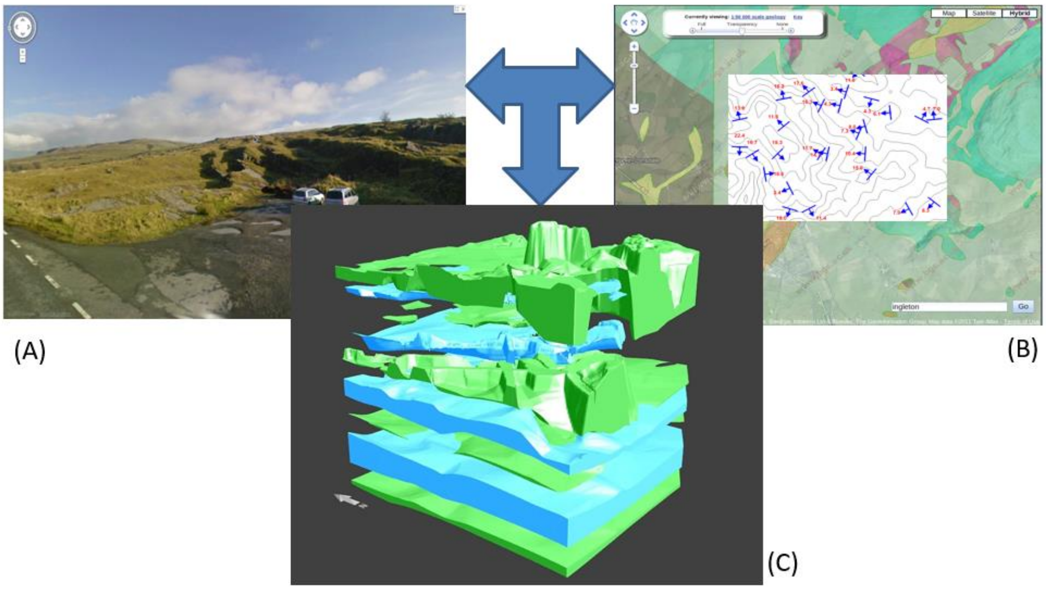


Figure 1: An illustration of geological fieldwork where (A) real scene and (B) geological maps plus geological data need to be translated into a 3D model (C) by the geologists. Image (A) is an image taken in Ingleton during one of the field trips by the School of Earth and Environment (SEE), University of Leeds. Image (B) is a screen shot from British Geological Survey (BGS n.d.), with some arbitrary strike and dip data. Image (C) is a 3D geological model by (MLU n.d.). The three are not related to each other.

2.2.1 Geological mapping

For the theoretical and precise definitions of maps, scales, projections and other aspects of general mapping the reader is referred to (Bertin 1983, sec.III Maps). The ubiquity of Geographical Information Systems (GIS) such as Google Maps and others and their role in location-based services (LBS) are evidence of the power of conventional mapping to a wider audience. Mapping is the foundation of different disciplines including geological sciences (Liben, L. Kastens, K. A. Stevenson 2002; Xu et al. 2000). The effectiveness and wider usage of geological maps is discussed by (Liben, L. Kastens, K. A. Stevenson 2002).

The definition given by SEE for geologic maps is *"Geological maps represent the solid geology at the Earth's surface unconcealed by vegetation, soil or buildings"*(Houghton n.d.). Geological mapping is just another "layer" of conventional mapping, although similar to conventional mapping *"Geological maps are made for a variety of purposes and the purpose typically dictates the nature of the map units"* (Groshong 2008, p.4). Also "*Geological maps show the distribution at the earth's surface of different kinds of earth materials. To geologists, maps are fundamental tool*" (Maltman 1990, chap.1).

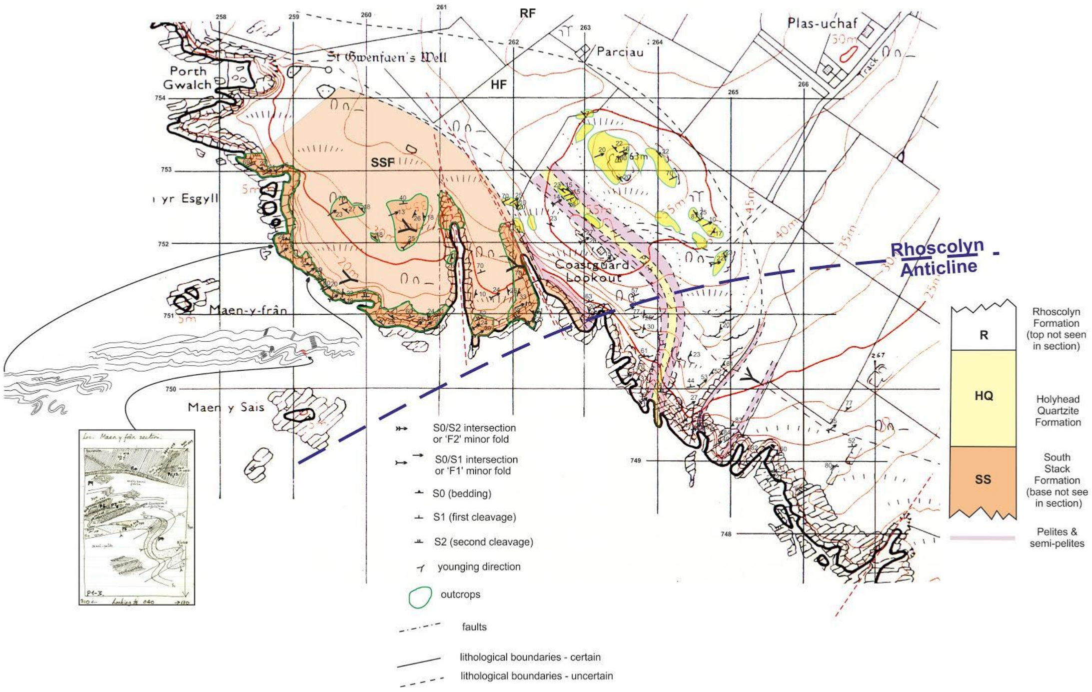


Figure 2: Geological map of Roscolyn area of Anglesey, Wales, UK (Lloyd 2014).

Similar to general purpose maps, geologic maps also come in different scales and are produced for different purposes but usually use a topographic map as the base. There are conventions where organisations follow a specific mapping scale but then publish the maps in different scales(Roberts 2013, p.2). Rock types and geological formations are illustrated using colour codes with or without symbols. These vary by different authors and thus requires legends to explain colour codes and other representations (Fossen 2010, p.8). Geological maps are used by various disciplines within Earth Sciences. Although like general purpose maps geological maps are also meant to help in visualizing the geology in 3D (Houghton n.d.), for the purposes of this research structural maps are of interest.

In the UK, as shown in Figure 2, the geographic coordinates used is the UK National Grid. This is 100km squares which are used to locate objects on a geological map. These 100 km squares are then subdivided into smaller squares in order to increase accuracy of locating objects within a map. Whilst a two letter code (e.g. TL) locates an object within a 100 km square, a two letter code and four digit “grid reference” (e.g. TL3670) provides an accuracy of 10lm square area.

2.2.2 Map reading difficulties

This is a wide area of research. Researchers have been studying the difficulty of reading maps for various purposes such as navigation, generating topographic and geological maps. One of the steps in navigating using maps is determining a location on a topographic map. One study where blindfolded subjects were lead to a location and were not allowed to discover the field, none of the subjects were able to locate themselves on a topographic map (Herbert & Thompson 1991). This study highlights the extreme case of reading topographic maps. Due to the variety purposes of using maps and different types of maps, the focus in this section is on the use of maps (topographic or geological) for geological fieldwork by novice geologists.

The difficulties children and adults have reading maps is described by Ishikawa and (Kastens & Ishikawa 2005; Liben & Downs 1993). The person-map-space experiments carried out by (Liben & Downs 1993) was also used by (Kastens & Ishikawa 2005). The latter focuses on geology students' use of maps in the real world when a user is required to carry out tasks by relating the map to the real world. Kastens and Ishikawa (Kastens & Ishikawa 2005) highlight the following difficulties:

- Location correspondence: user location in relation to the map
- Representational correspondence: relationship between user, the map and the space represented.
- Configurationally correspondence: user is able to judge the consistency of the features on the map compared to the real scene.
- Directional correspondence: user needs to align map to the real world
- Perspective taking: user needs to envision different points of view using the above correspondences.

An online self-study guide to help students improve their map reading skills is also produced by them (Kastens et al. 1996). Some spatial skills can be improved by training, but such skills may not be transferable to other tasks and improvement depends on individual spatial abilities (Hegarty 2004; Hegarty et al. 2009).

One of the obvious map reading tasks is to locate oneself on a map. To do this one needs to understand the relationship between the map, the represented space and oneself according to (Liben & Downs 1993). The relationship between the map and the represented space requires the ability to match objects from the space (3D) to symbols on the map (2D) (Kastens & Ishikawa 2005). In the same study they also state that in a previous study using unpublished data children do worse than college students in matching these symbols to objects in the real world.

Two-dimensional topographic maps which are used as the basis maps for the majority of field trips and field work purposes do not show the geometry of the rock that is exposed, for example underlying strata may be vertical, horizontal or dipping in one direction or another (Murck & Skinner 2012). Maps "*rely heavily on spatial* *information to relay meaning*" (Winn 1991), which means such spatial information needs to be read correctly by the map user to get the meaning conveyed. Geological maps and cross sections are interpretative information (Kaufmann & Martin 2008). This is due to the nature of the geological mapping and also the limitation of projecting such spatial information onto a 2D surface such as a map.

Therefore any attempt to represent or visualize any 3D geological structure or phenomena in 2D, whether maps or diagrams (especially geological maps), will cause difficulties for student geologists to visualize at least the third dimension (Turner 1992, p.3) let alone the 4th which is the time dimension. These difficulties have been acknowledged and there have been suggestions that 3D visualization is one way of addressing these difficulties: "*stereo visualization is one method for helping students understand relationships that may be challenging to visualize using flat, two-dimensional map displays*" (Rapp et al. 2007).

The underlying strata of geological structures cannot be seen in 2D geological maps, and such maps would only show *representations* of types of the strata and not their actual shapes (Reynolds et al. 2006; Kastens & Ishikawa 2006). Block diagrams which are one of the other most common illustrations used by geologists (Reynolds et al. 2006; Kastens & Ishikawa 2005) are another attempt at depicting 3D geological features in 2D and show a small proportion of the actual 3D structure (Jones et al. 2009).

2.3 Traditional fieldwork tools

For the purpose of this research, first-hand observation of student fieldwork and the expertise of staff at SEE were relied on, as well as literature on traditional fieldwork tools. For more detailed information regarding these tools, the reader is referred to (Lisle et al. 2011, chap.2; Coe 2010, chap.2; Compton 1985).

During two separate fieldtrips, one in Ingleton, North Yorkshire, England; and one in Anglesey, Wales; students were observed as they were being educated in map reading, triangulation, keeping a geological diary (notebook), use of compass and clinometers, and structural analysis paper-based stereonets. During these two trips, novice geologists relied on maps, pen and notebook as essential fieldwork tools. For the purpose of this research, compass clinometers and stereonets require more details and introduction. These two tools are introduced in the next two subsections.

2.3.1 Compass clinometers

Figure 3: A Silva MOD-15 Compass Clinometer

Traditionally, geologists have used compasses to determine geographic orientation of bedding and strikes, and clinometers to determine inclination of rocks. Vendors have produced what are known as compass-clinometers. British geologists have traditionally used Swedish models such as a Silva Ranger shown in Figure 3. American geologists tend to use Brunton compass which is made by a US company Brunton Inc. These are basic tools which are designed to be simple and easy to use. However, it is fair to say that due to the difficulty of understanding strike and dip concepts (Kastens 2009) there has been the need for tutorials and demonstrations in order to accurately apply these simple tools. Indeed, at the fieldwork observations of the second-year students' trip to Anglesey, some still needed reminding of how to use their compass clinometers.

Compass clinometers are used for various purposes. For the purpose of work in subsequent chapters a brief instruction is needed to explain how they can be used. As it is not an easy concept to illustrate it is best to view a video explanation of these instructions such as this one by Dr. Meere (2013).

To measure dip angle one needs first determine a horizontal line on the surface, this makes the strike line whilst the line perpendicular to it towards the bottom of the surface would constitute the dip line. Then, to take a dip angle measurement:

1. Set the clinometer to East – West
2. Hold the compass clinometer vertically and aligned on the surface along the dip angle line (perpendicular to the strike line).
3. Read the angle the black needle makes as it is tilted on the surface as shown in Figure 4.

Figure 4: Dr Meere is taking a dip angle with the black needle visible. The compass is facing Dr Meere so the dip angle is not visible. Image captured from (Meere 2013).

To measure strike angle:

1. Hold the compass clinometer along the strike line.
2. Turn the face of the compass so that the red needle is aligned with the red arrow on the compass.
3. Read either of the two angles from either side of the compass as shown in Figure 5.

Figure 5: Dr Meere is reading a strike line angle whilst holding the compass along the strike line on the surface. Image captured from (Meere 2013).

2.3.2 Stereonets

A stereonet (stereographic net), stereogram or stereographic projection is "*the projection of the latitude and longitude lines of a hemisphere onto a circular graph*" (Groshong 2008, p.44). For the purpose of geological fieldwork it is "*a lower hemisphere graph on to which a variety of geological data can be plotted*" (Houghton n.d.). There are two types of stereonets based on the way latitude and longitude are projected on the circular graph. One is known the equal-area net also known as the Schmidt or Lambert net and the other is the equal-angle stereonet or Wulff net (Groshong 2008; Pollard & Fletcher 2005).

If the stereonet represents the lower hemisphere, then the measurements marked on a stereonet are the intersections of planes and lines with a 2D surface above a lower hemisphere of lines coming from the zenith (vertical line on the centre) of the hemisphere as depicted in Figure 6. One of the tools used both during fieldwork and on campus by students from SEE is a stereonet (Butler n.d.). There are many desktop and recently smart phone apps (MidlandValley 2013a) for doing stereographic projection such as an online tool called Visible Geology (Cockett 2014), which also offers block model visualization as well as visualizing stereonets in 3D.

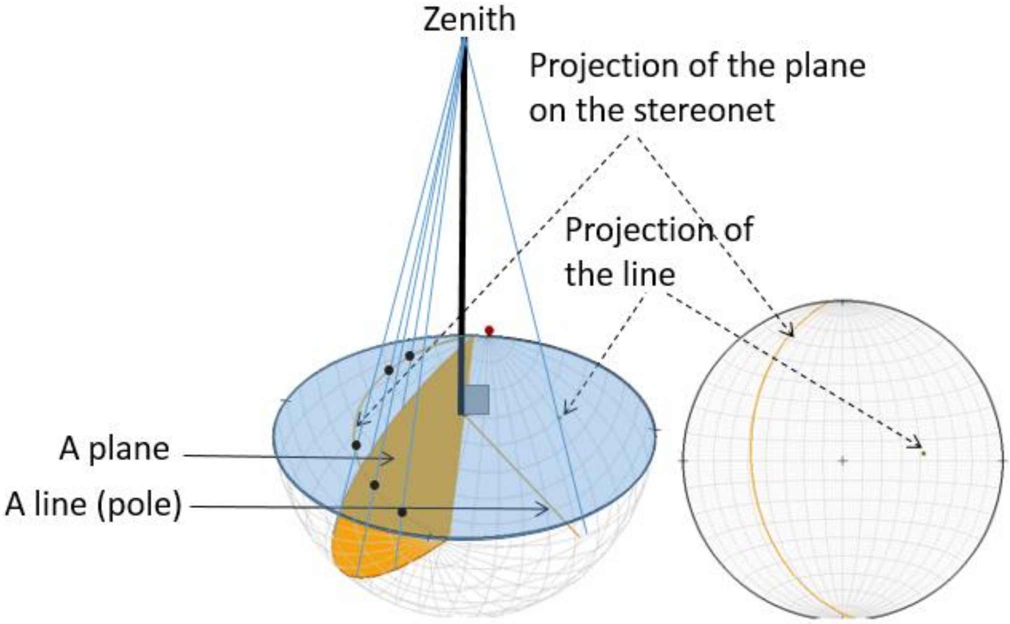


Figure 6: On the left, lower hemisphere, representation of a plane (yellow half of a great circular plane within the sphere) and a line (half a pole goring through the centre of the sphere). On the right, representing the same values projected on the stereonet. Image inspired by illustrations of (Fossen 2010, sec.Appendix B) and graphics obtained by visible geology web application (Cockett 2014).

A picture of an empty equal-angle stereonet is shown in Figure 7 (left). A technique is used by educators to mark strike and orientation measurements on stereonets using a stereonet paper underneath a transparent tracing paper. This technique is taught by the SEE, too (Houghton n.d.). Stereonets are a practical way of analyzing measurements using pen and paper (Knox-Robinson & Gardoll 1998), having projected some planar values, for example, then other structural measurements can be deducted using simple calculations such as a fold's axial plane and various structural measurements related to the axis.

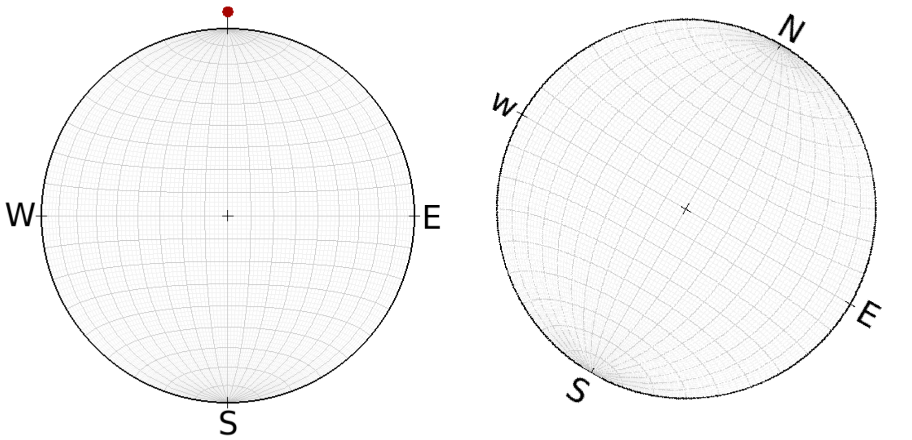


Figure 7: On the left Wullf net (equal angle) stereonet, screen shot from (Cockett 2014) marked with magnetic directions, on the right the same representing the rotated transparent sheet.

2.4 Spatial cognition

In the last section fieldwork tools related to the current work were discussed. A stereonet is used to project a sphere onto a plane, for geologists and geographers it means projecting real 3D world (Earth) onto a 2D plane (paper or digital). These are tools that assist with simplifying complicated structures in the real world onto a 2D plane for analysis. In this section we need to cover relevant cognition topics related to the present work.

The body of research in spatial cognition and spatial ability in different disciplines is extensive and "*One of the areas of earth sciences that requires spatial abilities in particular is structural geology*" (Y Kali & Orion 1996). Research at the intersection of cognitive science and geosciences and learning is known as *geocognition* (Turner & Libarkin 2012). Recent technology seems to have brought such research into focus. At least two special publications were dedicated to this area of research by Geological Society of America (Manduca & Mogk 2006; Kastens & Manduca 2012), and other work was presented at the proceedings of AAPG's Hedberg Research Conference in 2013 (Krantz et al. 2013).

There are three categories of spatial ability (Linn & Petersen 1985): spatial perception, mental rotation and spatial visualization. Spatial perception, according to Liben and Peterson (1985), is the task in which "*subjects are required to determine spatial relationships with respect to the orientation of their own bodies, in spite of distracting information*", and they cite the water level example test (discussed later) as an example. The mental rotation category is the ability to rotate 2D or 3D shapes whilst the spatial visualization category is a combination of the previous two (Linn &

Petersen 1985; Black 2005; Liben & Titus 2012). Various tests have been developed for these categories, a recent example is Perceptual Ability Test (Hegarty et al. 2009) and an earlier example is Mental Rotations Test (Vandenberg & Kuse 1978). This thesis is based on the first category (spatial perception), although the two other categories are also relevant.

Individual spatial abilities as well as spatial layouts in different scales are studied by psychologists (Hegarty et al. 2006). There is a body of research on the role played by spatial abilities in geosciences by geoscientists (Schöning et al. 2008; Goodchild & Janelle 2010; Kastens et al. 2009; Xiaqing & Qingquan 2005). There are various spatial ability tests developed by geoscientists; such as GeoSAT (Y Kali & Orion 1996).

2.4.1 Spatial orientation

Psychologist and philosopher Jean Piaget studied children's understanding of horizontality using a simple test called the "water level task". The task is carried out by showing subjects (children) pictures of bottles and asking them to mark the water levels if the bottles were half full of water in different positions (Liben & Titus 2012). An illustration of different water levels in different positions of a flask representation is shown in Figure 8.

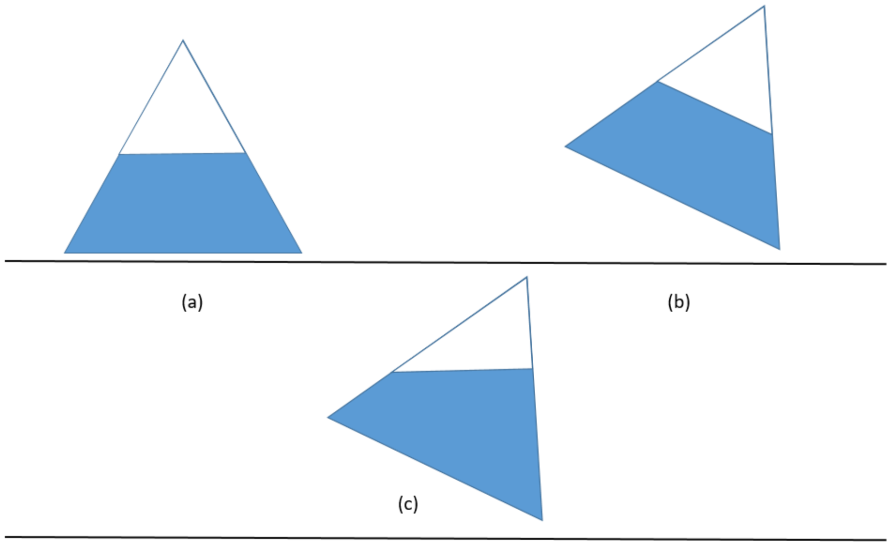


Figure 8: Illustration of Piaget’s water level flask, (a) shows a flask which is half full on a horizontal surface showing the water level with the surface the flask is on, (b) shows how the flask tilted slightly and how the water level should not be drawn inside the flask and (c) shows the flask tilted again but with correct line of the water level inside the flask.

Concepts such as horizontality and verticality are the basic teachings of geological education. Piaget’s work on children's conception of space is the source of work for teaching geology (Kastens & Ishikawa 2006). The widely used "water level example" to teach fundamental concepts such as strike and dip (discussed in Chapter 4) come from his work (Liben & Titus 2012).

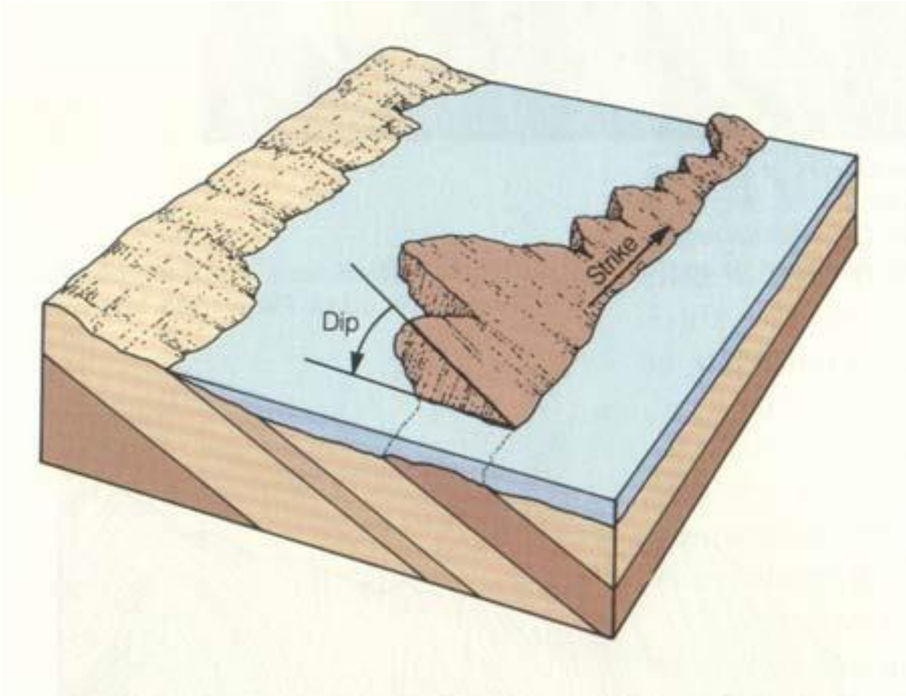


Figure 9: Strike and dip illustration using water level example. The horizontal surface lapping against the inclined surfaces show the water level, the intersection of the water level with the tilted rock-bedding forms the strike line whilst the angle with the inclined surface forms the dipping angle. Image from (Morelock 2005).

The concept of strike and dip (discussed in detail in Chapter four), is taught by geologists at the SEE. To make it easier to teach this difficult (Kastens 2009) concept, in the SEE and within literature a real world phenomena called "water level example"(Liben & Titus 2012) is used. This is a simple example of drawing or actually showing examples in the field where water laps against a tilted rock-bedding surface (Figure 9). A strike line would be the line formed by the water meeting the rock and dip being the angle of such a tilted surface with the horizontal water surface. The concept is illustrated in Figure 9 and will be discussed in more detail in chapter four section 4.2.

2.4.2 2D v 3D divide in geosciences

From the interviews with staff at SEE it became clear that many do not have an urgent need of 3D visualization whilst doing their own work. By definition any 3D visualization, whether block or geological models, means more "interpolation" with perhaps the same data that 2D maps are produced. Upon asking "*what is the process?"* of novice geologists arriving at such a level of experience, there seemed to be a leap in the learning to visualize 2D geological/topographic maps into the third dimension.

One of the recommendations of a half-day discussion session between geologists, petrochemical company directors and others who attended a research conference in June 2013 (Krantz et al. 2013) was that 2D visualization of such a cross section is sometimes preferred to a 3D model from a computer program. The reasons given by one of the submissions in the proceedings were: "*ease of use, low cost and versatility in a variety of field environments"* and "*lack of digital base maps, elevation models*" as well as "*practice using the software*" (Shackleton et al. 2013). This was discussed with senior staff is the SEE who also agreed. Yet a familiar sight of other events is many companies and institutions showing their 3D models and visualizations to the attendees. However, from the interviews with staff and students at SEE as well as the literature in section 2.5, it is clear that novice geologists cannot visualize the third dimension with the "ease" that professional geologists do (Reynolds & Johnson 2005; Whitmeyer et al. 2009).

2.5 Understanding the issues

Professionals and novice geologists face different issues and carry out different tasks during fieldwork. Research carried out on issues faced by undergraduates is not easily extrapolated to professionals (Turner & Libarkin 2012). By novice, we mean undergraduate students studying geology in general in their first and second years of their studies.

This section reviews the literature in geological fieldwork education for novices, and the difficulties novices may have with tools and representations such as 2D maps. The issues raised in the literature are then tested via observations from real student field trips. In addition to this, interviews were conducted with staff and students at SEE to better understand the issues mentioned in the literature.

Two students from the MSc class of 2012 were interviewed using semi structured interviews. Undergraduate students were not interviewed due to the fact that they may not know what the issues they may be facing. This was based on the rationale that MSc students may have some hindsight of the issues they may have faced during their undergraduate years. Also, the spatial ability test by (Yael Kali & Orion 1996) which investigated reasoning by high school students even in the case of those with higher spatial ability does not indicate that the novices were aware of the issues they are facing. The interviews and issues raised were considered in the context of understanding the issues.

From the start of this research the Geological Society of London’s Geotectonics mail-list, which is an online electronic discussion forum has been a source of learning about professional discussions, issues and difficulties in geological fieldwork education. There have been various discussion threads regarding new technology including smartphone and tablet usage for fieldwork. This has also shown that the matters in the literature and observed first-hand are not specific to an area or an institution.

To reach out to the geoscience community for their input into the issues focused on in this research, two blog posts (Hama 2013b; Hama 2013a) were published on the Geological Society of London's blog. The idea was to reach out to the community who may be dealing with these issues or may be developing a fieldwork app.

In the first blog post these specific questions were asked hoping for answers:

- What specific problems are you/your students having in the field? Is it reading geological maps? Spatial problems?
- What digital tools (apps or otherwise) are you using to address the above issues?
- Do you have any geological app development projects to share?

The follow up post was an introduction to the difficulties discussed in the next section. It was also a brief outline of the work carried out in chapter three. This was still done hoping that others who might have been dealing with similar problems could get in touch and further collaboration could be developed. There was little involvement by the community and one other researcher got in touch to refer this research to one mapping app development project.

In addition to these, a one day trip was organised to the headquarters of British Geological Society to meet with software engineers who are behind the iGeology iOS application and iGeology3D Android application. Various visualization and desktop solutions were discussed. Also, two fieldwork education focused conferences were attended. The outcome of these were contribution to the understanding of the state of the art in the visualization domain of geological fieldwork for novices and experts.

2.5.1 Issues from the literature

Whitmeyer, Feely et al (2009) describe certain issues faced by novice geologists as “conceptual difficulties” and divide them into the following points:

- “Understanding and visualizing the *3-d nature of geologic structures* and how they intersect topography, which is particularly apparent when students are confronted with geologic features on 2-D surfaces, such as outcrops or geologic maps, and are asked to extrapolate the features into the third dimension.

- *Extrapolating small-scale observations to larger scales* (e.g. relating information from a field outcrop to a regional geological map); and
- *Visualizing the evolution and modifications of geologic structures* and landforms through time, both forward into the future and backward into geologic history"

Work by (Kastens & Ishikawa 2006) considers the issues of 3D visualization faced by novices. Kastens and Ishikawa (2006) describe the task of identifying minerals by a petrologist, they state that it is done by the shape, colour and texture of the mineral. They question novices could undertake such a task, stating that novices need to compare the minerals to a catalogue until they become experts by creating their own mental catalogue. They describe "*three groups of geoscience tasks*": *"(1) describing and interpreting objects, (2) comprehending spatial properties and processes, (3) metaphorical usage of spatial thinking*". This is a different take on the issues faced by novices compared to those mentioned at the start of this section (Whitmeyer et al. 2009).

The conceptual difficulties in 3D visualization outlined by Whitmeyer (2009) are generic issues and require further breakdown and understanding. The analysis of them was carried out in an iterative process in the following steps: (1) understand and research each point and break it down to a set of individual points, (2) generate a list of possible aids for each point, (3) research possible solution on mobile devices.

2.5.1.1 Three dimensional nature of geological structures

The complex 3D nature of geological field work and how various outcrops are related during fieldwork requires a great deal of spatial understanding, as outcrops are located in the space around the students (Thurmond et al. 2005). Hence, the "three dimensional nature of geological structures" can be broken down into:

- **The geometry of the structures:** novices and professionals need to have an idea what the geometry of a particular outcrop could be like. Indeed, tools and techniques such as measuring orientation of planar and linear structures are taken by geologists.
- **Identifying boundaries on outcrops**: to relate an outcrop to an underlying stratum. This means identifying different rock types on outcrops, if there are more than one, and identifying how far each stretch compared to other

outcrops or the local/field topography. For instance correctly identifying boundaries of the possible strata on a given outcrop is a main part of mapping boundaries on geological maps as dipping of the beds affect the way the lines are drawn on contour maps and that affects the interpretation of geological maps (Lisle et al. 2011).

- **Visualizing the underlying strata:** each of the identified rocks cropping out means that their continuations is buried under the ground and form part of a stratum. The tools and techniques used for the geometry of the structures can help novices think in 3D nature of the structure.
- **The overall picture**: considering all the rock types and structures in the field then having an overall view of what are the geological "features" that needs to be noted. 3D dimensions of the structures also include each structure's spatial relationship with structures that together form the geology.

An additional task often required of students is "... *to extrapolate the features into the third dimension*" (Whitmeyer et al. 2009). This is a spatial reasoning task which is not specific to geological fieldwork, but perhaps is harder than other disciplines due to the complex nature of Earth's geology. Scientists have studied this task and developed spatial ability tests such as visual penetration tests and other relevant spatial ability tests (Yael Kali & Orion 1996).

In some cases the learners do not have a field scale geological or topographic map, even if they had such maps the students are unable to have a field view visualization rather than a plan view conventional 2D maps. The difficulty here is extrapolating what is on the map, which is a spherical spatial data projected over a 2D plane, back to the real scene when determining rock boundaries. This falls into both the "topographic" and "projective" category of geoscience tasks outlined by Kastens and Ishikawa (2006).

2.5.1.2 Extrapolation of small scale features to larger scales

Maps are produced with a certain scale, and geological sciences have relied on maps for centuries. Therefore interpretation of maps includes interpreting and understanding scale (Maltman 1990, chap.2). Carrying out fieldwork also means considering some features (such as a rock type or a rock geometry or other) in small scale and others in larger scales.

Broadly speaking, this scaling issue happens when a novice geologist is asked to relate a particular observation (for instance metre scale folds) into a regional (kilometre scale) geological area. Difficulties of understanding geological phenomena in different orders of magnitude are also found for professionals, as discussed by (McCaffrey et al. 2010). For example, they state *"processes operating in rifted margin and foreland fold/thrust belts can span up to eight orders of magnitude in length*" (McCaffrey et al. 2010, p.22).

The issue could be in part due to the use of a single-sized geological or topographic map once out in the field. However, there is a clear order that requires first the structure in question to be understood or visualized in its three dimensions before being considered in a wider area of geology. Therefore, as stated by (McCaffrey et al. 2010), visualizing any structures should at least be done in its actual geometrical scale. That is why virtual outcrops (discussed later) could be one way of addressing extrapolation between various scales.

2.5.1.3 Visualizing evolution

Earth has been changing continuously for 4.6 million years (Wicander & Monroe 2010). The succession of epochs and geological periods of time is known as “Geological Time” (Fookes 1997; Murck & Skinner 2012). “Geological Time” is a very wide subject and rather complicated (Cox & Richard 2005).

Visualization of the evolution of any geological structure depends on how far one would want to look at the history of the evolution. That will also depend on the nature of the formations, the history and the evolution stages the formation would have gone through.

Obtaining data related to a specific geological time and 3D models isn't trivial. That may be why (Rossetti & Valeriano 2007) have resorted to a hypothetical reconstruction of an area’s geological time terrain. Even in their example, areas of the reconstruction had to be left with question marks, as they could not find relevant data to use. Like the scaling difficulty, the current state of the structures needs to be visualized first.

2.5.2 First hand fieldwork

As the focus of this thesis was on difficulties confronted by novice geologists, introductory level geological fieldtrips were chosen. I attended two different field trips to the same location, namely Ingleton, North Yorkshire, England. Ingleton is an area in North Yorkshire, England with interesting geological formations for educators.

The SEE, as part of undergraduate and postgraduate teaching take students out to Ingleton. There are various field trips arranged to Ingleton, the aims and objects of each trip varies according to the aims and level of education of the students attending.

One of the two trips to Ingleton was an MSc level field trip, as there is at least one field trip which is tailored as an introductory level fieldwork recap for students, as well as fieldtrips for first year undergraduate students. The aim of the field trip is described as: “*to help students understand 3D geological geometry.*” According to one of the guides of this trip, a set of instructions and few stops at each field trip is a standard way of taking the students through the fieldwork.

The other Ingleton field work that I attended was for undergraduate first year students. An SEE debrief document (see Appendix I) describes the aims and objectives of the trip. The aims and objectives can be summarised as: basic concepts of geological field work by carrying out geological field investigation, learning to use traditional geological tools (compass and clinometers), field sketching and map location and basic introduction to geological mapping.

In order to better understand the field trip’s aims and objectives, these were the questions that needed to be answered: (1) what are the goals of the field trip? (2) what are the instructions given to the students to achieve those goals? and (3) what are the specific problems students are facing in achieving those goals.

A third trip that I attended is a second year undergraduate field trip to the area around the village of Rhoscolyn in Anglesey, Wales. Students study more complicated geological structures compared to Ingleton in their first year. The aims and objectives of the field trip are different as mapping is the main objective of the trip. Students learn how to take a variety of measurements from various rock formations aided by conventional tools and techniques such as stereonets and geological and topological maps.

The Rhoscolyn trip is not beginner fieldwork, but they learn new skills so they are still novices. This trip also gives us an indication where students go from the basic introductory fieldwork in Ingleton in their first year. In this fieldtrip they are asked to use those basic fieldwork skills they learned to make geological interpretations, mapping and derive geological evolution.

The challenges students face in this fieldtrip are the same as the ones discussed in 2.5.1. The students face the difficulties such as extrapolating a 2D feature from a map or an outcrop and try to visualize the 3D nature of the complicated geology of the anticline (Reynolds & Johnson 2005). Therefore, when it comes to potential solutions, this stage of the students will also be considered (more in Chapter 6).

2.5.3 Analysis of first hand fieldwork:

A breakdown of the tasks carried out in the two field trips to Ingleton are listed in Table 1. The first column lists the tasks, the second shows the instructions that are typically given to students, the third outlines potential problems, the fourth column references the issue within (Whitmeyer et al. 2009) and the last column lists possible solutions considered.

The considerations in the last column (Possible Solutions) were by no means final solutions for the problems in the middle column of Table 1. The next chapters of this research address how the outcomes of this analysis has progressed. These solutions are generally handheld device based technology based solutions. The reason why the solutions have not been limited to handheld devices was that there could be desktop visualization techniques that could be ported to handheld devices.

The tasks for the undergraduate trip are slightly different in that there are also the sub disciplines within earth sciences education taught at SEE. Therefore students are guided by specialist educators in their own specialties such as geophysicists, structural geologists. Both tasks are combined and listed in the first column.

Tasks	Instructions	Issue(s)	In literature, e.g. (Whitmeyer et al. 2009)	Possible solution(s)
Overall view of regional geology	Awareness of geological settings	• Having a geological map • Having a cross section • Knowing how to interpreter them	Visualizing and understanding 3D from outcrops	• Viewing a geological map • Viewing a cross section • Ease of interpretation
Locate yourself	UTC grid reference match with map	• Zooming in/out • Map reading	Extrapolation of structures require own location	• Global Positioning System (GPS) + Zooming + overview map
Observations (locate)	Find where in the site (field)	• Zooming the field in/out • Map reading	Outcrop/feature locations	
Observations (Identify rock)	Varies	• Varies	NA	• Catalogue
Observations (Sketch)	• Do many • Clarity • Plot lots of data • Clean and readable	• Projection, scaling of geometry (personal) • Practical sketching issues	Visualizing 3D nature & applying small scale to larger scale.	• Digital • Higher resolution • Accurate data plotting • Editable and readable

Tasks	Instructions	Issue(s)	**In literature, e.g.** (Whitmeyer et al. 2009)	Possible solution(s)
Observations (Putting rock into context)	• Plot data on map • Draw own map	• Reading maps • Drawing maps	Understanding 3D nature	• Human eye view data • (AR) draping data over camera view.
How location fits into area	• 10cm to 10 meter then to quarry	• Some observations cannot be applied to larger scales	Small scale observation to large scale	• Viewing a feature on a local model or regional model or on 2D/3D maps
Making assumptions as field trip progresses	• Making a conceptual model • Visualizing a particular s layout, its relation to topography	• Construct/Reconstruct model • The major issue often is how topography intersects with 3D geology.	- Visualizing 3D nature of geological structures	• Viewing geological boundaries large scale • Different data viewing options, 2D maps, 3D maps and 3D model

Table 1: Summary of tasks, instructions, issues, cross referencing the issues within (Whitmeyer et al. 2009) and possible solutions for these issues are shown. The table starts with the tasks carried out by a student, then lists the instructions typically given by an educator in the field, the issues that could arise from a generic geological perception perspective.

2.5.4 Summary of the issues

From the literature, fieldwork observations and interviews (beginning of 2.5), the "conceptual" difficulties novice geologists face whilst carrying out introductory fieldwork can be summarised as follows:

Relating field data to the field: novice geologists have difficulty in relating map data to outcrops. In light of the issues outlined by (Whitmeyer et al. 2009) in section 2.5.1, this is a stage before "extrapolating 2D features to the third dimension", as students need to match data on the map to the ground. There has been work based on mapping with this issue in mind (De Donatis & Bruciatelli 2006). Any proposed solution for a fieldwork application has to address this before any other.

Extrapolating 2D features to the third dimension: This is part of the first point by (Whitmeyer et al. 2009). Whether looking at a 2D map or an actual outcrop in the field, there is still the complex structure that needs to be visualized from a limited number of observations. Any 2D or even 3D representation, whether a map or a DEM, will still have the limitation of the geological clues on the ground for a novice to try and visualize the represented structures. The reason for this is that such representations, by definition would use “representations” which require some interpretation by users. Moreover, different representations in 2D would still need to be extrapolated into the third dimension just as it is with maps in general.

Visualizing the underlying geometry: due to the complexity of geological structures and the limited outcrop visibility representation including 2D maps, block model, cross section or even 3D geological model may not eliminate this difficulty. Each of the representations requires learning to interpret them. Map reading difficulties were discussed in 2.2.2. Block models and cross section drawn on 2D paper would probably entail similar difficulties but have not been discussed in the present work. Researchers refer to "disembedding" (Reynolds 2012; Kastens & Ishikawa 2006), because trying to visualize the geological structures means ignoring the trivial clues and focusing on important observations within a complex scene, landscape or photograph.

Extrapolation of small scale features to larger scales: discussed in 2.5.1.2, in the case of a student with an area map, there is still the need to refer to a field-scale map, even if students would have to interpret representations from both maps and taking into account what is on the ground. This thesis does not address this issue directly in but conducts research that is essential for in designing any solution.

Visualizing the evolution: as discussed in 2.5.1.3 this falls outside the scope of this thesis. Without tangible and tailored assistance, imagining these complex processes, is a difficult task for students to do it in their heads. What makes this harder is that there has been little research in this area.

2.6 Geological Information Systems

We have just considered the challenges facing novice learners. As subsequently chapters will consider how technology can be used to provide solutions, it is important to consider the digital techniques that are currently employed in learning and teaching geological fieldwork.

Geological information systems go back to as early as 1978 (Bie & Gabert 1981). Also, Geographic Information Systems (GIS) applications are used by geoscientists for mapping such as digital maps and digital globes for the purpose of research and education.

Organizations and companies which specialise in visualizing geology, especially in the hydrocarbon sector, have dominated this area of visualization (Whitmeyer, Feely et al 2009). Their commercial desktop applications are industry standard when it comes to 3D visualization of geological data, for instance ESRI's ArcGIS, Schlumberger's Petrel and Midland Valley's Move suites. These packages are installed on specialist computer laboratories for postgraduates in the SEE at the University of Leeds. Students are also taught to use these packages as these are the packages that they would have to learn when they start working for prospective employers.

These commercial applications have 2D mapping tools, which have been used on portable devices such as ruggedized laptop computers (Whitmeyer & Mogk 2009) by researchers, but research into the use of them on modern smart phones and tablets is still in its infancy. One criticism, amongst others (Whitmeyer et al. 2010), that is relevant in the context of this thesis, is the separation of the 3D modelling and visualizations (e.g. ArcScene) from the GIS mapping functionality (Brooks & Whalley 2005), (e.g. ArcMap of ESRI).

2.6.1 Current geology apps categorisation

Mobile GIS and location based services (LBS) on modern smart phones and tablet devices extend beyond the requirements of current user demands and will play a major role in future (Frank et al. 2004). However, the use of smartphones as geological tools for students during fieldwork is not still adopted.

Despite the focus of mobile mapping (Soon & Roe 2008), data collection usage of mobile devices in fieldwork (Ahmed and Pinkwart 2012), and the increasing capabilities of current tablets and smartphones, there has been little research into the visualization of fieldwork data on such devices. The mobile "version" of these systems (mobile GIS) for geological fieldwork for novice geologists is still in its early stages, and its main use seems to be for data collection and map based analysis (Miller 2006).

A review of apps related to geological fieldwork was required to be able to pinpoint the state of the art within these types of applications. Based on the main use and functionality of these applications they can be divided into three categories:

- Data collection: apps to take geological measurements or just the simple task of taking camera shots, such as RockLogger (RockGecko 2011), GeoCam or Midland Valley's FieldMove Clino (MidlandValley 2013a).
- Data viewing: viewing data like maps (geological or not), measurements, notes or sketches, such as BGS iGeology & iGeology3D, ESRI's ArcGIS app (ESRI 2013) and even Google maps and Google Earth.
- Data analysis: data processing and analysis, either in 2D (mapping) or 3D (modelling). Geologists have used ruggedized computers and mobile computation for mapping and geological analysis before smartphones (Clegg et al. 2006). ESRI's ArcGIS app is a mapping example, with functionality such as measuring areas and distances and viewing different, maps and own maps from ArcGIS servers. There is still no available app; despite best efforts of looking for one, to view; edit or generate 3D geological models.

2.6.2 3D models in the field

Geologist educators such as Bond & Wightman (2012) are not surprised that students cannot conceptualise 3D geological models using 2D maps. They outline three reasons: "*1) lack of human skills in 3D visualization; 2) a geologist's need to apply reasoning to enable 3D model conceptualisation, prior to visualization; and 3) the additional need to test conceptualised geological models by thinking about the evolution through time (a fourth dimension)"*. So the question is why do we not give students 3D models of the field area on a smartphone/tablet? Software vendors such as Midland Valley is said to be working towards this (Dunlop et al. 2013).

The idea of taking out a geological model on a smartphone or tablet is not futuristic if we look at the advance in CAD applications such as the FormIT app by AutoDesk. After all it means porting some data format to another and viewing it on a tablet.

However, even the idea of showing novice geologists geological models in the field raised the question of “are we giving students the final answer if we give them the field model on a tablet application to start with” on more than one occasion by different people. The answer to this is that if the aim of research is to assist novice geologists to “think in 3D”, then even if such a model is provided on a device it does not mean that students can automatically imagine the structure and geometry of the rocks.

2.6.3 Digital Outcrop Models

Digital Outcrop Models (DOM) are defined as a collection of different types of data processed to produce a 3D model of geological outcrop such as dense point cloud acquired by Light Detection and Ranging (LiDAR) scanning and digital photography from Single Lens Reflex (SLR) cameras (Jones et al. 2009; K. McCaffrey et al. 2005), Other models are compiled by adding digital (differential GPS) and field sedimentological and structural data as well (Fabuel-Perez et al. 2010). An example is given of a resolution of approximately 1:1 by (Jones et al. 2009).

The process of generating DOMs require specific equipment and software. It starts with a laser scanner directed at a specific area (an outcrop) which produces a point cloud of accurate x, y, z which are GPS coordinates with z being altitude. This point cloud itself is a digital elevation model (DEM). This model can then be draped over with an orthorectified air photo which produces a digital outcrop model(Bellian et al. 2005).

One can imagine that availability of such 3D models on modern day smartphones would assist novice and professional geologists to “visit” or “revisit” field outcrops they would want to see or have seen. The ability to use the GPS points to calculate distances, obtain geological measurements (e.g. bedding dip and strike) and view the outcrop from different angles would assist in better comprehension.

The technology and the process required to produce Digital Outcrop Models (DOM) is discussed in detail by Bellian et al. (2005). This technology was considered an “*unrealistic demand on available hardware performance*” by McCaffrey et al. (2008) few years ago, which begs the question whether current tablet and ruggedized laptop machines have come far enough to make it a realistic option to address the issues raised? Whilst considering this technology this research was able to view one of those models on an Apple iPad II using open source 3D library called (NinevehGL 2014).

2.6.4 Digital globes

Digital globes such as Google Earth and NASA's World Wind, their history and usage in geological mapping in the field is described by (Whitmeyer et al. 2010). The authors and others argue that a simple platform requiring basic scripting using KML (Keyhole Markup Language) will revolutionise geological mapping (Resch & Hillen 2013), data visualization and spatial analysis (De Paor & Whitmeyer 2011).

Google Earth and World Wind are not just another GIS application. The idea behind them originates from US Vice President Al Gore's speech in January 1998 (ISD5 1998; Gore 1998) outlining "*a visionary information system of enormous scope and with significant potential value for education and collaborative research*" (Grossner et al. 2008) whilst Google was not yet incorporated (GoogleInc 2004). In the speech he said "*I believe we need a 'Digital Earth'. A multi-resolution, three-dimensional representation of the planet, into which we can embed vast quantities of geo-referenced data*" (Gore 1998).

The *importance* of Google Earth in geosciences is well documented (Lisle 2006; Kennedy 2009; Sheppard & Cizek 2009; Goodchild 2008; Yu & Gong 2011; Schultz et al. 2008; Whitmeyer et al. 2012; Patterson 2007). One reference that stands out from that list is (Whitmeyer et al. 2012) which is a special paper by Geological Society of America (GSA). As described in the introduction (Bailey et al. 2012), in an event held in January 2011 at Google Inc. headquarters. The special paper is structured on four different sections (themes) where various contributors outline the use of Google Earth for geosciences, for example, integration with LIDAR (Crosby 2012). The sections are: "data visualization", "digital geologic mapping", "virtual field experience" and "educational models, learning methods and assessment".

The special paper dedicated to Google Earth by (Whitmeyer et al. 2012) contains few references to iPad, iPhone and smartphones. The only paper where interaction with existing 3D photorealistic models is described (Wang et al. 2012) on an iPad is the one which does not involve Google Earth.

Even Google Earth is far from the imagination laid out by Mr Al Gore. The advanced features of Google Earth, provides the following: viewing timelines, KML, Internal Browser, Google Earth Offline, what is known as leap motion, drawing paths, time slider and viewing GPS tracks (GoogleEarth 2015). Details of some of the data sources, interoperability with mainstream GIS applications such as ArcGIS is given by (Visser et al. 2013).

As for NASA's World Wind, an open source project which has changed in terms of API for mobile devices since the start of this research, it offers developers more options than Google Earth. The World Wind API, architecture, available data and an example of its implementation is given by (Rios et al. 2014). The documentation, nowadays, supports libraries that can be used by iOS developers out of the box that has following functionality: 3D terrain from F (NASA 2000), ASTER GDEM (Tachikawa & Hato 2011) and NET (USGS 2014) elevation data, sets of various imagery from Bing, OSM, terrain imagery, collection of shapes. An example app for developers also includes functionality such as a location tracker and path follower which could be used to track the path walked during fieldwork (GoWorldWind.Org 2015; Rios et al. 2014).

Despite the above, both Google Earth and World Wind still lack versions for smart devices that come close to offering the functionality of the respective desktop versions. Therefore, given the popularity and the gravity of these tools, it is essential when researching tools and techniques to assist visualization in the field to bear in mind how such visualization could also be imported into say Google Earth. Also, conventional geological mapping representations such as traditional strike and dip symbols, may not be compatible with the 2.5D or 3D visualizations used in digital globes, as will be discussed in chapter five.

2.7 Smartphone era

"The most profound technologies are those that disappear" said Mark Weiser in 1991 (Weiser 1991), who is credited with coining the term “ubiquitous computing”. Ubiquitous or pervasive computing, challenges and also some *"pervasive computing projects"*, which in today's smartphone era could be described as "smartphone projects", are outlined by (Satyanarayanan 2001). For a brief history of different operating systems (OS) from the 1990s and currently leading smartphone OS's, the reader is referred to (Hall & Anderson 2009). The leading operating systems, release history, nature of the operating systems and platform theories are discussed by (Kenney & Pon 2011).

Despite the claim that smartphones have revolutionised many areas (Lane et al. 2010; Amft & Lukowicz 2009), including geological fieldwork (Welsh 2012), they are yet to be used for geological fieldwork by students as a replacement for traditional tools.

An iPhone6 is equipped with various chips, such as Microelectromechanical systems (MEMS): accelerometers and gyroscopes, GPS receiver, electronic compass, biometric scanning and barometric sensor (TearDown.Com 2014). That is after seven years from the 1st generation iPhone which only had an accelerometer MEMS (Allan 2011, chap.1) enabling the device to rotate the user interface for gaming purposes.

One sensor that stands out in the wider usage of smartphones and within the context of this research is GPS which led the chief technical officer of Google Earth to state " *what makes smartphones smart, in large measure, is their sense of location*" (Fallows 2013). For the purpose of this research the other sensors that stand out are: gyroscope MEMS (a technical description can be found in (Nihtianov & Luque 2014, pt.13)), and the electronic compass on wide range of devices. These two chips are what enables smartphones and tablets as geological data capture tools (for further detail see chapter four).

2.7.1 App ecosystem

Before the emergence of smartphones and tablets, it was predicted that *"as computing becomes more pervasive, the nature of applications must change accordingly."* (Henricksen et al. 2002). By pervasive, it is not just availability of processing power but also *"gracefully integrated with human users"* (Satyanarayanan 2001). This pervasiveness of mobile computing has led to the emergence of an app ecosystem.

Before the launch of Apple's app store in July 2008 (Müller et al. 2011; Wasserman 2010), developers were targeting desktop machines and there was focus on browser based application (web). Software or hardware vendors were not involved directly in the process. With the advent of apps and the centralised nature of app development on the different app stores (Gilbert et al. 2011) vendors are now directly involved. Also, the tools and APIs offered by these app store operators have simplified developing apps (Wasserman 2010).

Details regarding app stores, the relationship between developers and consumers via these app store operators, developer programs and various ways of installing apps on various devices is described by (Müller et al. 2011). The way developers release applications is described in "food web" analogy (Lin & Ye 2009). Either developers have to go through vendors (such as Apple) or they can go through them or not (such as Google). In the case of the Android Play store, apps released via the app store are not reviewed manually but are monitored by Google.

2.7.2 Smartphone architecture

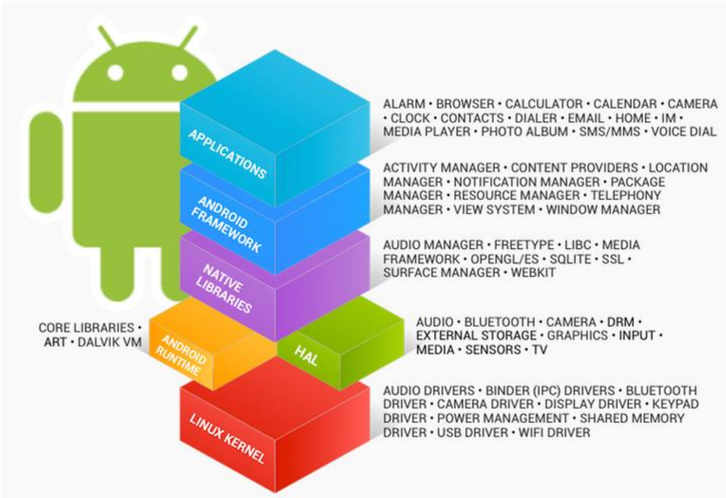


Figure 10: Android architecture by Google, image from (Google 2014b).

A basic architecture of a modern smartphone is outlined by (Lange et al. 2011) which is similar to the architecture shown in Figure 10 for Google's Android OS, although the Dalvik Virtual Machine is now replaced in the Android 5.0. Apple's iOS has a similar architecture too, they are not radically different from the OS's described by (Satyanarayanan 2001). Therefore a typical smartphone is composed of a Kernel managing the hardware, followed by other layers of the operating system up to the third party and vendor applications.

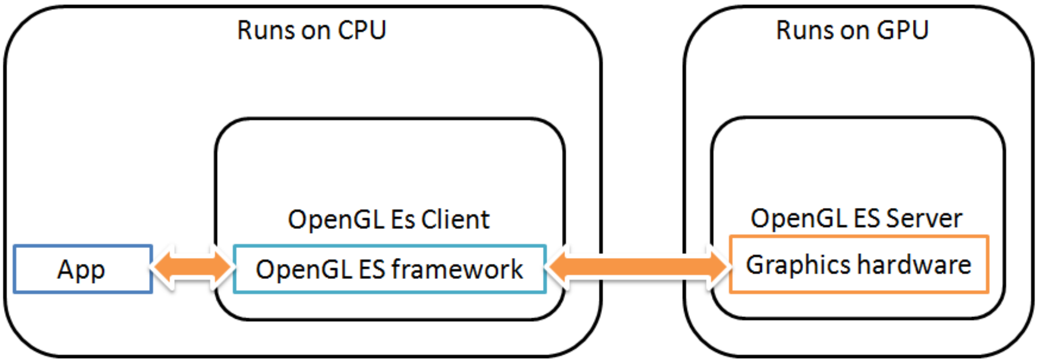


Figure 11: OpenGL ES processing location between CPU and GPU on Apple iOS devices. Figure is redrawn from the one published for developers (AppleiOSAPI 2014b) under terms outlined by Apple (Apple Inc 2014).

The layer of interest for this research is the "native libraries" shown in Figure 10. That is where graphics libraries such as OpenGL ES (ES for Embedded Systems) for Android and Apple's iOS are, access to the graphics library means these devices can run GPU (Graphics Processing Unit) demanding applications. On Windows

Phone (WP) 8 operating systems, this layer includes Direct3D equivalent to OpenGL ES (Microsoft 2014).

The graphics libraries run on the Graphics Processing Units (GPU) rather than the Central Processing Units (CPU). For example, (Cheng & Wang 2011) describes the architecture of an application making use of OpenGL ES libraries on an Apple iOS operating System. The use of GPU for applications used in the context of this research can be a hurdle as limited processing power means less number of objects could be rendered. Apple's Metal graphics API (AppleiOSAPI 2014a) for its A8 chips shows that smartphone vendors promise developers as well as users better graphics experience for future applications.

2.7.3 Graphics on smartphones

Smartphone operating systems utilise graphics libraries such as OpenGL ES (Khronos 2015), Direct3D (Microsoft 2014) or more recently Metal (AppleiOSAPI 2014a) for rendering 3D graphics. An overview of APIs for mobile devices is given by (Noguera et al. 2011). On desktop machines it has been possible to do this within browsers using WebGL (Khronos Group) for a while. However, Android and iOS default browsers received WebGL support in 2014 starting with Android 5.0 Chromium WebView (Google 2014a) and iOS8 (Apple 2014). WebGL is the JavaScript way of rendering graphics on browsers which enable us to interact with Google Earth like applications from the browsers. This is the core of a divide between the two sides of native versus web apps (Charland & Leroux 2011).

The role of graphics and 3D games on mobile computing before the advent of modern smartphones is outlined by (Chehimi et al. 2006). The types of GPU used on smartphones, programming APIs and comparison with desktop GPUs are outlined by (Cheng & Wang 2011). Modern smartphones have only built and added to this role as was expected by people like (Chehimi et al. 2008). Apple iPhones first used gyroscopes in 2007, with 3D graphics to turn them into gaming consoles (Goggin 2009).

The power of 3D graphics on these devices has not been only utilised for gaming, as it is the intention of thesis, it has been utilised in various disciplines. AutoDesk which specialises in Computer Aided Design (CAD) released an app in 2013 called "Form it" (Autodesk 2014). A screen shot of a CAD project is shown in Figure 12. The app does not just showcase the graphics and sense of location and orientation ability of an iPad, it also shows that touch based interactions on these devices are also capable of letting users interact with such a rich 3D environment with ease.

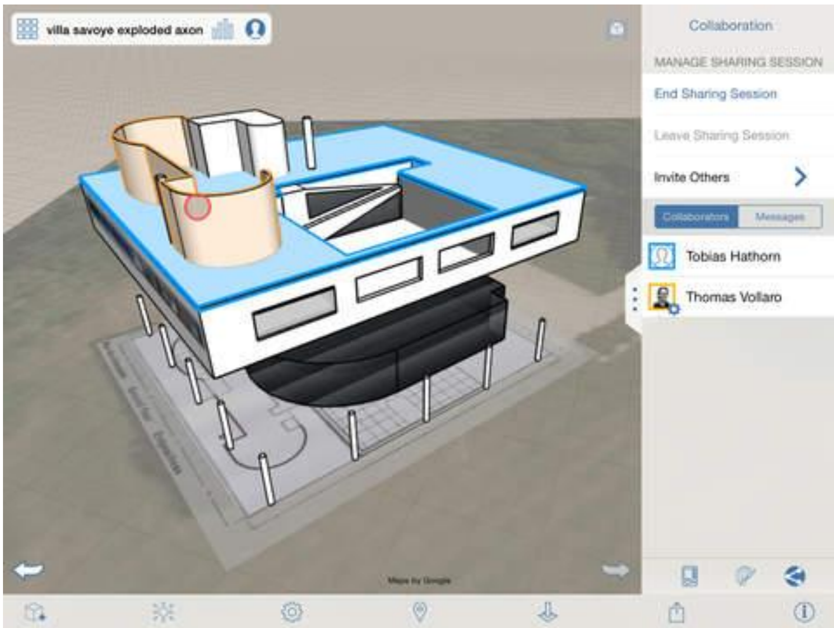


Figure 12: iPad screen shot of Autodesk FormIt app. The image shows how a potential building design would look on a section of a map or satellite image of a location.

The geological community itself has seen the benefit of the graphics processing of these devices and hence the release of iGeology3D by BGS. However, so far leading geological modelling software vendors such as Schlumberger and Midland Valley have not released apps as clients or substitutes for their desktop packages (Petrel and Move respectively). Midland Valley has released FieldMove Clino which captures various field measurements (MidlandValley 2013a) without any 3D interface visualization functionality. The Pro version of FieldMove Clino includes more functionality including 2D stereonet plotting [R!].

2.7.4 3D visualization on smartphones

A brief history of the emergence of the field of scientific visualization where this thesis lies is given by (Wright 2007). A definition, however, for visualization if not self-explanatory could be *"visualization is the transformation of data or information into pictures"* (Schroeder et al. 1997, sec.1.1). The definition simply states that a visualization is meant to turn data or information into a picture that could be understood or interpreted by humans more easily. Scientific visualization is a broad subject and due to the scope of this thesis there is no need to discuss it in details.

The challenge in 3D visualization for a software engineer includes a set of new challenges that are specific to visualizing objects and representations within a 3D virtual space (Teyseyre & Campo 2009). 3D visualization on mobile devices in the context of geological fieldwork has advantages and disadvantages compared to desktop machines. Inherent disadvantages are those related to hardware and software limitations as well as interaction techniques. However, it is the advantages that this thesis is interested in.

The ability to process an image taken in the field, and the integration of GPS and other connectivity methods into the graphics processing power of these devices are unique compared to desktop machines. Therefore, it is assumed smartphones and tablets, despite the limitations compared to desktop machines, could provide opportunities for 3D visualization that are not possible on desktop machines. For example, instead of adding a pre-loaded rock texture, a user could take a picture of the rock surface in the field and use it as texture for a shape representing the rock. It sounds trivial, but the fact that this provides a source of photorealistic textures for shapes in a 3D environment which is an advantage office machines cannot have. This in turn is assumed to provide users with a better visual experience.

Another example of the advance of 3D graphics on smartphones and tablets is the ability to integrate the chips on smartphones and tablets into the graphics rendering engines. There are software development kits (SDKs) such as Qualcomm Vuforia for Android and iOS with supporting tools for Windows, OSX and Linux platforms (Qualcomm 2015). The Vuforia application workflow and implementation, as well as an example, is described by (Xiao & Lifeng 2014). An example of the use of AR in the context of geological fieldwork is the BGS iGeology3D Android app (Westhead et al. 2012), (a screen shot shown in Figure 13), which is discussed in detail in chapter three.

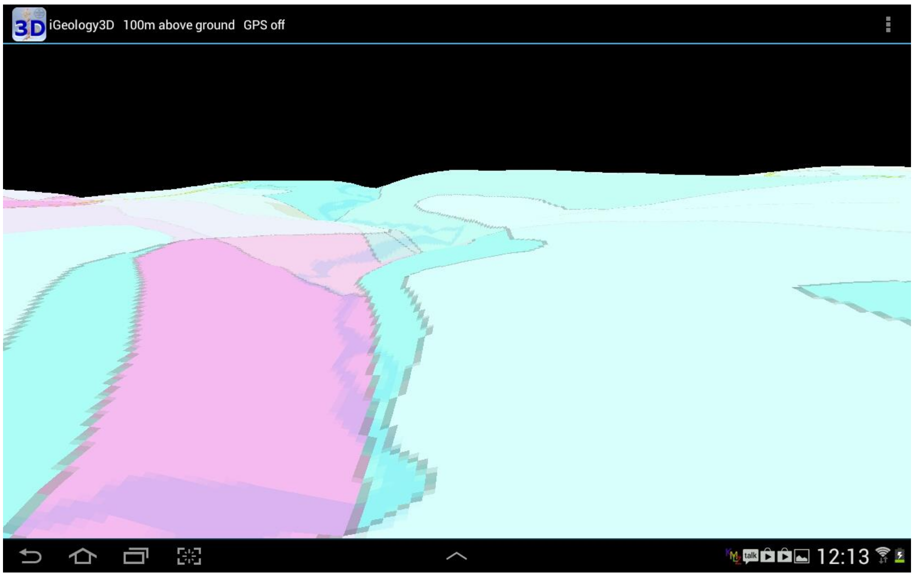


Figure 13: iGeology3D screen capture. Showing a digital elevation model draped with geological data. There are two ways of viewing the model on the app, one while using the app with camera on (using own location) and the other whilst browsing a remote location. In this picture the location is remote, therefore the camera is turned off.

2.7.5 Fieldwork connectivity

There are inherent limitations to mobile computation as described by (Burigat & Chittaro 2005) such as computation power, amount of memory and storage space compared to modern laptop and desktop machines. Due to the mobile nature of these devices it is not possible to create clusters out of them or even easily upgrade their chips to better specification in terms of computation power or memory space.

Mobile computing in the age of smart devices and cloud computing has its advantages and challenges (Ilarri et al. 2010; Soon & Roe 2008) as well as requirements and workflows. The traditional computation model of a client server architecture that is even more consolidated by reliance on the cloud for data access from anywhere keeps mobile devices naturally connected to servers.

On the other hand, geological fieldwork often occurs at locations which are not well connected via phone lines or wired or wireless internet connection. Indeed the two locations discussed later and used as case studies in this research had limited GPS connectivity and almost no GSM connection except at the start and finish points at one of the two locations. Coverage, is based on areas with population (OfCom 2013, p.58) not where geological fieldwork is carried out. For example, the United Kingdom 3G mobile network is accessible for 99% of the population. The geographical coverage is shown in Figure 14. Developed countries could find solutions to provide coverage for areas without any population. This could be in the form of temporary internet connection for such purposes such as use of drones or balloons by Facebook and Google respectively (John 2015; Katikala 2014).

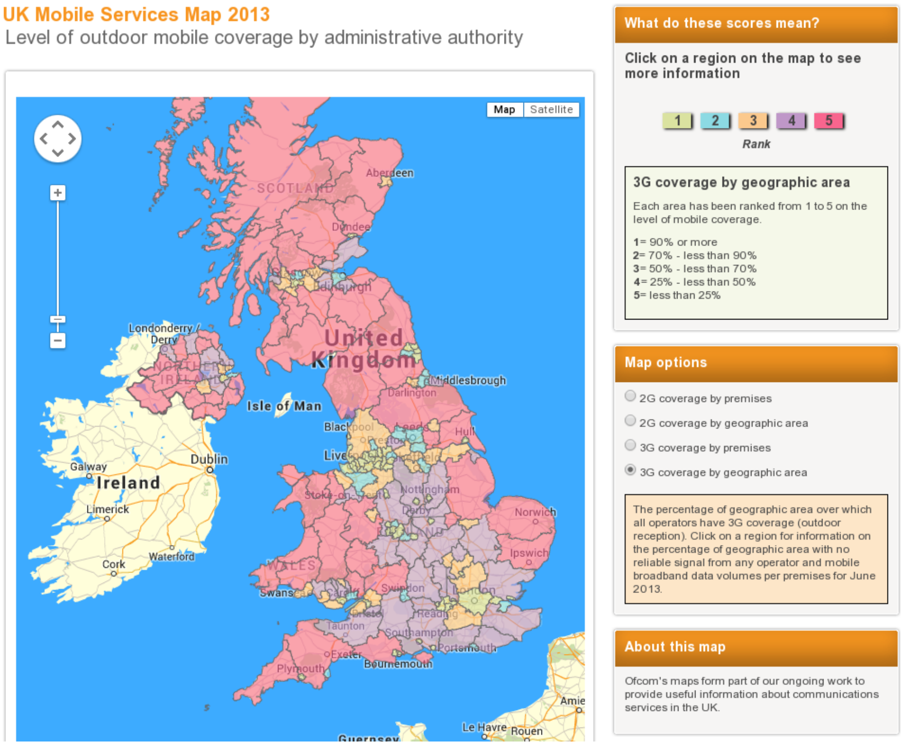


Figure 14: UK mobile services map 2013 by Ofcom (OfCom 2014). Screen shot taken 20th January 2015.

2.8 Summary

This chapter introduced various topics related to the subsequent chapters. It started with introducing geological fieldwork, then moving to traditional tools used in the field such as maps, compass clinometers and stereonets. Followed by spatial cognition topics relevant to this work. It also introduced computer science topics including geological information systems and categorization of recent apps developed for the use during geological fieldwork.

The issues facing novice geologists were analysed systematically starting from published work by geologists and cognitive scientists. First-hand observations during student field trips were reported and analysed. Interviews with geologist educators and students were carried out to break down the issues to solvable levels. These were summarised in 2.5.4.

Other technologies used in geological fieldwork by professionals were also discussed. One of those being taking a 3D geological model (usually used on desktop computers) to the field or the use of Digital Outcrop Models on smartphones and tablets. The crucial question here is this: even if a 3D model of the geology is given to students, does it solve the difficulties discussed in 2.2.2 about 2D maps? The answer is probably no. A geological model itself is an interpretation and visualization of the real geological structures studied by novice geologists who lack spatial skills required to interpret the model and apply it into the real world.

Finally, this chapter introduced topics relevant to introductory fieldwork in geological sciences, cognitive science topics as well as those from computer science. The next step, therefore, is to find out whether current apps from Android and iOS app stores could address the issues summarised in 2.5.4.

Chapter three

3 Current apps for fieldwork

3.1 Introduction

The main issues facing novice geologists in field geology education are summarised in section 2.5.4. The previous chapter indicates that there is literature on those issues, both from geological education and from cognitive science perspective. Therefore, before suggesting any solutions for any of these issues there is need to find out if any solutions have already been developed given the increasing prevalence of apps today. Therefore, an explorative study was carried out.

The aim of the explorative study described in this chapter focused on apps that would go beyond capturing geological measurements, although even these were limited at the time only to Android OS, that is why apps such as RockLogger (RockGecko 2013) were not considered. The aim was an exploratory field evaluation, to understand the capabilities and limitations of available apps for supporting teaching geology in the field. The study was designed based on the normal flow and activities of typical introductory geological field trips.

The evaluation was carried out during two field trips: an MSc and an undergraduate field trip. Both trips were arranged by the School of Earth and Environment as introductory student field trips to Ingleton, North Yorkshire. The MSc trip was on 5th October 2012 and the undergraduate trip was on 31st October 2012. The aim of the MSc field trip is described as "to revise data collection and fundamental field concepts" (SEE 2014). Therefore it is an introductory field trip and there were students who were coming from disciplines other than geology.

3.2 Method

To see if there is any difference between carrying out field tasks using conventional tools versus digital equivalents, an expert assessment (an educator geologist based at the SEE) could assess two different results for the same task. The assessment could be similar to their own usual fieldwork assignment assessment. Looking for clues that could determine which technique yields better results.

The tasks for the evaluation were tailored to match the field trip stops and activities for each group of participants. There were two versions of each task, a conventional version and a tablet computer-aided version. The comparison was between the tasks carried out using either of the two versions of the tasks to see if there would be any benefit of the tablets used.

The tasks were evaluated by an expert. The marks by the expert could decide whether there were any benefits of using the tablets together with the conventional tools. In a field trip such as this, this would mean capturing more accurate data or making more accurate analysis.

As a separate part of the exploratory study, a questionnaire was prepared to obtain some background data from students, such as subjective “spatial skills” and “map reading skills” and other data such as smartphone/tablet ownership and use of mobile applications. The “spatial skills” was left for the students to understand without any explanation. The questionnaire was given to students who may or may not have participated in the evaluation tasks.

3.2.1 Participants

The questionnaire was completed by 15 students from the MSc field trip. However, there were 19 participants in the evaluation itself. There was eight participants in "tablet-aided" group and total of 11 students in the “conventional” group.

Table 2 outlines the breakdown of the participants. Nine students were from the MSc field trip and 10 from the undergraduate field trip. Out of the nine from the MSc trip, five participants were in the “conventional and tablet-aided” group, and four in the “tablet-aided”. Out of the 10 participants from the undergraduate trip, four were in “tablet-aided” group and six in the “conventional”. The number of students who participated was purely based on the time available within the respective two field trips. The MSc trip participants were not necessarily amongst the 15 who participated in the questionnaire.

Group	MSc Trip	Undergrad. Trip	Total
Tablet	4	4	8
Conventional	5	6	11

Table 2: Participants based on type of task and trip.

3.2.2 Materials

The two field trips had different aims and objectives as well as different students, despite going to the same area and looking at the same geology. Therefore the tasks were slightly different for the two groups.

As stated in the method (section 3.2) there were two types of tasks: conventional and tablet-aided. The conventional version of the tasks were carried using conventional tools such as pen and notebook, whilst the tablet-aided version was carried out with the benefit of tablet computers.

Before the MSc field trip, the “Geology map of Ingleborough” was draped over Google Earth’s DEM, and for the undergraduates the “Ingleton geology map” was used. The maps were draped onto Google Earth using a KML UK gridline guide by (Nearby.org.uk 2006).

3.2.2.1 Fieldwork maps

Participants were doing their own fieldwork as well as participating in the study. Hence they were in possession of hardcopies of maps. One of the maps was used by both groups, they were printed on different size papers. Therefore, for the purpose of this study they are numbered, the student group who used them is stated, and on what size paper they were printed is also stated. The maps used were as follows:

Map one: MSc group. Given to students printed on an A3 sheet.

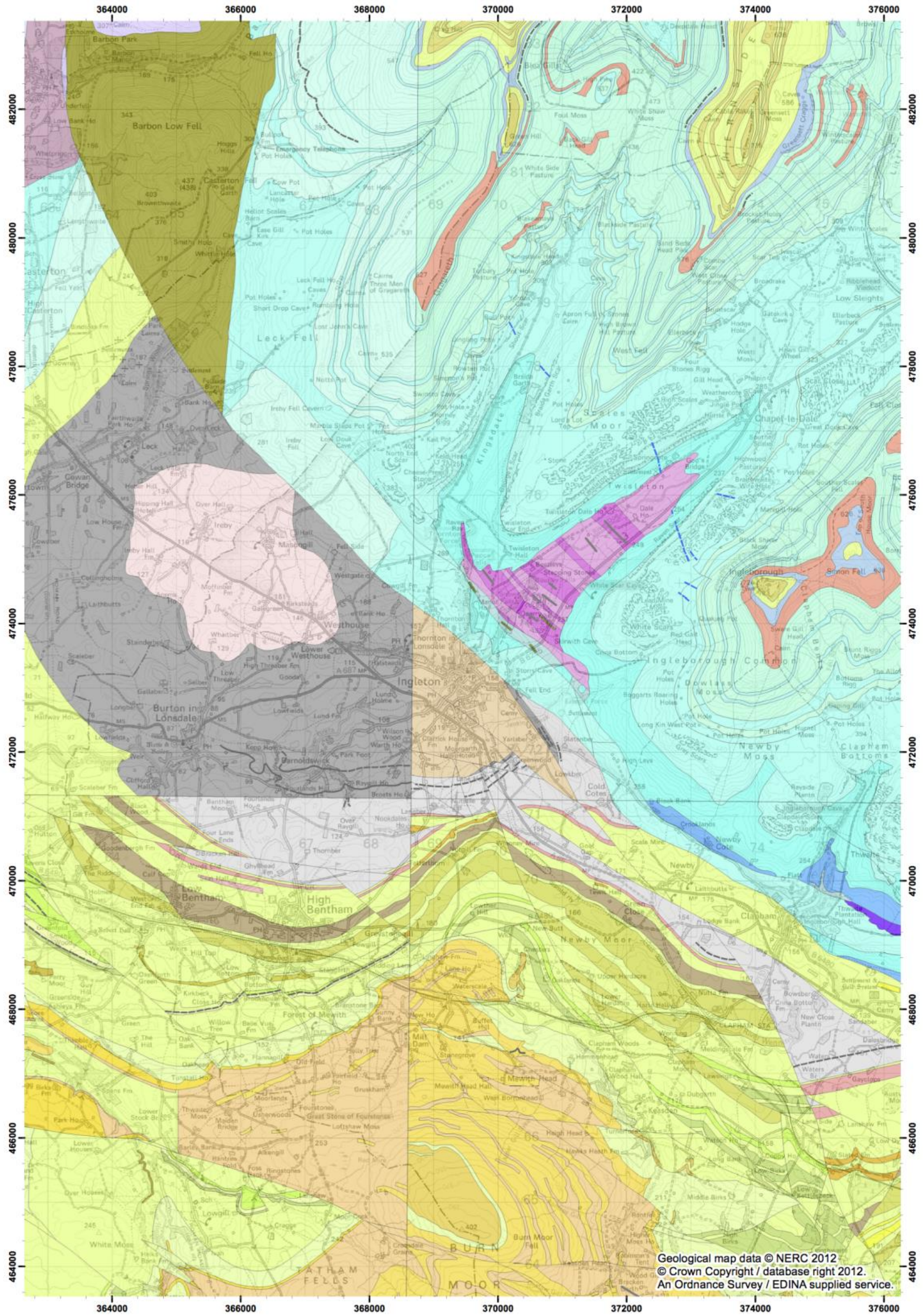


Figure 15: Geology map of Ingleborough**,** 1:25,000 geology map of Ingleborough on 1:10,000 Ordinance Survey base map.

- **Map two: MSc & undergraduates:** printed on an A4 sheet

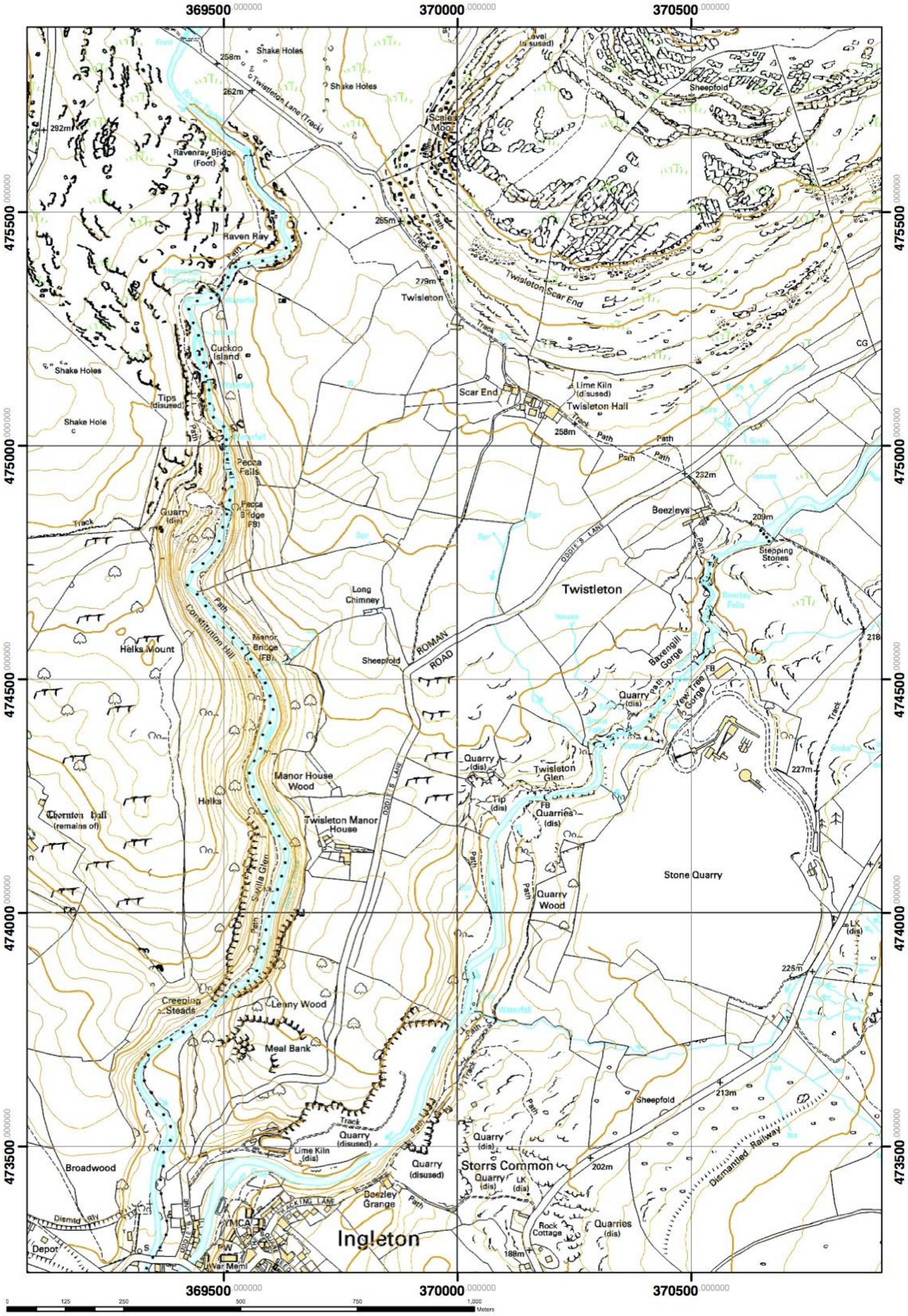


Figure 16: Ordinance Survey map: 1:10,000 (1km square grid) OS Map

- **Map three: Undergraduates:** printed on A4

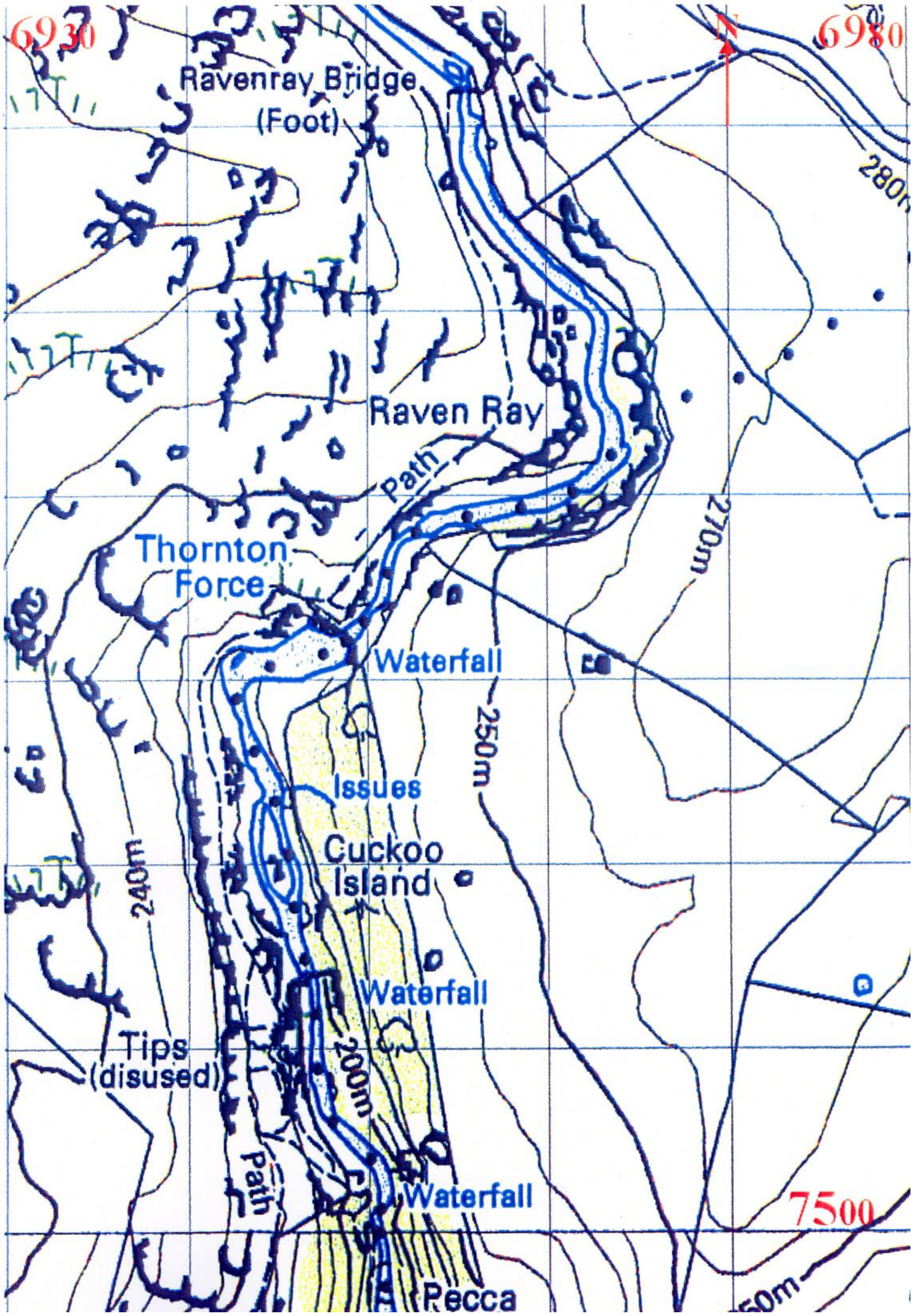


Figure 17: Thornton force map: 100m square grid OS topography. 1:2500, covering about 7500m2 area

- **Map four: Undergraduates:** printed on an A4 sheet

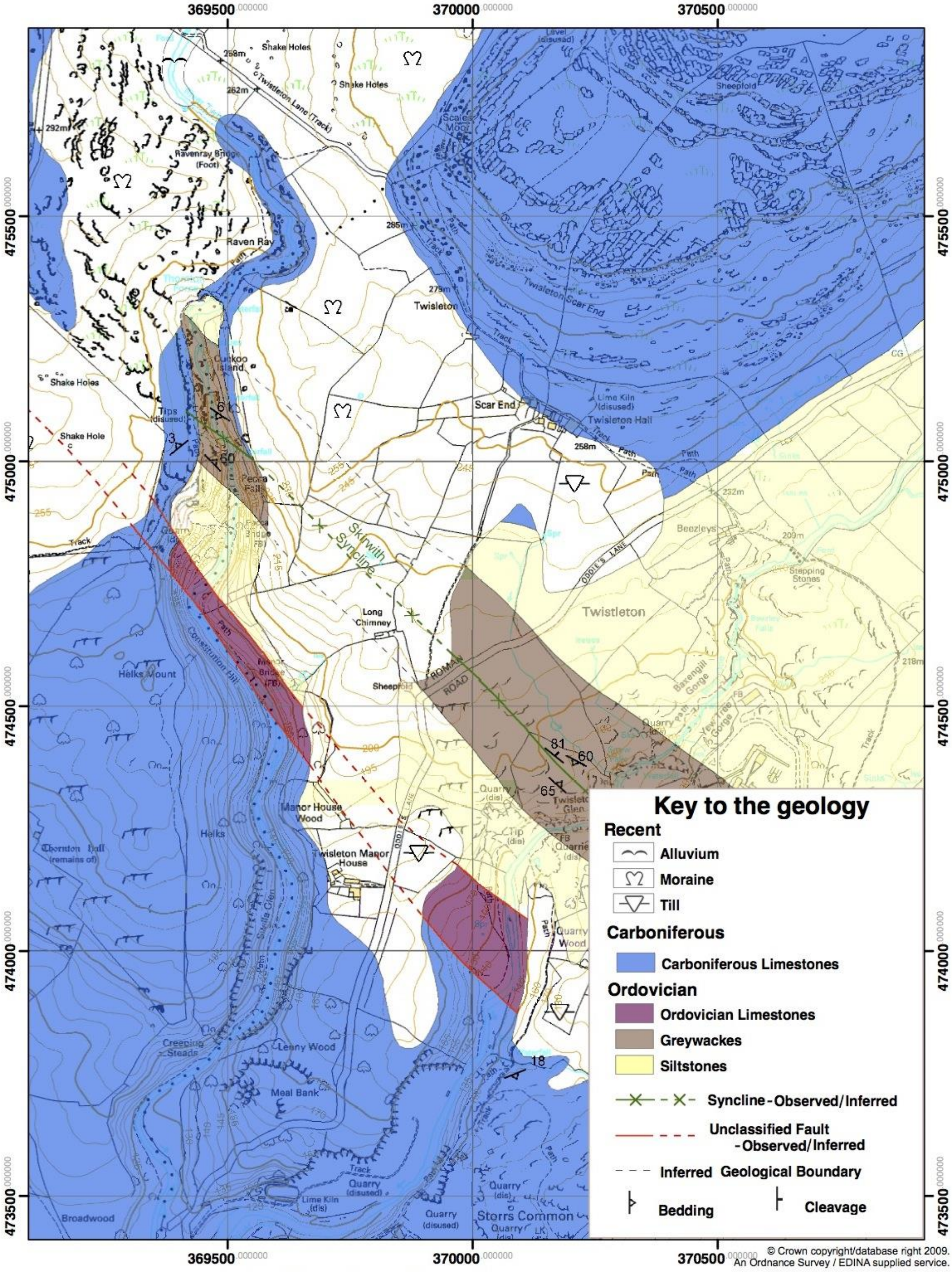


Figure 18: Ingleton geology map: Geology of Ingleton as mapped by Jack Soper at 1:10 000 scale, showing drift and bedrock. Re-drawn by Clare Gordon.

3.2.2.2 Hardware and software

Two tablet devices were used, a Samsung Galaxy Tablet 10.1 running Android 4.0.4 ICS (Ice Cream Sandwich version) and an iPad2 running iOS6. The apps used for the evaluation were:

- iGeology2D and iGeology3D
- Google Earth (3D) and Google Maps (2D).
- Polaris Mobile Office Suite for MSc students for sketching, but undergraduates used a sketching application called "PicsArt" instead.
- "SayCheese" a camera app as it is able to stamp pictures with GPS and time stamps.

3.2.2.3 Questionnaire

Participants were able to answer the questions by answering yes, no or not applicable based on the "if" statement in the questions. The questionnaire was given to the MSc students on the bus on the way out to the field. The age, gender and nationality of the students were not recorded. The number of students who were approached was 16, but only 15 of them participated. Students were approached on the bus using a Samsung Tablet which had the questionnaires on it. The questions contained in the questionnaire and the results are shown in Table 3.

Type 'y' or 'n', questions with an IF can be left blank depending on the IF statement

Q/U	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Do you own a smartphone/tablet?	Y	Y	Y	Y	N	N	Y		Y	Y	Y	Y	Y	Y	Y	Y
Do you have a smartphone/tablet today with you today?	Y	N	Y	Y		N	Y		Y	Y	Y	Y	Y	Y	Y	Y
Did you familiarize yourself with the location before coming?	N	N	Y	Y	Y	N	Y		Y	Y	N	N	Y*	N	Y	Y
Do you have a camera with you today?	Y	N	N	N	Y	N	N		Y	Y	N	Y		N	N	Y
Do you think your spatial skills are of a reasonable level?	Y	Y	Y	Y	Y	Y	Y		Y	Y	Y	N		Y	Y	Y
Do you think your map reading skills are of a reasonable level?	Y	Y	Y	Y	Y	Y	Y		Y	Y	Y	Y		Y	Y	Y
Do you know what KML is?	N	N	N	N	Y	Y	N		N	N	N	N		Y	N	N
IF you have a smartphone/tablet, are you going to use it?	N	Y	0	N			Y		Y	N	N	N	N	Y	Y	0
IF you are going to use a smartphone/tablet have you downloaded specialist apps?		N					N		N					Y		

Table 3: The actual questionnaire given to the MSc fieldtrip participants and the results of their answers. This was a document for the office package on a Samsung Android Tablet.

3.2.3 Procedure

The conventional version of the tasks was carried out without any input from the researcher (Layik). For the tablet-aided version, the researcher remained with the participant to assist with using the apps, for instance to show the map on Google Earth. After a basic run though the relevant apps, the tablet was then given to the participant and the researcher only intervened if help was requested.

Participants carried out the tasks sequentially as they progressed during their respective field trips. For instance the MSc group carried out task one at the start of the trip whilst they progressed further in the field trip they carried out the third task. The undergraduate students carried out the second task at the beginning of the trip and carried out the third task further into the field.

The procedure for participating in a task version was to do it either in conventional or tablet-aided version. Only the MSc students could participate in different versions of different tasks. The tasks used in the procedure for MSs and undergraduate participants were as follows:

1. **Regional Geology (MSc only)**: the wording for conventional and tablet-aided version of the task is shown in Figure 19.

Task 1: General awareness of the regional geology

You have 5 minutes to complete each section.

A) Please describe very briefly the regional geological setting using the 2D geological map, studying your traditional method of discovering about the regional geology.

B) Please describe very briefly the regional geological setting using the 3D DEM and satellite imagery, with geological data, 2D geological maps with ability to zoom in and out. You will be guided through iGeology 3D and Google Earth applications.

Task	A		B	
User	Time		Time	
U1				

Figure 19: actual wording of the task 1 for both versions of the task. The tasks is to “describe very briefly the regional geological setting” using the conventional or tablet-aided tools.

In this task MSc students explored the area geology. The aim of the task was to determine if the tablets can aid with understanding the regional geology. For the conventional version participants used the “Geology map of Ingleborough” (see Figure 15). The participants of the tablet-aided version explored the area using the same map draped o Google Earth DEM. The latter group were also shown the same area using data from British Geological Survey (BGS) using their iGology3D app, for example a screen shot is shown in Figure 20.

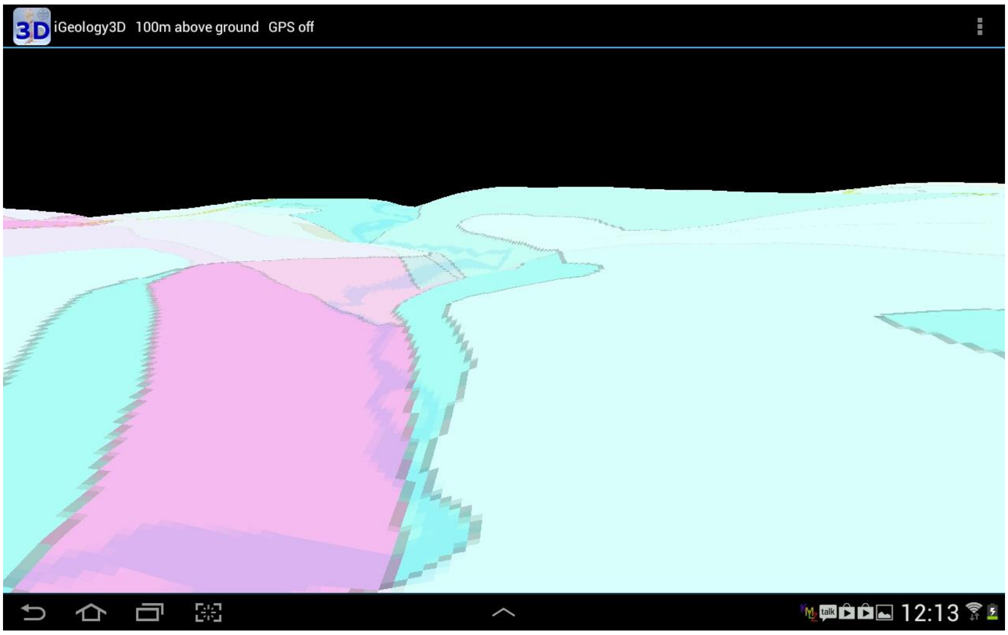


Figure 20: iGeology3D screen shot from Ingleton area for illustration purposes only. The DEM and geological data belong to BGS.

2. **Locate yourself (Undergraduates only):** in this task undergraduates locate their current location on a topographic map as they do when doing fieldwork. The aim of the task is self-defined, to see if GPS could be any better than conventional methods of locating a position on a map. For the conventional version participants locate themselves either by triangulation or reading their topographic maps. The map used for the field trip can be found in Figure 17. For tablet-aided group, they see their location on Google Earth using the device GPS.

3. **Extrapolate feature (both):** in this task participants have to interpret a geological unconformity by sketching their own interpretation, in other words they were sketching field relationships from maps. The aim of the task was again to find out if the digital device can assist with extrapolating a geological feature onto the real scene.

Conventional version participants study a highlighted geological unconformity on geological maps, and then draw a sketch of the real scene. For the-tablet aided version participants had the benefit of the same map draped over Google Earth.

MSc and undergraduate users had separate sketching apps as indicated in materials section. The participants in both versions of the task were free to use field data and obviously observer the scene as they were carrying out the task.

3.3 Results

3.3.1 Questionnaire Results

The questionnaire gives a little background to the students' own judgement about their "spatial skills" as well as relevant technology to use in their fieldwork. A summary of the results is in Figure 21.

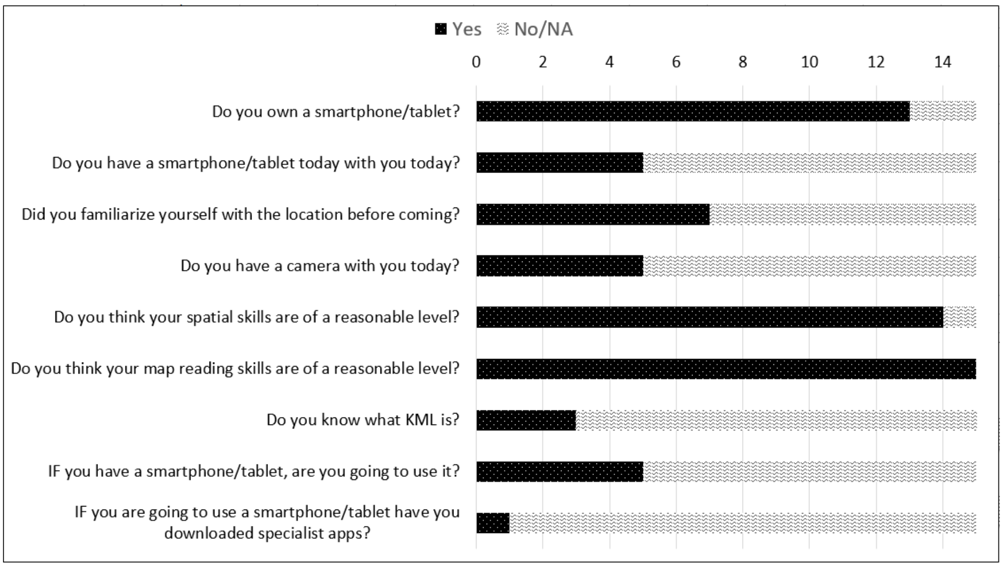


Figure 21: MSc students' questionnaire results. The stacked bar chart shows actual numbers of results of "Yes" versus "No and not applicable".

The majority of the students owned a "smartphone/tablet" (13 out of 15) and the same proportion had their "smartphones/tablets" with them. Also, around a third of the students had a digital camera with them. However, only a third of the students intended to use their "smartphones/tablets" on the trip, and only one student indicated he or she had downloaded the iGeology app for the trip.

Everyone indicated they had a "reasonable" map reading skills, and only one student indicated that his/her spatial skills were not up to a "reasonable" level. Given that KML is not widely known technology, it was not surprising that only two participants were aware of KML.

3.3.2 Task results

The conventional version of task one was captured on printed sheets given to the participants. For task two undergraduate students put cross marks on the maps they were using during their fieldwork. Pictures were taken of the maps for those who participated. For the conventional version of task three, both MSc and undergraduate students were sketching for their own fieldwork, again pictures were taken of those who participated (Figure 27-A is an example). The tablet-aided versions were of course recorded using the tablet used.

The qualitative data (sketches and answers to questions) from tasks one and two were analysed by an expert. The “own location” data from task two was analysed separately. Any indication that students who used the tablet computers would have done “better” than the conventional group, would mean there is already digital tools that could improve geological fieldwork experience for students. The results, however, were nowhere near this.

Task 1: Regional Geology (MSc group)

Three examples of the results from conventional and tablet aided versions of Task 1 is shown in Figure 22.

A	B
0.5-2m thick limestone beds dipping 120/20s. Outcrops 0.5-2m thick limestone beds dipping 120/20s.	Unconformable unit overlies sediment in valley below. A stream has cut a valley down to pin/purple units (folded?). Resolution is poor for high zoom layers!
Uniform rock types in North East, with a fold feature present around the side. The rock type marked as a blue unit cross cuts the grey 'pink' in the west to form an unconformity. In the south the rock bedding appears to be more faulted and	The local geology is clearly shown on the 3d dem image and can be directly related to the current location. This shows the slate and its relation to the valley. It can also be used to analyse topography which is particularly useful
The area consists of limestone beds of uniform thickens nearing between ~1 and 5m. These have been tilting to the SW by ~30°	Looking NW similar dipping beds as at loc.1.1 are apparent. Also apparent on iPad. To the west topo. drops ogy – lowland representing thinner PG beds to west as on map.

Figure 22: Three answers for each of the two versions of task one (A conventional, B tablet-aided). The typographic errors are left as they were typed by the students on the Samsung Tablet for the tablet-aided tasks. The conventional results (A) were transcribed from paper sheets.

When the expert reviewed all the results, he noted: *"The traditional method ones have focused on the immediate area around them whilst the tablet-aided ones are more in the context, but obviously this could be due to something or individual differences due to the limited number of participants"*.

The participants of the tablet-aided subtask seem to have focused on the technology whilst the other group have given a more consistent reply to the question for the task carried out. This could be due to individual differences, as suggested by the expert. Whether this had anything to do with the ability to zoom in and out (ability to see more than the printed map region) using the different tablet applications may also be a plausible explanation.

Task 2: Locate yourself (Undergraduate group)

The accuracy was estimated by comparing the maps on which the participants had put their locations (crosses) with a copy of the same map with a "radius around point" projected over it. There were two crosses for each participant on each map to compare; one before triangulating their location and one after triangulation.

A radius around a point is multiple circles around a centre point on a map for estimating distance from the centre. The centre was assigned as the location indicated by the Samsung Tablet GPS where participants carried out the task. The circles were drawn at 10m intervals starting from 10m up to 120m.

The accuracy without triangulation was an average of 112m (SD 22.8m). After triangulation they achieved an average of 12m (SD 4.47m). The range of the Samsung Galaxy Tab's GPS accuracy at the location was recorded as between 8 – 16 metres. These were noted during the task carried out by the participants.

For triangulation students needed to recognise a feature on the printed map from their immediate surroundings. Only then were they successfully able to use their compass-clinometers to locate themselves. The lead geologist referred students to a symbol on map three which was referring to an object (shed) in the vicinity. This further assisted the undergraduates in triangulating their location.

Task 3: Extrapolate feature (both groups)

The extrapolation task was slightly different for each group. For the MSc group the unconformity was chosen to be the hillside of Raven valley in Figure 23, which shows map one draped over the Google Earth DEM (October 2012).

The resolution of the elevation model here seems reasonable, one participant noted: "*The local geology is clearly shown on the 3d dem image and can be directly related to the current location. This shows the slate and its relation to the valley. It can also be used to analyse topography which is particularly useful*".

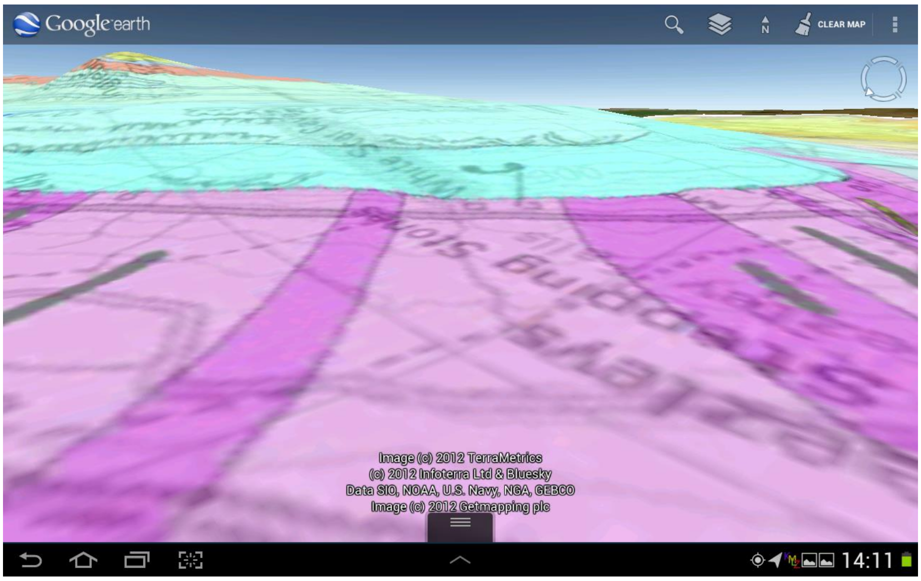
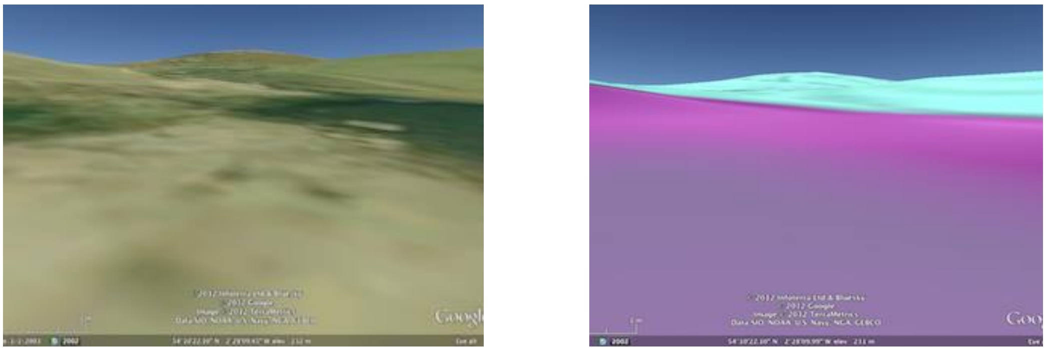


Figure 23: Map one draped over Google earth (October 2012) showing the limestone and carboniferous unconformity. The screen shot is taken from OS Grid SD 70453 75004 towards NE showing the east side of the Raven valley.

Figure 24: Thornton Force waterfalls. The unconformity is shown as a red line. The picture was taken using “SayCheese” app that imprints GPS and other data on photos.

The unconformity for the undergraduate group was the exposure at Thornton Force. It soon becomes clear that the elevation model and satellite imagery resolution is a serious limitation. A picture of the scene is shown in Figure 24. When we view the same location using Google Earth (October 2012) with the same map draped over it, screen shots shown in Figure 25 is what we could see, and the same position is shown in Figure 26.

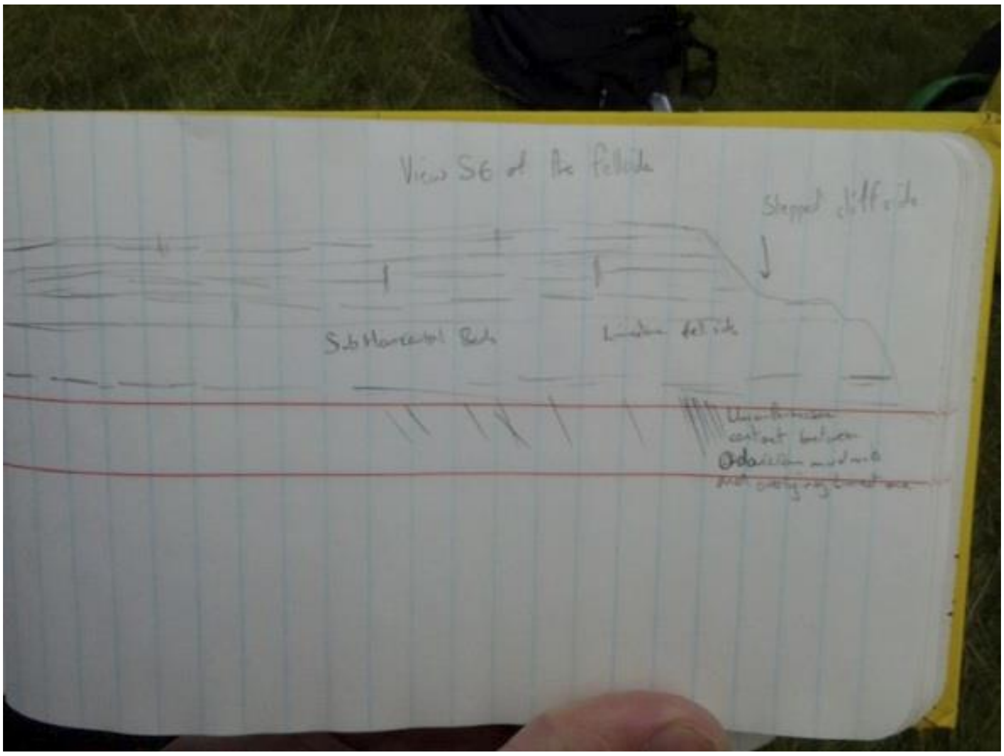


(A) (B)

Figure 25: Thornton Force in Google Earth. Showing same position and view direction of the camera in Figure 24 with (B) and without (A) map one draped over the scene. Screen shot taken November 2012. (A) It is not possible to see trace of the unconformity, (B) Although the pink and blue colours show the unconformity, the DEM cannot show where the boundary lies.

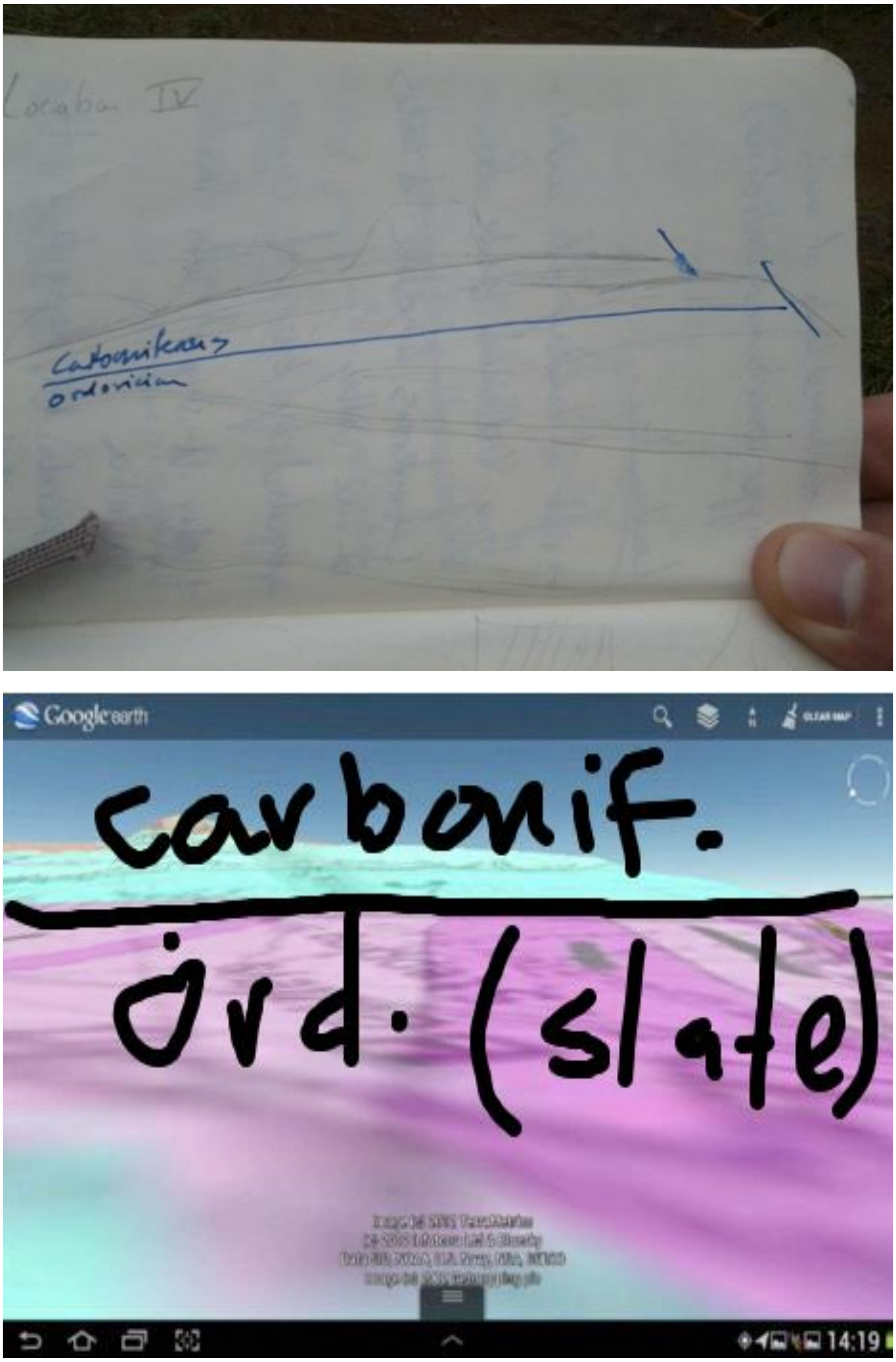
(A) (B)

Figure 26: The same location from above (241m elevation), again with (B) and without (A) map one draped over the scene. (A) Shows that it is possible to recognise the waterfall location but not where the uniformity lies. (B) Again it illustrates the DEM and map resolution fails to represent the unconformity any clearer than just two different colours.


(A)

(B)

Figure 27: The expert notes that this participant was not aided by the tablet despite the clarity of the unconformity shown by the “thin” red line in (B) by participant number nine, whilst the conventional sketch shown in (A) by participant number four shows more details of the structure of the geology.



(A)

(B)

Figure 28: The expert refers to these images when suggesting that the digital version of the sketch (B) captures more details than the conventional sketch drawn in (A).

The expert analysing the sketches made for the conventional and tablet-aided version of the task noted: "*User 1 have done a good sketch with a less detailed digital version, in fact the digital sketch is confusing despite the clear background geological map. However, user 4 is the other way round and has more details on the digital sketch but very little detail on the pen and notebook sketch*". User one's sketches are shown in Figure 27 and user four's sketches are shown in Figure 28.

3.4 Discussion

Three different tasks were given to two different groups of students. The first task was designed to test students understanding of regional geology. The second task was dedicated to a slightly different aspect of fieldwork not directly related to visualization techniques. Task three is one which has been acknowledged as an issue (see section 2.5.4) and one that visualization could play a role in it.

First of all turning to benefits of smart devices, there are benefits of using them in fieldwork to support various field tasks. The main benefit of digital devices is that students can take more than the printed maps out to the field, for example students were able to see data from BGS on their iGeology app. They can also take any other material (text or visual) if they wish to given the fact that the majority own smart devices; from the results of the questionnaire. The amount of data captured by these devices is almost impossible to be captured on field notebooks.

Another benefit of these devices is that they allow students to bring home more information than when using conventional tools. For example, a key task in geological field trips is recording various details, and a simple app like "SayCheese" can record GPS and direction details on the pictures taken by students. Google's "My Tracks" app can record the reconnaissance using the device GPS and can be exported or views on mapping tools.

There were, however, more problems. Lack of high level resolution data for outcrops in Google Earth satellite imagery and the DEM soon became clear. It also became clear that the apps used for the evaluation are not designed to optimise the tasks undertaken. Similarly, iGeology3D also failed to assist students with either task one or task three.

Satellite image resolution *"refers to the size of the smallest feature that can be seen in an image"*, in a digital image the smallest unit is a pixel, the area represented by a pixel is the image resolution (Conway 1989, p.27). In addition to the satellite image resolution, there is also the DEM resolution which is the sampling rate for each altitude sample.

Google Earth DEM varies in resolution for different parts of the world using different sources starting with SRTM data. The SRTM data for the US the resolution is 30m whilst for the UK and certainly for the case study area of Ingleton, it is 90m with contour lines at 50m intervals. As for the satellite imagery, the resolution is 15m (InfoTerra 2013). A different satellite mission may provide up to 2m DEM resolution, with 1m contour lines and satellite imagery of 0.5m (InfoTerra 2013), but such data was not available at the time of the study. As for satellite imagery the SRTM 30cm data was commercially released after this study was completed (Navulur 2015).

Alternatively, perhaps if the high-resolution topography map, (the undergraduates' “Thornton Force Map”; 1:2500 scale) was draped with the data from the geology map (1:10,000 scale), the evaluation could have produced some different results.

Given the “right” resolution, Google street view imagery for field areas integrated with KML technology could prove to be a valuable tool. Currently it is not possible to add custom DEM or satellite imagery to Google Earth applications.

There were more limitations to the evaluation. One of these is the type of the tasks carried out during the field trip. Neither group were carrying out any mapping tasks, which is a fundamental activity in the teaching of geology students. Another limitation of this study was that participants were already on a tight scheduled field trip. The majority of the tasks were carried out during lunch and during other breaks. Ideally the participants would have more time to focus on the evaluation tasks, rather than doing both their fieldwork and the evaluation tasks.

3.5 Summary

The purpose of this exploratory field study was to explore the extent to which current apps on Android and Apple's app-store were able to support some of the tasks documented in section 2.5.2. The tasks used in this study focus on interpreting the geology studied by the students rather than capturing data.

There was the considerable improvment between the accuracy for determining a location on the map in task two for the undergraduates before and after triangulation. The result of the other two tasks show that there was little evidence of any improvement when students had the benefit of the apps. Whether this was due to the quality of the data or the visualization is not clear.

Thus, this study highlighted the limitations in terms of data and functionality of apps for generic field work that may assist geological analysis. The maps imported into Google Earth and cached DEM of the field trip area could assist the MSc students whilst failed to be of any use in the case of the undergraduate students.

Will high resolution DEM and satellite imagery solve any of the underlying cognitive issues? Would higher resolution data make extrapolation from 2D to 3D easier for novice geologists? The spatial cognition section in 2.4 guides us to think about novel visualization techniques to find some answers.

Regarding the increasing power of smartphones and tablets, are they reliable for use as geological measurement tools? These are the questions the next chapters will attempt to answer. It is now time to find out how reliable these devices are as measurement tools before we consider graphics power to assist novice geologists with geological analysis.

Chapter Four

4 Orientation measurements using an iPad

4.1 Introduction

Chapter three ended with questions regarding various aspects of the use of smart devices in the field including the reliability of such devices as a precursor to other use in the field. One of such apps is FieldMove Clino, which was released on Apple's App Store by Midland Valley in October 2013 (MidlandValley 2013b) on the iOS platform. RockLogger had already been on the Android app market (Google Play) for a while. However, there has not been a published study on how reliable is it to use these devices as an alternative to conventional compass clinometers. The study by (Murphy 2013) from the SEE does not compare measurements taken using RockLogger against any other measurement.

These apps run on devices such as Apple's iPads and Samsung's Galaxy tablets, which are equipped with sensors including magnetometers, gyroscopes and accelerometers. These sensors or chips known as MEMS (Micro-Electro-Mechanical Systems) enable these devices to determine device orientation (Barthold et al. 2011).

Moreover, the devices' GPS sensors make it straightforward for students to determine their position, as described in the last chapter. The professional community itself is still discussing how suitable smart devices are as a measurement tool and whether they are alternatives to century-old robust tools such as a Silva compass clinometer (Bistacchi 2014).

This chapter describes one of the methods that is used to measure orientation in Earth science. It will then describe a method for doing the same using smart devices using an Apple iPad2 device. It will then outline an evaluation of the accuracy of this method and its implementation, and comparing conventional measurements with app based technology, namely FieldMove Clino.

4.2 Measuring orientation: strike and dip

The orientation of various structures is measured differently in different disciplines. In structural geology, the orientation of a planar structure such as a bedding plane of an outcrop is measured by recording "strike" and "dip" (Pollard & Fletcher 2005) (see Figure 29). *Dip* is determined by both *dip angle* and *dip direction* (Twiss & Moores 1992).

The *dip angle* is the angle between a bedding plane and the horizontal plane (Twiss & Moores 1992; Pollard & Fletcher 2005). *Strike* is a horizontal angle with geographic north (Twiss & Moores 1992; Pollard & Fletcher 2005).

A *strike line* is a line formed by the intersection of a horizontal surface with inclined planar structure (Twiss & Moores 1992; Pollard & Fletcher 2005). One of the two directions of this line can be used to record *strike*.

A *dip line* is defined as the direction of the steepest angle of a bedding plane, perpendicular to strike, and is also known as the *trend* by British geologists (Twiss & Moores 1992), this is called *dip direction* by (Pollard & Fletcher 2005) and throughout this chapter.

A *dip direction* is also defined as the compass bearing of either of two opposite-facing planes for each strike line (Twiss & Moores 1992), measured in degrees and approximated to 45° segments (N, E, S, W, NE, SE, SW, NW) (Twiss & Moores 1992).

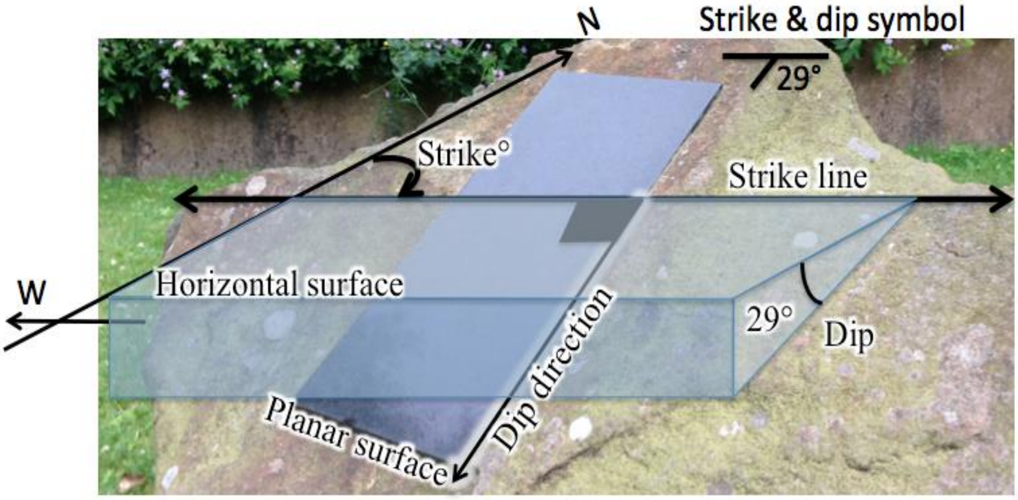


Figure 29: Strike, dip and dip direction illustration using an inclined and a horizontal plane.

Methods of measuring strike and dip using traditional tools such as a Silva compass clinometer are outlined by (Barnes & Lisle 2004). However, in the case of devices such as a compass clinometer the user has to align it in a particular way to take either strike or dip.

4.3 Implementation

Devices such as the iPad2 are equipped with sensors for various purposes. Manuals for determining compass headings using magnetometers are available from vendors

(Honeywell 2014). However, iPad2 and similar devices come with their own Application Programming Interface (API) that contains recommendations for getting a compass heading.

This section describes the details of how dip angle and dip direction may be measured on an iPad2. To calculate dip angle we need to know the screen normal of the iPad2. To calculate the dip direction we also need to know the orientation of the iPad2 relative to north, for which there are two methods.

4.3.1 Measuring dip

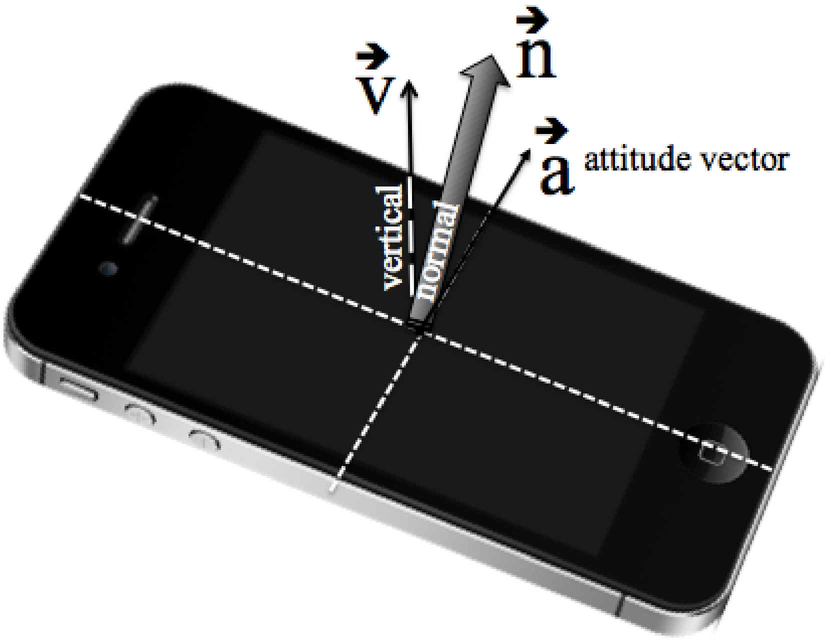


Figure 30: Calculating normal vector to the screen of an iPhone using 3d vector arithmetic.

Apple's API's Core Motion framework contains a class called CMAttitude (available from iOS5.0 onwards). This is given in the reference within which it was initialized, which by default is set to the x-axis pointing to geographic north.

In order to find dip angle and dip direction of a device first the normal vector to the screen of the device is required. The different vectors in relation to a device are shown in Figure 30.

The CMAattitude class contains various representations for the device *attitude*, including quaternions *[w(x,y,z)].* Let the device attitude be defined by the quaternion *q*, its conjugate is $q' = [q_w\ (-q_x, -q_y, -q_z, q_w)]$, and the normal of the device when it is flat on the ground as quaternion $v = [0(0,0,1)]$. Indeed, the rotation of the current quaternion is equal to the rotation of *v* to current rotation quaternion *q.* Applying quaternion rotation to a quaternion *q,* conjugate *q'* with a zero real number (*v*) = *q v q'* (Vince 2007; De Paor 1996). Thus, normal quaternion *n = q v q'*.

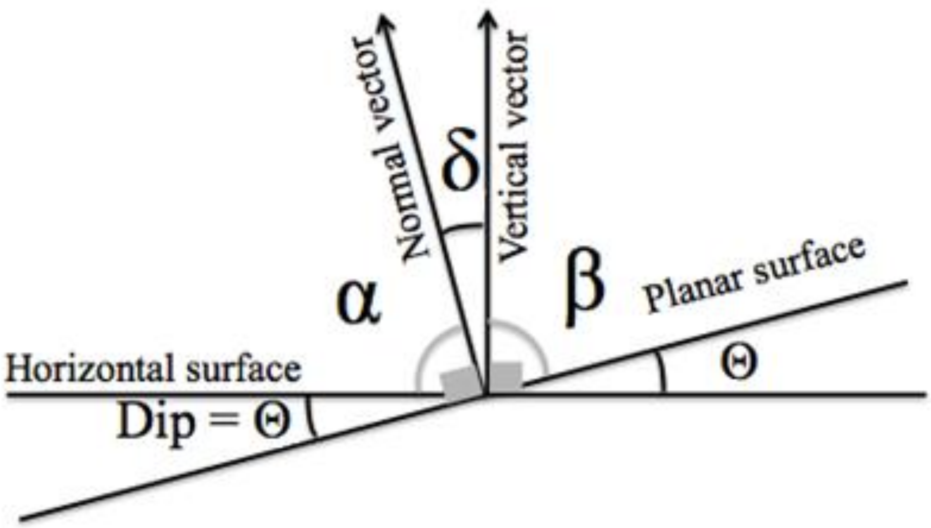


Figure 31: Illustration of calculating dip angle as the angle between vertical and normal vectors of a plane.

From Figure 31: $\delta + \alpha = 90$ & $\theta + \alpha = 90$ therefore $\delta = \theta$. Thus, the angle between the normal to the screen and the normal as the device is flat on ground quaternions equals the dip angle. The angle between present normal (*n*) and the flat on ground normal (*v*) quaternions (see Figure 30) can be calculated using the dot product of the two.

We can use the vector parts *(x,y,z)* of the quaternions *n* and *v* to calculate the two vector dot product.

dip angle (Θ) = $acos(n.v/|n|.|v|)$

4.3.2 Measuring dip direction

For dip direction measurements two API libraries were used. Let's call them by the API names: Core Motion and Core Location. Apple API gives the device attitude using Core Motion API, and a device "magnetic heading" in Core Location framework.

Having calculated the normal quaternion to the screen of an iPhone device, dip direction can be deducted. If as shown in Figure 32: *d(x,y,z)* is the resulting dip direction 3D vector, *v(0,0,1)* is the flat on ground vertical vector. Then using the vector part of the quaternion normal in the last section, a normal vector $n = (q_x,q_y,q_z)$.

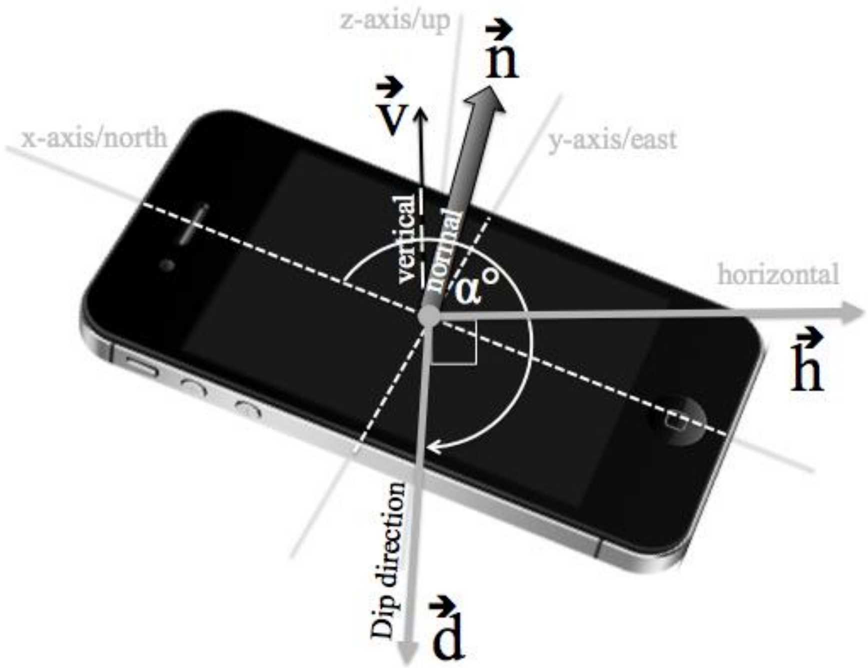


Figure 32: Calculation of dip direction using the Core Motion API.

In vector multiplication, the definition of the right hand rule is extending the right hand in the direction of one of the two vectors, and curling the fingers in the direction of the angle between the two vectors, the thumb will be the direction of their product (Weisstein 2016). Using the right hand rule vector multiplication in Figure 32:

h = *v n*, *h* is on the device surface, then *d* = *h n*

The result is vector *(d)* can be used to deduct the horizontal angle of rotation of the *x-axis*. This is because the *x-axis* of the vector was originally pointing to the north, the reference from which the dip direction is measured.

The arc tangent function of the result vector's (dy,dx) values is ±180 and is the dip direction angle from the north. If $atan(d_y, d_x) < 0$, $\alpha = 180 + atan(d_y, d_x)$.

The second way of calculating dip direction is using the Core Location API. For device compass-heading Apple recommends a class called CLHeading (from iOS 4.0 onwards) in the Core Location API. This contains both a magnetic heading and true heading angles, magnetic heading is what is used.

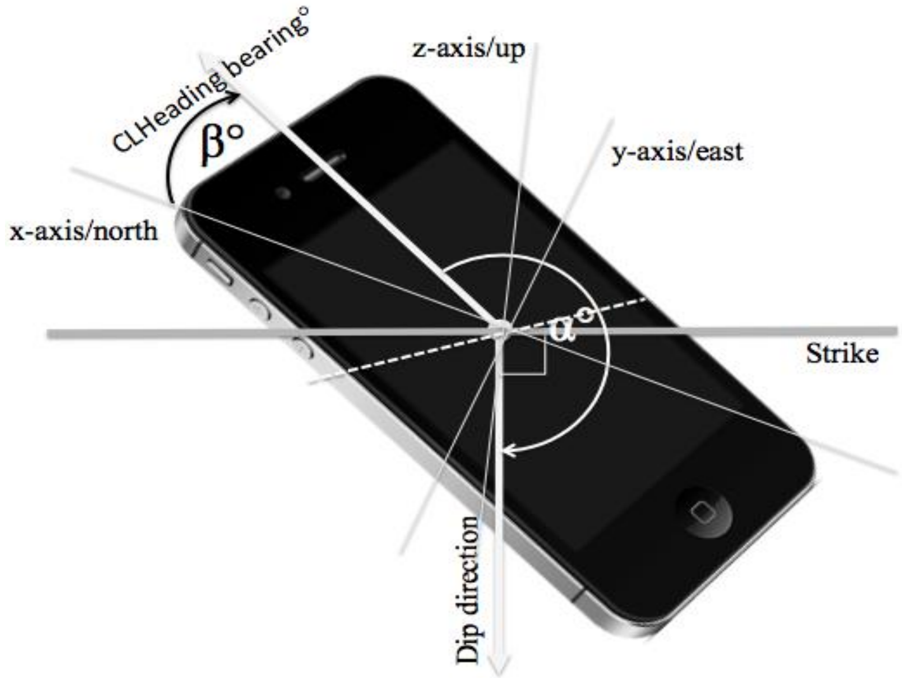


Figure 33: Calculating dip direction using Core Location API.

This angle points to the direction from the centre of the screen to the top of the device as shown in Figure 33, lets call this β, but dip direction is $\beta + \alpha$.

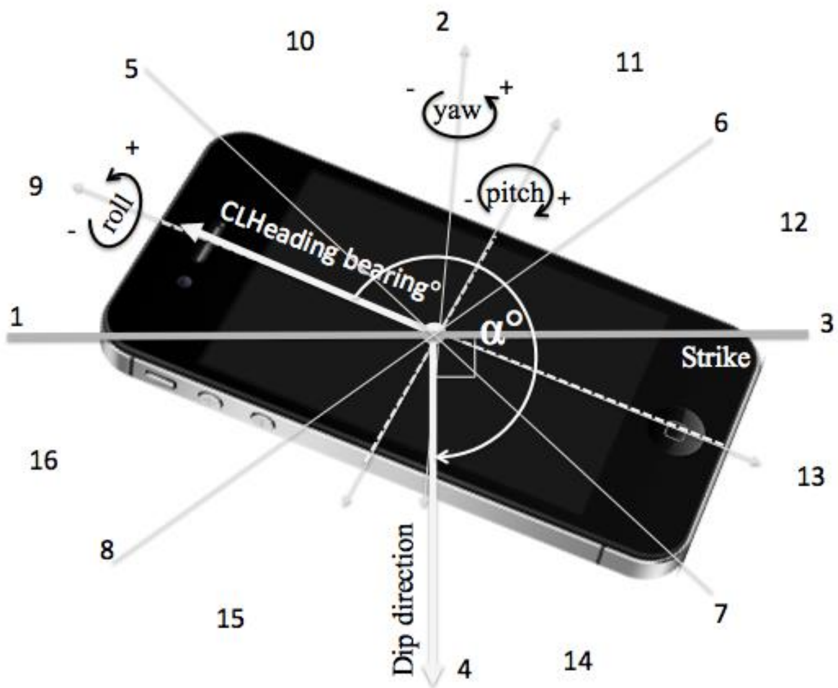


Figure 34: iPhone body reference nautical angles as right-hand rule and 16 angles in relation to CLHeading.

<table>
<tr><th>A</th><th>Pitch (p)</th><th>Roll (r)</th><th>Rt</th><th>β + α</th></tr>
<tr><td>1</td><td>0</td><td>> 0</td><td>-</td><td>α - 90</td></tr>
<tr><td>2</td><td>> 0</td><td>0</td><td>-</td><td>α + 180</td></tr>
<tr><td>3</td><td>0</td><td>0 ></td><td>-</td><td>α + 90</td></tr>
<tr><td>4</td><td>0 ></td><td>0</td><td>-</td><td>α</td></tr>
<tr><td>5</td><td colspan="2">||p|| = ||r|| & p,r >0</td><td>-</td><td>α + 135</td></tr>
<tr><td>6</td><td colspan="2">||p|| = ||r|| & p >0 & r <0</td><td>-</td><td>α - 135</td></tr>
<tr><td>7</td><td colspan="2">||p|| = ||r|| & p <0 & r >0</td><td>-</td><td>α + 45</td></tr>
<tr><td>8</td><td colspan="2">||p|| = ||r|| & p,r <0</td><td>-</td><td>α - 45</td></tr>
<tr><td>9</td><td colspan="2">p,r < 0 & ||p|| > ||r||</td><td>p/r</td><td>(1) + Rt x 45</td></tr>
<tr><td>10</td><td colspan="2">p,r < 0 & ||p|| |< ||r||</td><td>r/p</td><td>(2) - Rt x 45</td></tr>
<tr><td>11</td><td colspan="2">p < 0 & r > 0 & ||p|| > ||r||</td><td>p/r</td><td>(2) + Rt x 45</td></tr>
<tr><td>12</td><td colspan="2">p < 0 & r > 0 & ||p|| < ||r||</td><td>r/p</td><td>(3) - Rt x 45</td></tr>
<tr><td>13</td><td colspan="2">p < 0 & r > 0 & ||p|| < ||r||</td><td>p/r</td><td>(3) + Rt x 45</td></tr>
<tr><td>14</td><td colspan="2">p < 0 & r > 0 & ||p|| > ||r||</td><td>r/p</td><td>(4) - Rt x 45</td></tr>
<tr><td>15</td><td colspan="2">p,r > 0 & ||p|| > ||r||</td><td>p/r</td><td>(4) + Rt x 45</td></tr>
<tr><td>16</td><td colspan="2">p,r > 0 & ||p|| |< ||r||</td><td>r/p</td><td>(1) + Rt x 45</td></tr>
</table>

Table 4: All possible angles of dip direction using CLHeading class of Core Location API

As stated above, the device attitude is also given as Euler or Tait-Bryan angles (pitch, roll and yaw). The body reference of the device, the Euler angles and their rotations by right hand rules are shown in Figure 34.

There is not a single mathematical formula to determine *β + α*. There are 16 angles of *β* in relation to dip direction if the device is not vertical, as shown in Figure 34.

Angles 1 to 4 are known in Apple developer terms: portrait (opposite), inverse portrait (parallel), landscape with home button left (orthogonal right) or right (orthogonal left) respectively, where either pitch or roll is 0.

For angles 5, 6, 7 and 8 pitch and roll are equal. For the rest of the angles pitch and roll are non-zero values which vary from 1, 2, 3 and 4 by a ratio of up to ±45°. For implementation convenience Table 4 includes the condition and answer for $\beta + \alpha$.

4.4 Evaluation

The evaluation compared the accuracy of dip angle and dip direction measurements made using iPad2 apps with ground truth measurements taken by an experienced geologist in the traditional manner, using a Silva Ranger 515 compass clinometer.

The two apps were: the *FieldMove Clino* iOS app, developed by Midland Valley, a well-known structural geology consulting and software company. The other was our *Prototype*, which used one method for calculating the dip angle and two methods (*Core Motion* and *Core Location*) for calculating the dip direction (see section 4.3.2).

4.4.1 Method

4.4.1.1 Participants

An experienced geologist used a Silva Ranger 515 compass clinometer to take the ground truth measurements. I took the iPad2 measurements with skills that are meant to be equivalent to the target users for the app (novice geology students), someone who knows how to use the app to take the measurements.

4.4.1.2 Materials

The SEE has an area for undergraduate students to practice taking measurements based around Chancellor's Court. There are rocks with one or more pieces of flat various sized rectangular shapes fixed on them (Figure 1 shows one of them). Nineteen of these outcrops were used.

Both the *prototype* and the FieldMove Clino measurements were taken using the same Apple iPad2 tablet device running iOS 7.0.1. The prototype implementation is based on Objective-C, the native iOS language.

4.4.1.3 Procedure

The "ground truth" records taken by the geologist were taken twice. For FieldMove Clino and the prototype, three rounds of recordings were done. During each round the dip angle and dip direction were measured four times, at compass readings of approximately 0°, 90°, 180° and 270°. That is placing the iPad with top (holding the iPad with home button at bottom) facing east, south, west and north for each of the four measurements. For the prototype, both the Core Motion and Core Location methods were used for each measurement.

The dip and dip direction measurements from FieldMove Clino app were taken by using the default app settings. Taking a measurement using the app requires a tap on the clinometer section of the app followed by “save” button. Those taken from the prototype had a usable interface for the measurements to be captured, a screen shot of a typical measurement taken using the interface is shown in Figure 35. Every time a dip and dip direction angle was recorded using the prototype one dip angle and two dip direction angles were captured using both methods for capturing dip direction.

The records on FieldMove Clino were later exported using the functionality provided. The prototype was also designed so that similar functionality was available to export the records from the app for analysis. To reproduce the prototype the method section includes all instructions that can be implemented by any iOS developer.

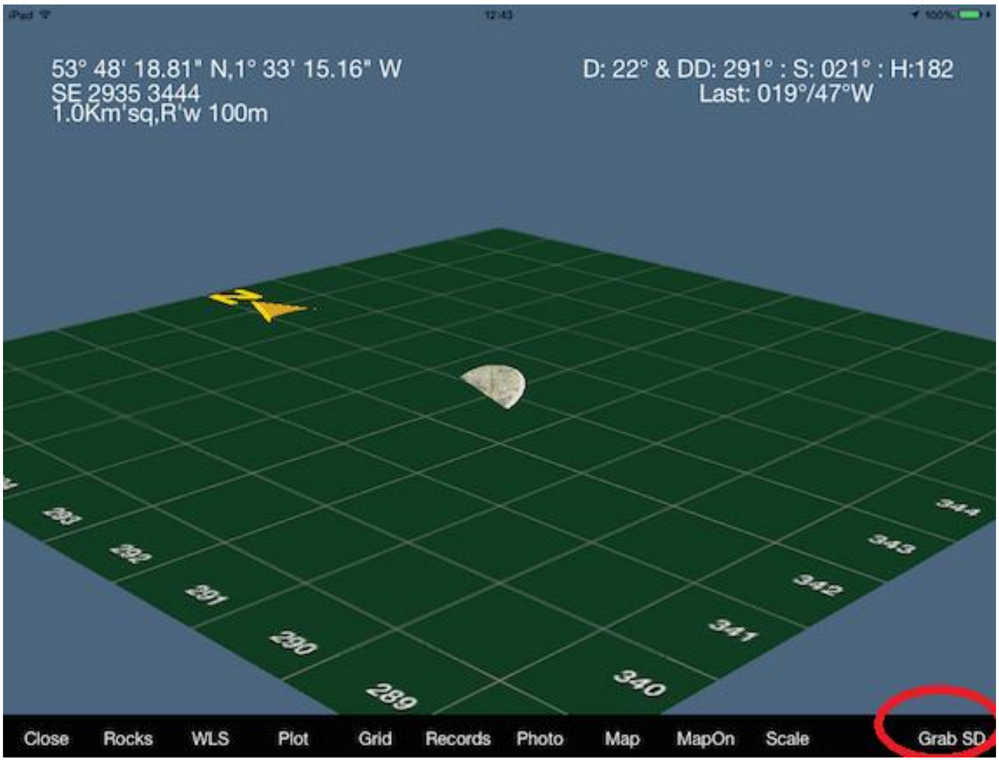


Figure 35: Screen capture of the graphical user interface of the prototype used for capturing the dip and dip direction measurements. The bottom right “Grab SD” button was the only meu button used.

4.4.2 Results and discussion

4.4.2.1 Dip angle

The mean dip angle measurements for each outcrop are listed in Table 5. As mentioned in the earlier, for the ground truth the average is from two measurements for each outcrop. For the FieldMove Clino and the prototype, the average is from 12 records for each outcrop.

Outcrop #	Ground Truth°	FieldMove Clino (average°)	Prototype (average°)
1	10	10	9
2	10	10	9
3	18	16	16
4	16	14	13
5	28	28	28
6	8	8	7
7	8	8	7
8	18	18	17
9	6	7	7
10	2	2	1
11	8	7	6
12	2	2	1
13	6	5	4
14	9	12	12
15	30	30	29
16	10	8	7
17	80	86	85
18	90	89	89
19	82	85	84

Table 5: Mean dip angle of each outcrop from all three methods. Ground truth shows an average of two measurements, the other two averages are from 12 records each.

According to [WOO76] and a geologist in the School of Earth and Environment at the University of Leeds, an accuracy of 2° for dip angle is acceptable. For FieldMove

84% of the measurements satisfied this accuracy threshold, compared to 79% of the prototype measurements.

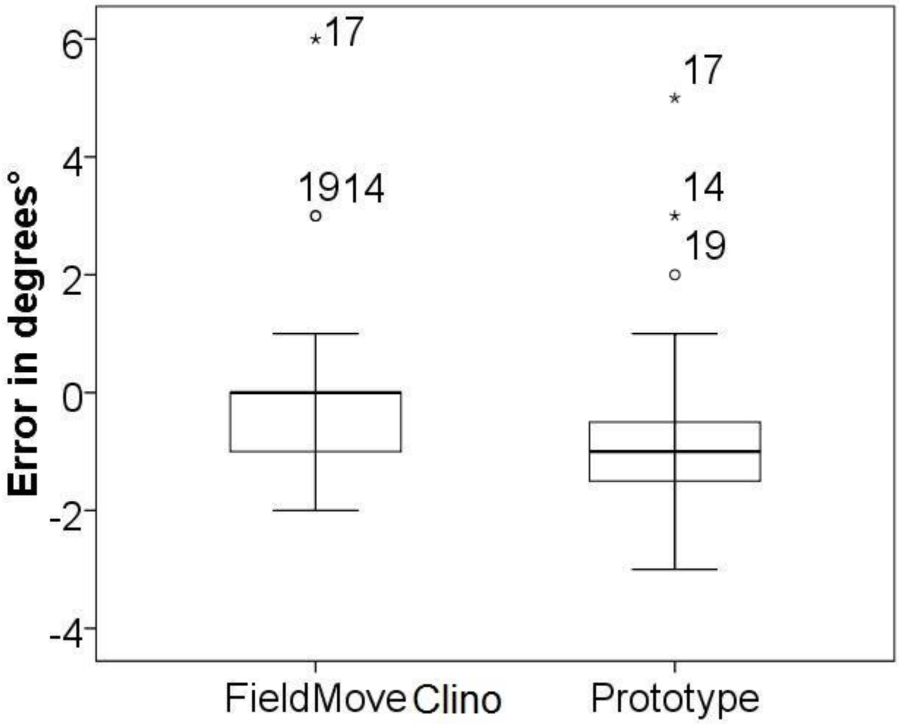


Figure 36: Dip angle error distribution for FieldMove Clino and the prototype methods. The asterisks show "extreme outliers", the dots show "outliers" and the numbers next to the asterisks and dots correspond to the outcrop numbers. The box plot whiskers show the maximum and minimum values, excluding the outliers.

4.4.2.2 Dip direction

The averages of the three methods of recording dip direction are shown in Table 6. Like the dip records, the ground truth is an average of two rounds of measurement. The other two methods are an average of 12 records for each outcrop.

Unlike dip angle, the dip direction measurements varied considerably from one reading to the next with FieldMove Clino, and with the prototype's Core Location and Core Motion methods. This is reflected in the magnitude of the errors, relative to the ground truth measurement.

For dip direction the research literature does not provide an acceptable error criterion, but the same geologist indicated that an appropriate criterion can be 5°.

Outcrop #	Ground Truth°	FieldMove Clino (°)	Prototype Core Motion (°)	Prototype Core Location (°)
1	148	130	124	128
2	270	240	265	269
3	138	133	126	135
4	178	167	165	170
5	300	293	289	289
6	236	300	296	297
7	292	226	228	227
8	022	17	14	40
9	300	291	278	300
10	050	22	101	86
11	210	172	160	181
12	130	120	111	135
13	300	323	310	325
14	090	73	57	75
15	058	75	48	66
16	238	223	211	226
17	248	251	251	212
18	218	140	212	245
19	166	167	155	157

Table 6: Mean dip direction angles (from north) for each of the methods. The ground truth is an average of two rounds of recording whilst the other two are an average of 12 record for each outcrop.

The mean signed errors for FieldMove Clino, Core Motion and Core Location were -12° (*SD* = 30), -10° (*SD* = 28), and -2° (*SD* = 28) respectively. The mean absolute errors for FieldMove, Core Motion and Core Location were 23° (*SD* = 23), 23° (*SD* =

19), and 21° (SD = 19) respectively. The mean error distributions are shown in Figure 37.

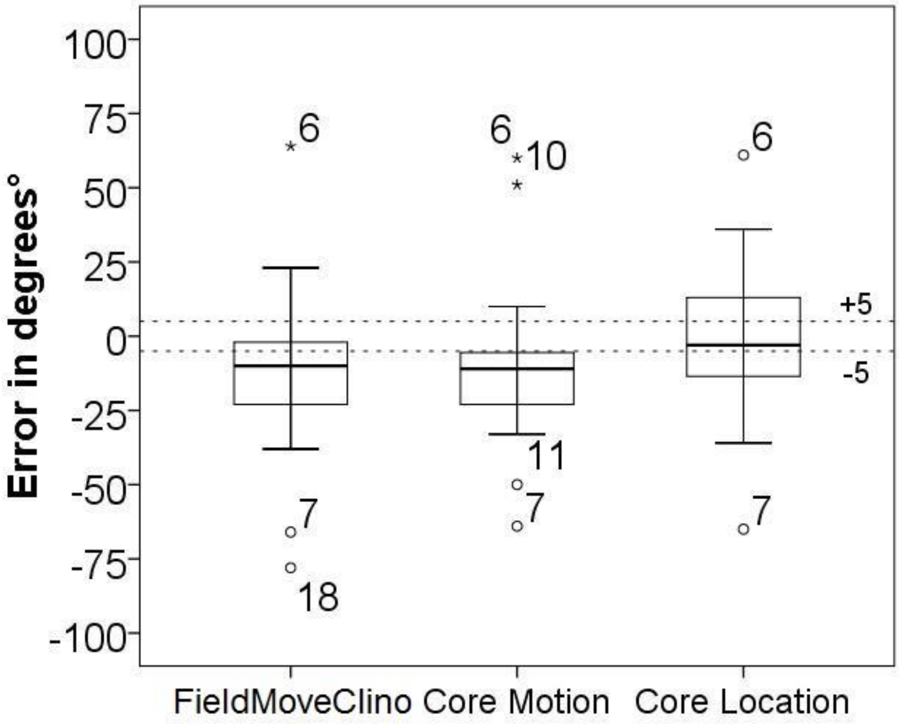


Figure 37: Dip direction signed error distribution for FieldMove Clino, Core Location and Core Motion. The asterisks show “extreme outliers”, dots show “outliers”, and the numbers next to the dots correspond to the outcrop numbers. The box plot whiskers show the maximum and minimum values, excluding the outliers. The acceptable error margin for dip direction readings is ±5°.

The reasons for the large errors in the dip direction could be attributed to various reasons. One of the reasons could be the “ground truth” itself and the error from the Silva Compass. Taking a different set of measurements using a different compass or perhaps the same compass could be one way of exploring this further. More likely reason could be the inherent inaccuracy of the magnetometer on the iPad device.

It is worth stating that the dip angle measurements were taken using the gyroscope chip only, whilst the dip direction measurements were taken using data from both the gyroscope and magnetometer chips. In the case of the gyroscope, it is reported to be reliable and precise, but if the calculation requires more time and reliance on previous measurements it may become unreliable (Shanklin et al. 2011). This caution does not apply for taking dip measurements. Hence, the results confirm this and show that both the prototype and FieldMove Clino readings are accurate and consistent (reproducible) for taking dip angles.

As for the magnetometer used for the dip direction measurements (regardless of the method), there is evidence that it performs according to the strength of the magnetic field it measures (Blankenbach et al. 2011).

Overall, the results show that the magnetometer is not consistent in reproducing the same recording for the same outcrop. It is also not accurate if accuracy is dictated by a 5° error margin.

4.5 Silva device errors

It has not been possible to find information regarding accuracy of the Silva device used in the experiment. Therefore, to indicate how the device measures up against the errors found in the experiment, one way is to compare it to itself. That is by getting a second set of measurements were obtained using the same device and the same expert who took the original (ground truth) measurements. There was a period of time between the two sets of measurements, so for this experiment multiple users were not involved, neither were multiple devices. The figures shown in Table 7 are the two set of measurements from the Silva device.

Outcrop	First round		Second round	
	Dip	Dip dir.	Dip	Dip dir.
1	10	148	005	120
2	10	270	005	278
3	18	138	016	138
4	16	178	016	166
5	28	300	030	290
6	08	236	008	306
7	08	292	010	238
8	18	022	020	16
9	06	300	008	278
10	02	050	002	30
11	08	210	006	182
12	02	130	005	202
13	06	300	004	290
14	09	090	010	50
15	30	058	030	58
16	10	238	008	218
17	80	248	086	246
18	90	218	090	220
19	82	166	074	264

Table 7: Two different rounds of measurements of dip and dip direction. They were taken using the same rocks and Silva compass-clinometer by the same expert.

The signed error of the above figures was calculated the same way it was done for the different methods in the study. The mean signed error for dip was -0.42° (SD = 3.24) and for strike it was -0.11° (SD = 39.11). The mean error for dip angle is between that of the prototype and FieldMove Clino whilst the standard deviation is bigger than the other two methods. However, while the mean signed error for strike is closer to zero compared to the other three methods, the standard deviation is bigger.

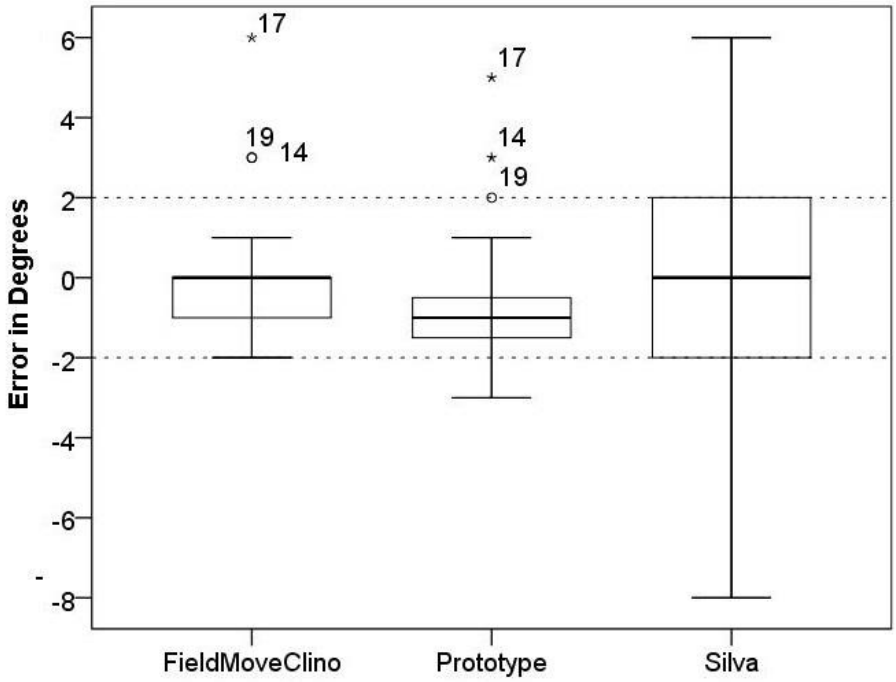


Figure 38: Dip angle signed error distribution for the Silva device compared to the other two methods. The acceptable error margin is ±2°.

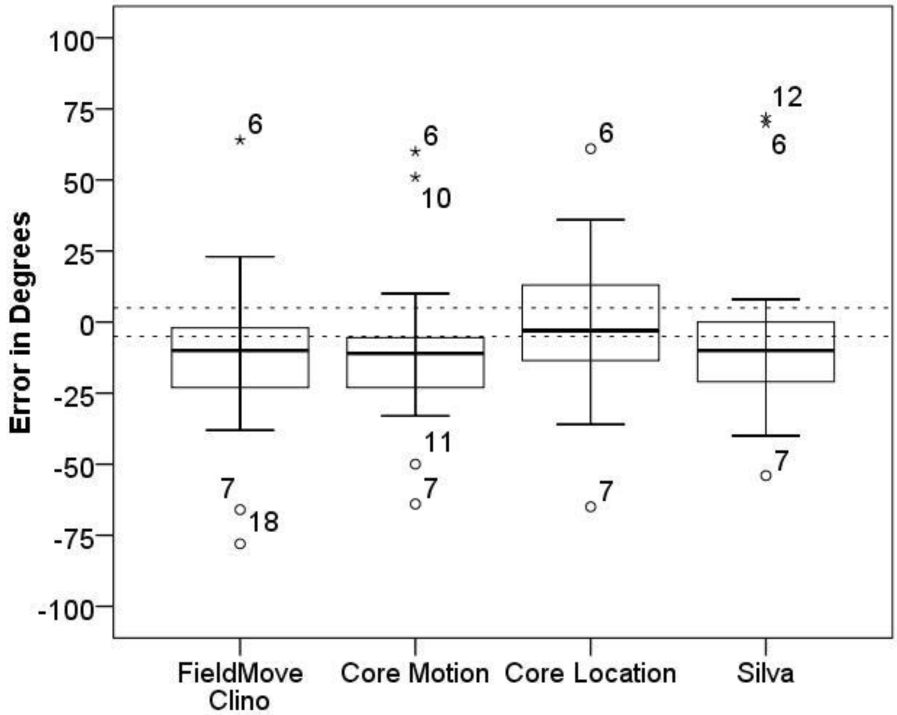


Figure 39: Dip direction signed error distribution for the Silva device compared to the other methods. The acceptable error margin for dip direction readings is ±5°.

Dip angle error distribution falls within the ±2° acceptable margin as shown in Figure 38. The outliers in the dip angle analysis belong to two high dip angles (outcrop number 17 and 19 with ground truth of 80° and 82° respectively), the third outlier is of outcrop number 14 with ground truth of 09° angle.

Dip direction error distribution, as shown in Figure 39, are outside the acceptable error margin of ±5°, which is similar to the other methods. The outliers for outcrop number 6 and 7 have a ground truth of 008-010° of dip direction for all methods except the Silva readings (outcrop 6 is 236° and outcrop 7 is 292°, see Table 6). These results are of course based on one measurement taken for the Silva whilst the other methods had the benefit of an average from 12 measurements. The outliers from the Silva reading could be, despite the premise of being ground truth, the magnetic reading could not be as accurate as a ground truth. Looking at Figure 38, there is no such outlier for the dip angles from the Silva readings.

4.6 Summary

This chapter described implementation of an iPad2 prototype app for making outcrop measurements, and evaluation of that app and a similar one from a well-known structural geology consulting and software company.

Dip angle measurements were of acceptable accuracy, but dip direction measurements were not. The mean signed error data from our prototype app indicates that if multiple measurements are made with the Core Location method then accurate dip directions may be measured. However, the results from the comparison of the Silva device recordings against the same ground truth, which was taken using the same device by the same expert, were not within the acceptable error margin. The experiment provides some insight into the accuracy of apps for recording strike and dip.

The chapter continued from the exploratory study to provide the precursor needed for the use of smart devices in the field, to test the reliability of these devices before turning to visualization for solutions of the issues discussed in the previous chapter. The work in the next chapter aims to see if visualizing dip and dip direction measurements is able to assist novice geologists perceive these concepts easier.

Chapter five

5 Strike and dip visualization

5.1 Introduction

In the last chapter the accuracy of an iPad2 device for use as a measurement tool was assessed. In this chapter we look at the question of *what graphical shape can represent strike and dip more intuitively*. This is different to representing the outcrop bedding or any planar surface in 3D space. There is no literature on this, and work on the visualization of 3D shapes in other contexts is of questionable relevance.

Representing *a shape* in a 3D environment is a 3D visualization problem whilst representing strike and dip involves representing two particular angles within geographic coordinate system. This is assumed to be an orientation issue within a wider spatial interpretation or geological extrapolation problem.

5.2 User evaluation

Human computer interaction (HCI) in the context of scientific research in computing plays the role of proof in other scientific disciplines (Trapp et al. 2010). The wider subject of HCI nowadays is referred to as "Interaction Design", and recommended reading from a pure computer science point of view is work by (Rogers et al. 2011). User experience (UX) is another term used in this context. The word evaluation is defined as *"systematic determination of the quality or value of something"* (Scriven 1991).

"Does it work?" is the overall question asked in *design science* research where the aim is serving a particular human purpose not a natural science fact or observation (March & Smith 1995). The authors state that there are two activities in design sciences, building and evaluating which is equivalent to discovery-justification in natural sciences (Trapp et al. 2010). Types of evaluation based on "*setting, user involvement and level of control*" are divided into three categories: control settings involving users, natural settings and any setting not involving users (Rogers et al. 2011, p.437). There are advantages and disadvantages for each of them. Lab studies can reveal problems with usability but not context of use whilst natural (or field) studies are good at revealing context of us but are expensive and difficult to conduct. Both control settings involving users and settings not involving users will be used in the studies outlined in the next three chapters. For more information, a comprehensive list of user experience methods is given by (Vermeeren et al. 2010).

In evaluations involving human subjects, a decision to be made is whether the evaluation needs to be within or between subjects. The implications of each of the two study designs is discussed by (Keren 2014, pt.8). Each user evaluation in subsequent chapters outlines the methods used and decisions made.

Analysis techniques discussed by (Rogers et al. 2011, chap.7) such as structured interviews and observations questionnaires are discussed in context of qualitative and quantitative methods by (Bryman 2012) to collect data. In this research these were employed to analyse the issues summarised in section 2.5.4. Other techniques such as a questionnaire was used to collect data prior to a user evaluation (as in chapter three) to understand participant demography and attitudes. Although a meeting to discuss field apps with BGS developers could be counted as focus group it was more a brainstorming session to identify possible functionality desired for fieldwork in general.

Geoscientists have used user evaluations based on the nature of their studies. The work by (Whitmeyer et al. 2009) which focuses on use of Google Earth in teaching geology was done using rating questionnaires. Other work related to spatial ability of novice geologists was done using multiple choice questions (Yael Kali & Orion 1996). More recent work, again related to spatial ability, has been carried out on computer screens but experts decided on the correct answer, feedback was recorded after showing participants the correct answer (Klopfer et al. 2013).

Due to the cross disciplinary nature of the research in this thesis the focus has not been on "interface" evaluation, but on the cognitive aspect of the proposed solutions for the issues in section 2.5.4. Therefore, there was the need to look beyond HCI into other disciplines such as psychology to find appropriate methods, one of those is be discussed next.

5.2.1 Staircase method

Psychophysics is defined by (Kingdom & Prins 2009) as "*sub-discipline of psychology concerned with the relationship of physical stimuli and subjective perception*". One of the categories of methods used is called threshold detection.

There are three types of threshold detection methods outlined by (Blackwell 1952): method of adjustment, serial exploration and constant stimuli. The body of literature that compares the statistical properties of each of these is outlined by (Jäkel & Wichmann 2006). One of the variations of what is known as "forced choice" threshold detection methods is the yes/no forced choice (FC) outlined by (Kingdom & Prins 2009). In yes/no FC a single *stimulus* is presented and a choice of either yes or no is forced on the participant at any time. The more frequently used methods are “alternative forced choice” (AFC) methods where the participant is prompted with more than one stimulus at any time.

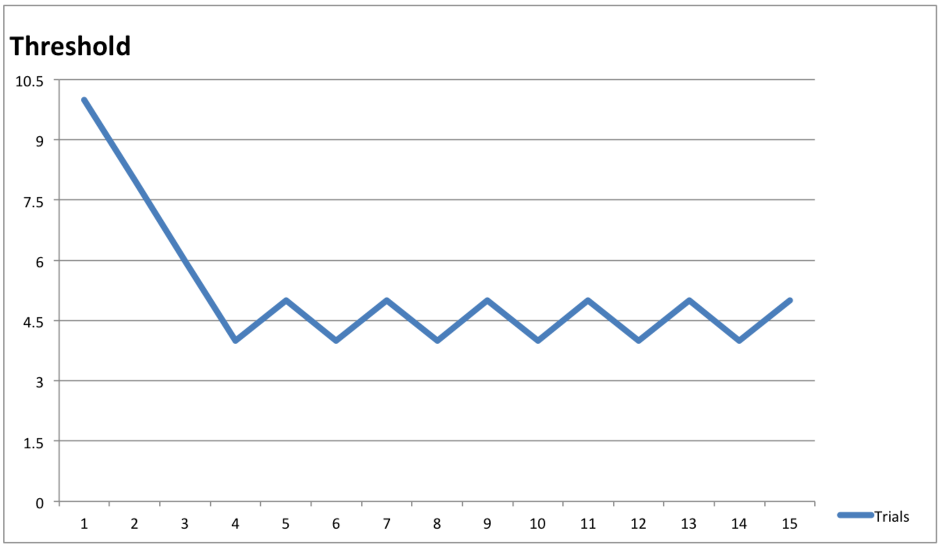


Figure 40: An ideal staircase threshold detection graph; around 50% positive detection. Redrawn from (Cornsweet 1962)

The *staircase method* (or up and down method) outlined by (Cornsweet 1962; Levitt 1971; Kingdom & Prins 2009) is an adjustment method for threshold detection based on a yes/no FC method. It is used for estimating a threshold at which users are likely to get 50% of their answers right when shown a particular stimulus. The method is used more widely in acoustic threshold detections but can also be used for visual stimulus detection too.

The method is best explained by an example. Threshold detection in the staircase method begins with a *provisional* high threshold that is easy to detect, the threshold is then decreased until detection becomes harder and a wrong detection happens. At the next reversal the threshold is increased making detection easier until another wrong detection happens in order to trigger another reversal. Figure 40 shows this process in an ideal scenario where the initial threshold hold is easy to detect and a sequence of three positive detections happen followed by what is called a “first reversal” and then equal number of correct and incorrect detections. In this example the test has a predetermined 15 *runs*.

For the staircase method there are certain parameters outlined by (Cornsweet 1962) and (Kingdom & Prins 2009, chap.5): (1) Provisional threshold: the starting value for the target threshold, (2) Step size: amount of change from previous provisional threshold, (3) Termination condition – the total number of runs and (4) Adjustment criteria: in which condition the “provisional condition” is changed by the “step size” amount.

There are various ways of meeting the adjustment criteria, the provisional threshold can be adjusted by the step size based on “one up one down”, “two down one up” or other ways. That is increasing or decreasing the provisional threshold by the number of correct/incorrect choices made by a participant.

The “first reversal" is the first reversal from a sequence of correct/incorrect choices made by a participant. According to (Cornsweet 1962) this can be set to “two, three or four” same answers before the first reversal. This is used as a point where the effect of the provisional threshold can be reduced by removing answers before the first reversal from the estimated threshold.

As part of the adjustment criteria there was one other condition that had to be satisfied. If a participant makes multiple correct/incorrect choices it means a limit on decrement and increments was needed. Arriving at the threshold and also getting out of an unexpected errors depending on the previous performance is determined by the step size (Cornsweet 1962). Therefore a lot of testing and preparation is required to make sure the chosen step size fulfils is appropriate.

In terms of number of participants for a staircase study, there were 34 participants in the study by (Jang et al. 2009), 32 in the study by (Khoe et al. 2000) a lot fewer subjects were used by (Blackwell 1952; Jäkel & Wichmann 2006).

The advantages and disadvantages of the staircase method is discussed by (Cornsweet 1962). One of the advantages is that it is quick for participants and data collection whilst the disadvantage is that much more time is spent by the experimenter during the set up stage.

5.2.2 Strike and dip perception experiment

Four different shapes were chosen to represent strike and dip, based on dimensionality and conventional use in teaching and cartography. These were: half disc (3D), square (2D), wedge (3D) and T-Letter (2D) shapes. The half-disc idea was borrowed from the 3D stereonet described in 2.3.2. The square shape was a natural choice for representing a planar surface. The wedge shape is borrowed from the examples of teaching strike and dip, as shown in section 4.2. Finally the T letter is borrowed from work by (Simpson et al. 2012) which comes from one of the symbols of representing strike and dip on a map (see (Groshong 2008, p.41)).

Representing two or three angles in 3D space is a problem not only for geologists. Mathematicians and others face similar problems. However, this is not just an exercise of representing two or three angles in 3D space. This experiment is about finding a more intuitive way of representing strike and dip in a geographic coordinate system that can be used in field app functionality. Therefore, options like the normal to a plane represented by an arrow to represent strike and dip were considered but was thought to go against the premise that such representation will be more intuitive. Such options are already used in specialist software packages that target professional geologists

The staircase method in the last section was chosen to compare the four different shapes chosen to represent a single strike and dip measurement. The method in the context of looking for a shape that would represent strike and dip *most intuitively* means an estimated number (threshold) by which an angle could vary that would be judged correctly 50% of the time. The study is looking to find, at least in the circumstances of the experiment, a shape with the lowest estimated threshold that would represent strike and dip in a 3D virtual environment.

As a result, there will also be an estimated threshold for each tested graphical shape. The threshold would be one estimated magnitude of angle of dip and one for strike. The estimated threshold would also indicate whether there would be any difference between the thresholds for strike and dip.

The staircase threshold detection method is applied to strike and dip only (see section 4.2), omitting dip direction. It is assumed that the graphical representation with lowest threshold for the dip and strike angle will also have the lowest threshold for dip direction.

The hypotheses are:

- For dip angle: the wedge-shape will have the lowest threshold. This is because it is assumed that by giving a triangular representation of the dip angle between the inclined surface and a horizontal reference the dip angle would be *clearer* to the viewer.
- For strike angle: all of the shapes are expected to have similar threshold except t-letter shape. This is because the rest have a bottom “horizontal” reference that would make it *clearer* to estimate the strike angle with the north in a horizontal plane in a 3D virtual space. This is not the case for the T shapes bottom end. In mapping context the T letter has no top or bottom ends.

- For both angles: the wedge shape would have the lowest threshold. This is because it has the advantage of having the advantage of focus on the dip angle and the bottom reference that other shapes have and t-letter doesn't.

Part of the experiment preparation included a pilot study. Three post-doctoral and two PhD students from a research group at the School of Computing at the University of Leeds participated in it. The results were analysed and checked to see if more modifications of the test set up were required. The purpose was to see what if any surprising or alarming results would be seen. Slight changes were made in the step size percentage (see section 5.3). The experiment user interface set up was also shown to two staff from the SEE and also a group of five MSc students from the SSE who noted some text presentation issues and also confirmed the overall "intuitiveness" of the experiment set up. These issues were addressed before the user interface was ready.

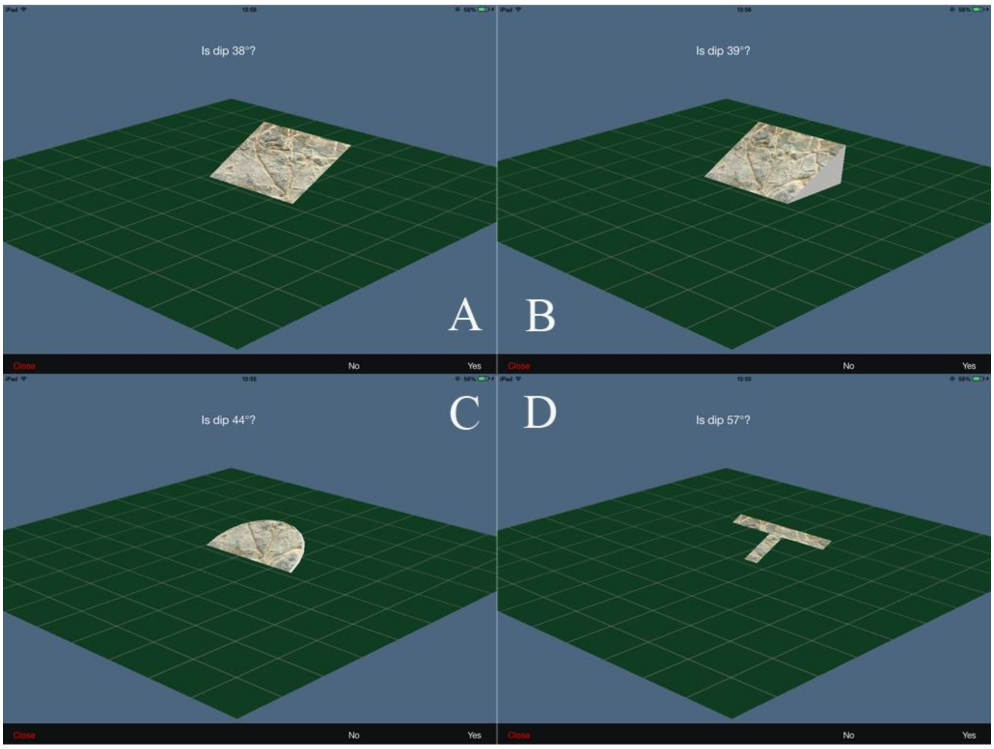


Figure 41: Screen shot from the experiment showing stimuli for dip experiment: (A) square, (B) wedge, (C) half disc and (D) t-letter model. The prompt angles shown are all wrong in this case as the correct dip is 4° for all four shapes.

5.3 Method

5.3.1 Participants

Sixteen undergraduates (4 female, 12 males) participated in the experiment all from the SEE. One of the 16 students was a third year and the rest were second year students. The average age was 20 years old (SD = 1). They were familiar with the concept of strike and dip and also had taken strike and dips and able to take strike and dip measurements (confirmed by staff).

5.3.2 Materials

The iPad2 used in this experiment was a standard device with no modifications. At the time of the experiment it was running iOS 7.0.1. The development was done using XCode 5, Apple’s IDE (Integrated Development Environment). The 3D rendering library used is built for Apple’s iOS framework based on OpenGLES and called NinevehGL version 0.9.0.1.

Each stimulus in this study was a shape representing either a dip or strike angle. Each stimulus was a 3D object for each of the four choices. A 3D object for each of these options were developed using Sketchup and Blender applications. An example stimulus and test setup scene is shown in Figure 41 for all four shapes for dip test mode. All shapes were designed in Sketchup with the same measurements and the same texture. The wedge shape required programming so that side of the wedge could change as the shape moved up and down. This was done using simple Pythagoras triangle calculations.

The same rock texture (see Figure 41) was applied to all models, using an image obtained from (Chure 2010) by searching Google Goggles for “bedding plane surface” in October 2013. The purpose is to give a conceptual indication to the user. This was part of the experiment set up and the staff and students who gave feedback about the setup agreed it should be used instead of a shade.

The staircase method conditions (see section 5.2.1) were as follows:

1. Provisional threshold (starting value): 30 for dip and 50 for strike.
2. Step size (amount of change from previous threshold): 30% based on testing and pilots.
3. Termination condition: per (Cornsweet 1962), pre-determined number 24.
4. Adjustment criteria: one up one down (one correct answer increment step size, one wrong answer decrement the step size)

Other conditions were:

5. The “first reversal” is defined as “the first time the participant makes two consecutive right answer followed by a wrong answer”.
6. The maximum adjustment criteria for correct detections was 2° for dip and 4° for strike whilst maximum increment step size was the starting provisional thresholds above.

The default initialization of the 3D scene of the NinevehGL library was used with exception of the following. Specular lighting was turned off. The default angle of view (or field of view FOV) was changed to 33° which is the viewing angle of an iPad2 device with a viewing distance of 15 inches based on the calculation in Figure 43. The default “camera position” was changed so that the camera does not look down the negative-z axis directly but looks from (*x=0.7,y=0.7,z=0.7*) of “camera position” (NGLCamera class). This is an oblique angle of looking at the stimulus, placed in the centre of the scene (0,0,0). This angle could be changed but a limit was applied to the strike rotation of 0 – 160 as minimum and maximum angles for aesthetics only.

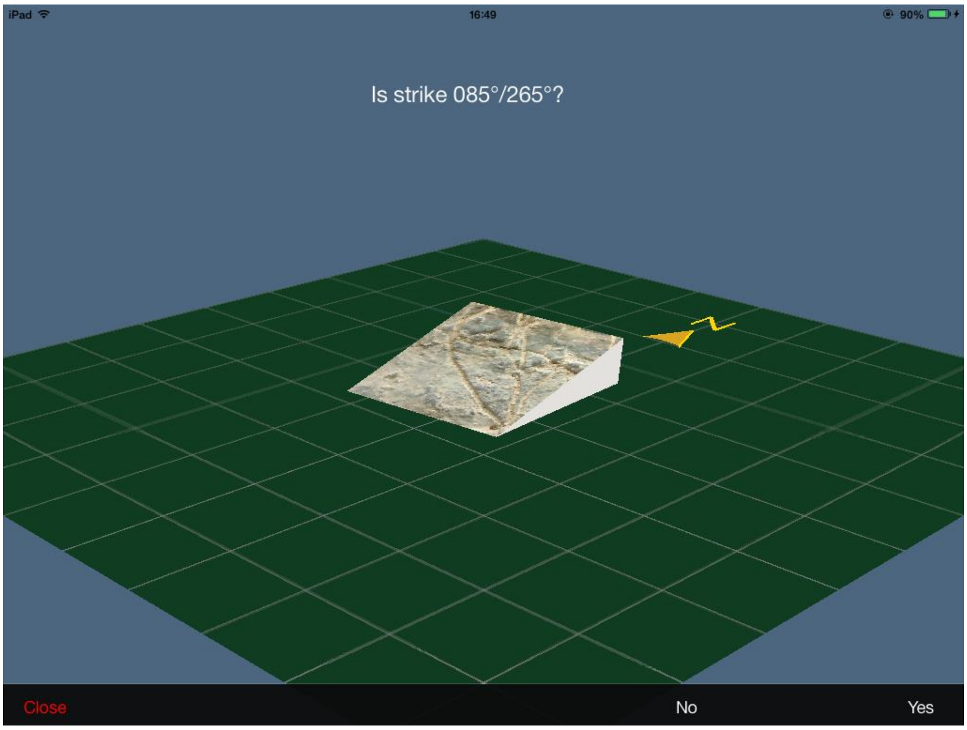


Figure 42: A typical scene from the experiment showing the wedge shape (3D object), with a question “Is strike 085°/265°”.

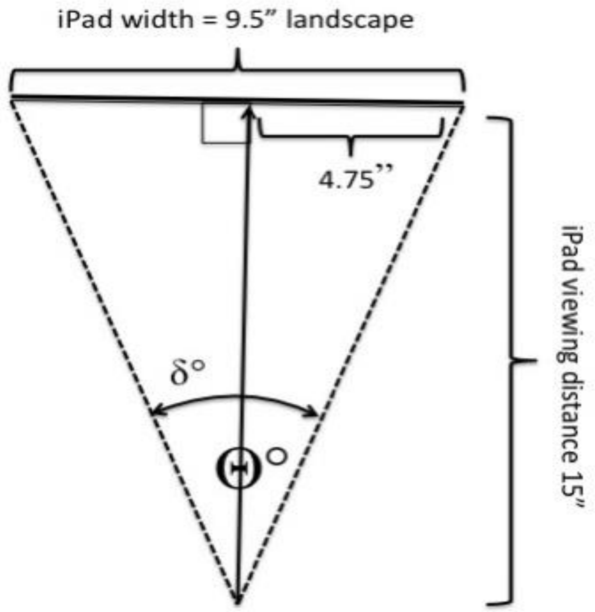


Figure 43: Calculation of iPad angle of view (FOV) from distance of 15 inches.

5.3.3 Procedure

The strike and dip *modes* were running consecutively. The modes were launched alternating on user sequence number to avoid order-confound. For odd participant number dip first and for the even ones strike first.

In each mode there were four *trials* for each of the four shapes (8 trials for both modes). Each *trial* consists of 24 *runs* including a single *stimulus* requiring a tap on "yes" or "no" button to continue. To avoid any bias due to order confound (Anderson et al. 2009, chap.2) in each mode, each of the four shapes were shown in Latin Square permutations. As there were four shapes, each row of the Latin Square was repeated four times (16/4).

An equal number of "right" and "wrong" stimuli were presented that is 12 each for each 24 run. The order of presenting right or wrong answer was based on a shuffling algorithm using Fisher-Yates (Fisher et al. 1949). This results in a pseudo random list of sequence of correct and incorrect answers for each run in each trial as shown in Table 8.

Trial #	Mode	Shape	Question	Actual angle	Answer received
1	Strike	Wedge	Is strike 85/265?	90/270	?
2	Strike	Wedge	Is strike 90/270?	45/235	?
…	…	…	…	…	…
17	Dip	Wedge	Is dip 45?	55	?
18	Dip	Wedge	Is dip 55?	55	?
…	…	…	…	…	..

Table 8: A hypothetical sequence of trials with equal right and wrong answers for a participant.

Each participant was asked to sit with an iPad2. Five out of 16 had the iPad placed on a table in front of them and the rest held it whilst sitting. To get participants familiar with the 3D test environment and graphical user interface they had to go through a demonstration session followed by a training session.

In the demonstration session, they were taken through all the trials with two runs each. During the demonstration they were also shown Figure 44 as an image on the iPad photos application to clarify any possible confusion due to strike reading conventions.

They were then asked to do a training session that was half of the number of the actual test runs (12). They were also given the opportunity to ask any questions during demonstration or training sessions.

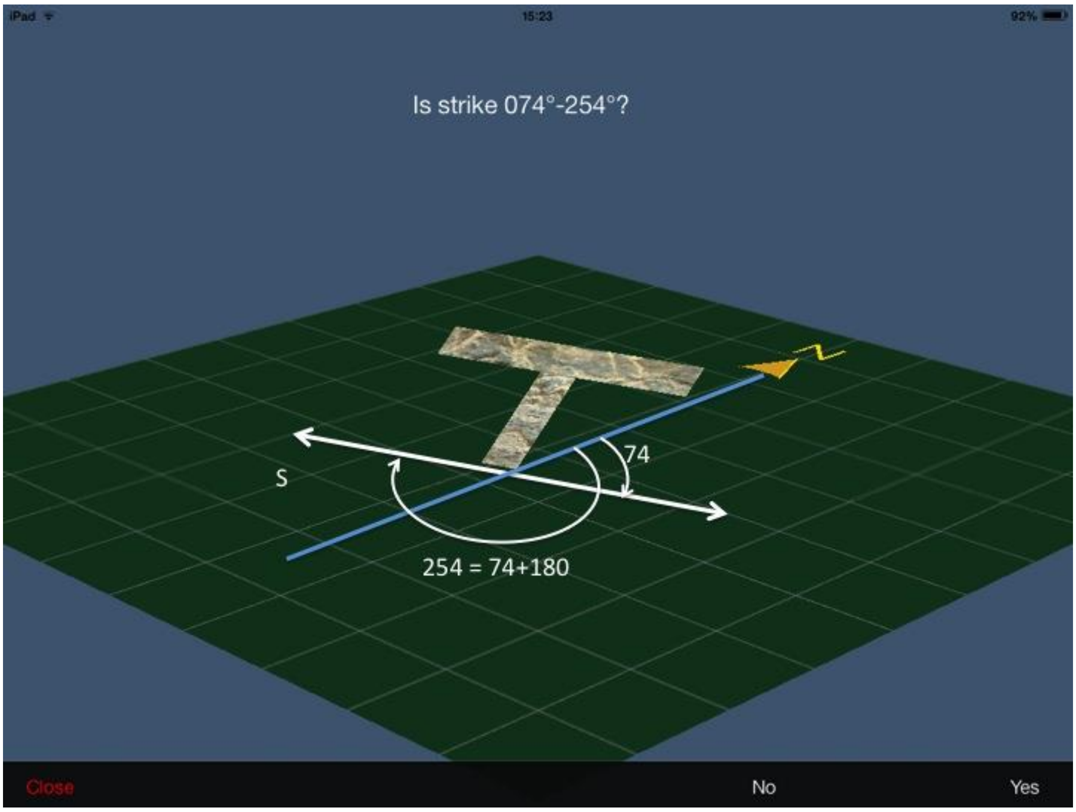


Figure 44: A screen shot of strike threshold detection. A T letter model with both angles of strike line angles shown to avoid confusion due to right hand or left hand conventions (Borradaile 2003, p.254).

5.3.4 Data collection

These parameters were recorded:

- Staircase parameters: starting value, step size, presented and actual random rotation angles, first reversals, participant answers for each run (the “right” or “wrong” answers), and total right and wrong counts for each trial.
- Time parameters: total time taken for each trial, time between trials was not included, timestamp of when the experiment launched.

5.4 Results

Standard statistical measures outlined by (Dixon & Massey 1957, chap.6) can be used along with conditions required for the staircase method. To analyse the data, there are methods outlined by (Cornsweet 1962) and (Levitt 1971) using the statistical measures. As the method was applied based on the four conditions outlined by (Cornsweet 1962), the analysis outlined there was adopted. To obtain an *estimated threshold* (Cornsweet 1962) suggests: mean of the step sizes from the first reversal onwards. The shape with overall lowest mean would give the "right" answer (i.e. most accurately representing strike and dip).

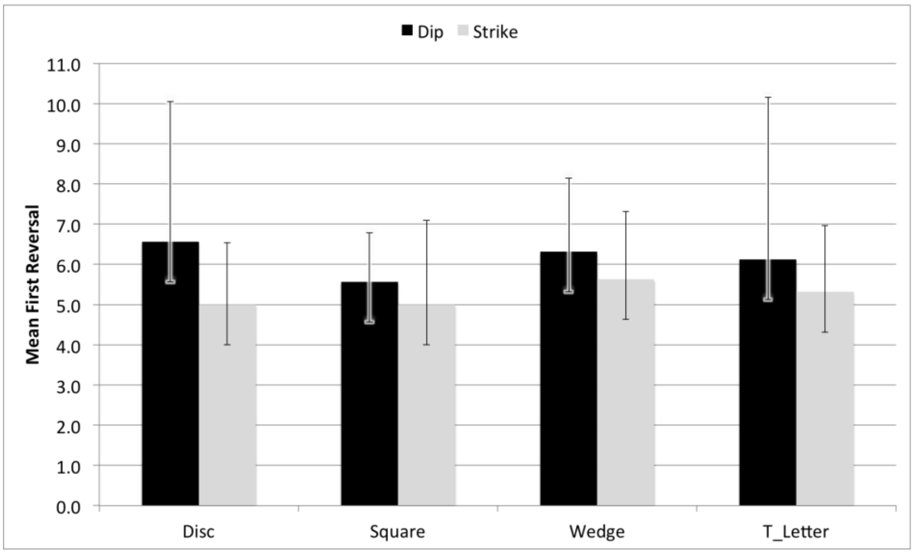


Figure 45: Mean first reversal of all participants for the four shapes. The error bars show standard deviations.

The parameter that affects the estimated mean thresholds is the "first reversal". If a participant does not arrive at a reasonable first reversal then there is a chance that the average could be for as little as one run or none at all. First reversal means are shown in Figure 45. The figure shows that all four shapes had a mean first reversal between 5 and 7 for strike and dip.

An example of how the first reversal can affect the means threshold is shown in Figure 46 and Figure 47. The two figures show the step sizes for user number one for strike and dip respectively. The lines show the first reversal positions for the respective shapes; the left side of the lines were discarded from the means reported above.

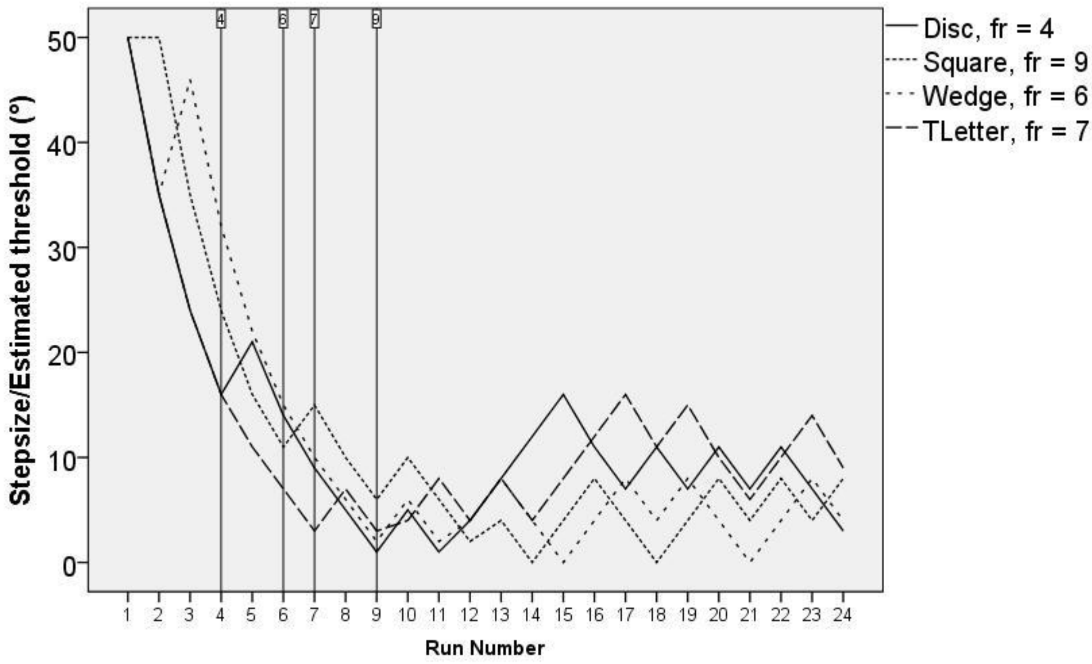


Figure 46: User number one step sizes (provisional threshold) for *strike* mode, and respective first reversal run positions compared to the total runs.

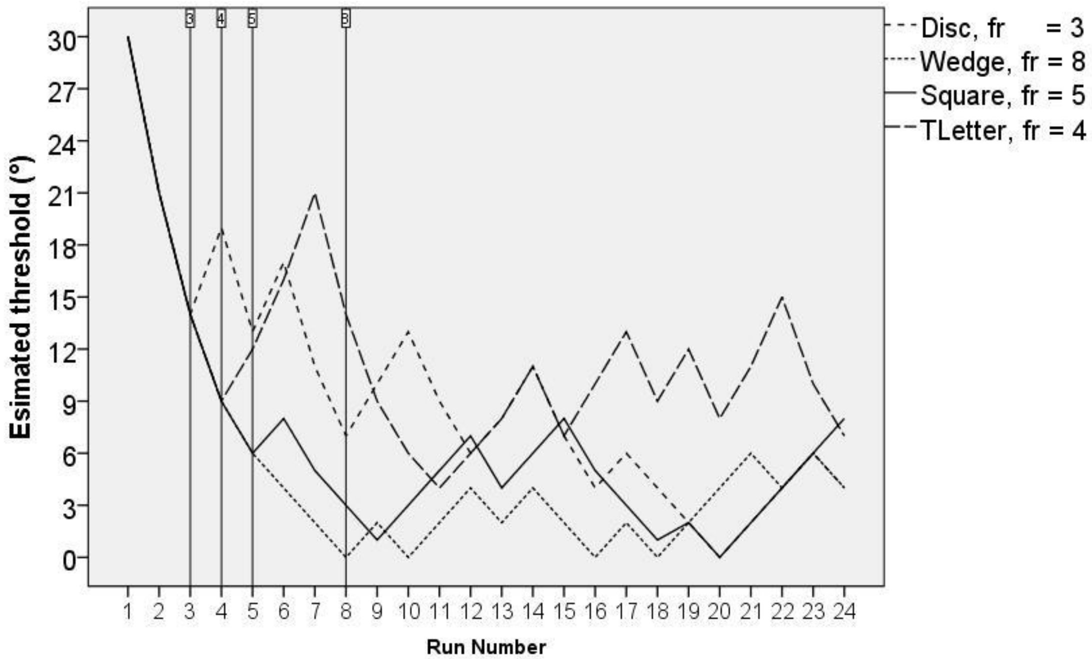


Figure 47: User number one step sizes (provisional threshold) for *dip* mode, and respective first reversal run positions.

By definition the threshold achieved using the staircase method represents a value where a stimulus is judged correctly 50% of the time. The average correct answers of all four shapes are shown in Figure 48 for both strike and dip. The mean is for all answers rather than from first reversal onwards, which means that correct answer percentages are slightly more as the definition of first reversal is “two correct answers followed by an incorrect one”. Despite that, the spread of the mean correct answers are between 49% and 65%.

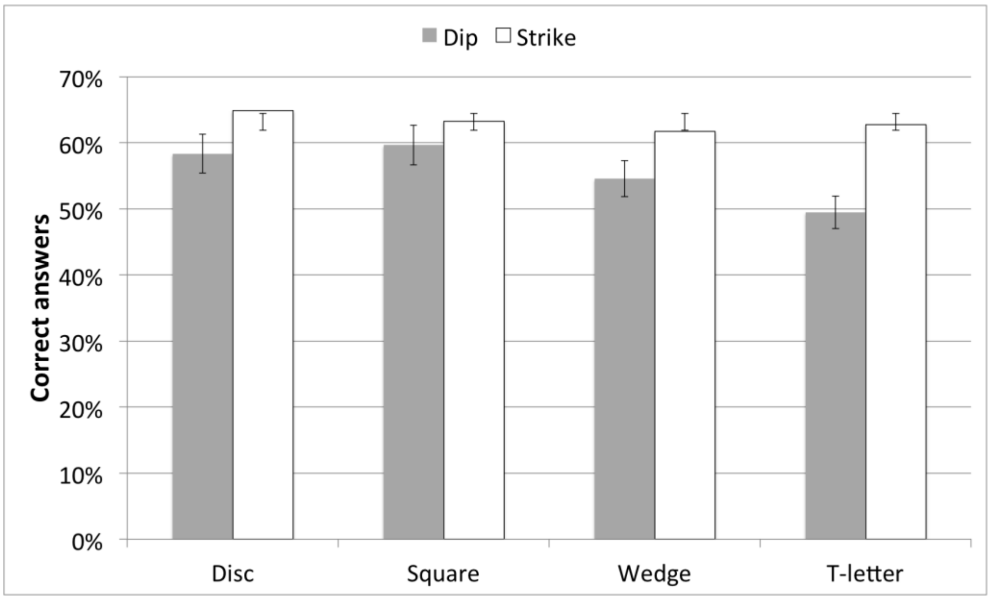


Figure 48: Mean correct answer percentages for all four shapes for strike and dip. Error bars show standard deviations.

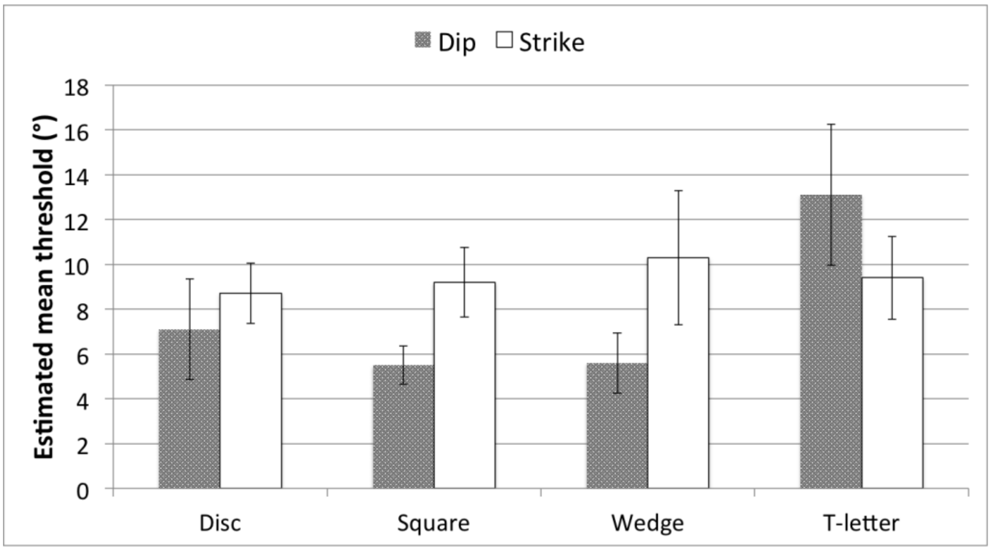


Figure 49: Estimated mean thresholds (degrees) and standard errors for all four shapes for both strike and dip. The lower the threshold the more intuitive the shape. Error bars show standard deviations.

These estimated threshold means were analysed using a two factor (shape × angle type) repeated measures analysis of variance (ANOVA). A † after a p value indicates that the Greenhouse-Geisser correction was applied, because the Mauchly sphericity test was significant. Overall, the dip threshold was significantly lower than the strike threshold ($F(1, 15) = 4.47$, $p = .05$), there was a main effect of shape ($F(2, 31) = 8.26$, $p = .001$†), and a significant angle type × shape interaction ($F(2, 32) = 7.64$, $p = .002$†). Post hoc, pair-wise comparisons performed using the marginal means showed that participants' threshold was significantly higher for the T shape than each of the other shapes ($p < .01$ in all cases). The underlying cause of these differences was the high threshold for dip angles with the T shape (see Figure 49).

5.5 Discussion

There is no clear winner (lowest mean threshold) for the same shape for both strike and dip. Figure 49 shows that the square shape (2D) has lowest estimated threshold mean (5.5°) and for dip whilst for strike the disc shape (3D) has the lowest threshold (8.7°).

Despite the familiarity (mentioned by participants) of the T-letter shape, it has the highest estimated means threshold for dip and second highest for strike. The low estimated mean threshold for the wedge shape was expected for dip angle (5.6° compared to 5.5° of square) as well as the overall similarity of the thresholds for all shapes for strike.

There are of course limitations to the study based on the conditions outlined in the method section 5.3. For strike it is possibly easier to see if the angle is correct if the angle was shown on a map view. This however, was not the focus of the study and could be one of its limitations. Another potential condition for a different study would be to repeat the study using a map as the ground view in the 3D environment.

5.6 Summary

There is a significant difference between the shapes tested to *represent* strike and dip in a 3D virtual environment. This could affect the spatial cognition of novice geologists.

A 3D object of the T symbol widely used in 2D mapping to represent strike and dip performs worst when compared with other graphical representations in the psychophysics method of staircase outlined above. This does not mean that any 2D model (square shape) would perform worst in the 3D environment, as it is statically (lowest mean threshold, see Figure 49) the best shape to represent strike and dip in this experiment.

There was not a clear winner between the shapes. Statistically the square shape was the best whilst the second shape was the disc. That means either of these two shapes could be used to represent strike and dip measurements in a 3D scene.

Chapter Six

6 Visualizing field data in 3D

6.1 Introduction

According to (K. J. W. McCaffrey et al. 2005) a typical piece of fieldwork in geology starts with observation and data collection and ends with a range of outputs such as a 2D map, a 3D model and others. For example a workflow, in its traditional form, may go through tasks outlined in section 2.5.2. It could also include other techniques used in learning and teaching of structural geology or other sub-disciplines of earth sciences. These techniques include creating or drawing cross sections, structure contour generation and stereonet plotting (see section 2.3.2).

Structure contours in structural geology are lines that connect points with equal elevations within a structure such as a bedding, unconformity etc (UCD n.d.). Structure contours for a surface *“are lines that are everywhere parallel to the local strike of the dipping surface. The local direction of the slope (dip) at any point is at the right angles to the trend of the contours”* (Lisle 2004, p.7). This is illustrated in Figure 50.

Each measurement (planar or linear) taken in the field is a data point that can be used to extrapolate or interpolate the structure of the geology both across the surface and into the sub-surface. There is, for example, literature on producing a structure contour from strike and dip measurements (Weijermars 1997, chap.6). This is a step by step of going from field observation and data collection to creating a model for the structure of the area in question.

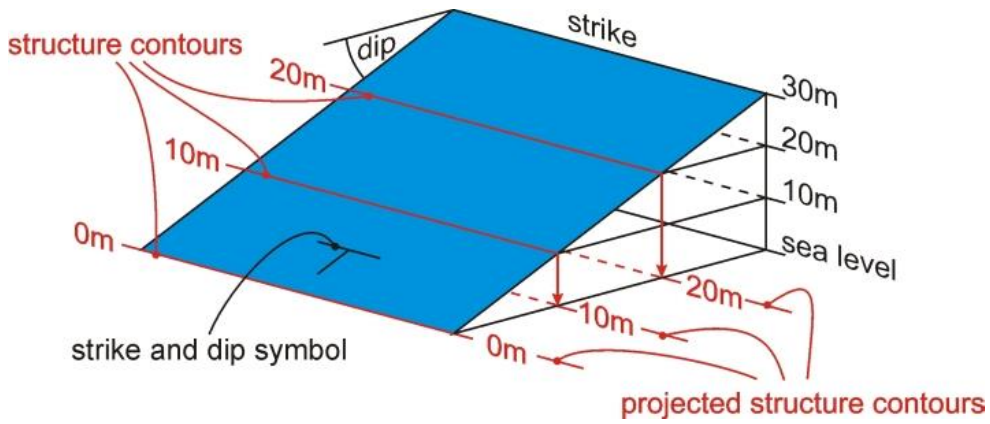


Figure 50: a block diagram of a planar structure extrapolated from a strike and dip measurement, the lines are straight, parallel and equally spaced, image from (UCD n.d.).

A natural next step from the work outlined in the previous chapters, in creating a novice-oriented application, would be to support some form of structure contour generation. By visualizing each measurement taken, it is possible to develop a basic 3D visualization to show captured field data on the go, which is spatially correct and adds to the 2D maps students possess and data recorded in their field notebooks.

Based on this rationale, a design idea was implemented to support visualizing field data using the results of the experiments in chapters four and five. This involves a concept where students would be able to collect data as they go along on their field trips and each planar or linear measurement is added to a field simulation scene where the ground represents geographic reference obtained from the device GPS. The screen shot in Figure 51 shows a single measurement within a 1km^2 field simulation. The visualization uses a disc shape to represent the single strike and dip measurement shown based on the results from the experiment in chapter four.

The question tested in this design is whether a basic 3D visualization for strike and dip measurements could *add* to the understanding of 3D structures represented on 2D maps. That is, instead of inspecting a 2D map, what if students were able to be presented with spatially meaningful representations of the structural data? To answer this question, this chapter describes an evaluation carried out by students from the SEE.

This is believed to be the first study of its kind. The wider cognitive studies carried out to aid 3D spatial cognition in general do not cover the use of 3D visualization of geological data to aid novice geologists. The evaluation scenario is an example of "extrapolation of 2D feature to the third dimension" point by (Whitmeyer et al. 2009) and discussed in detail in chapter two section 2.5.1.1.

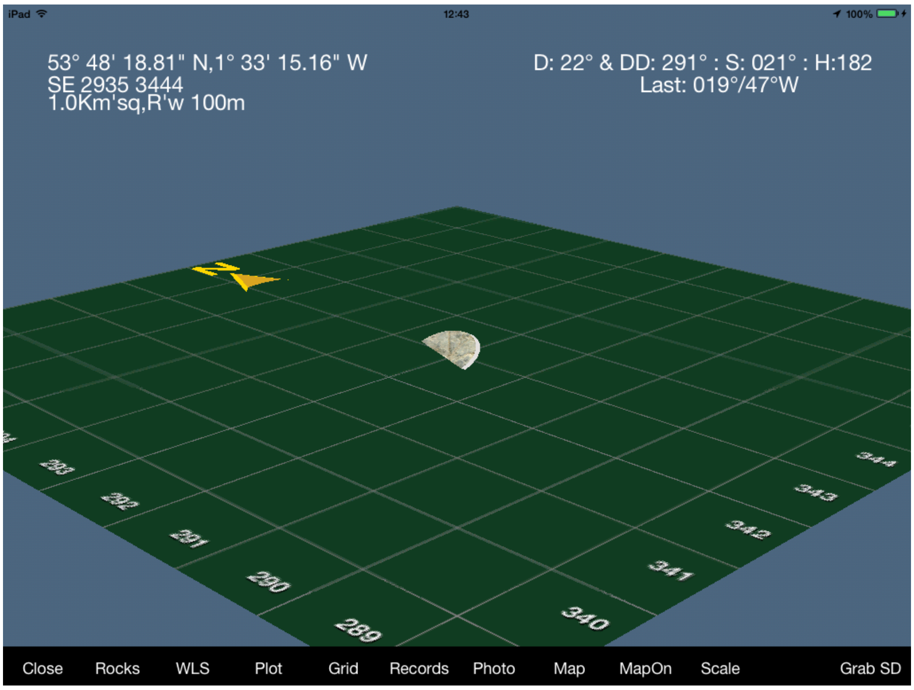


Figure 51: 3D field simulation where 1km^2 is represented by 10x10 squares of 10m^2. The half circle in the middle represents a strike and dip measurement recorded currently, which is also the geographic location of the user.

6.2 Method

To find evidence about whether a basic scenario of using 3D visualizations in the field can *add* anything to *assist* extrapolation of 2D observations/measurements into the third dimension, a between participants qualitative study was deemed appropriate. That is, giving one group the map they would normally get on a typical field trip, and the other group the map and the prototype basic 3D visualization plotted on the same map. The evaluation was carried out on campus, it could have been done on a fieldtrip with access to the real scene; this was considered to have the same effect on both groups.

Participants were divided into two groups, 2D group and 3D group. In the 2D group, students only worked with conventional maps. The 3D group, however, were able to see both the printed maps and a 3D visualization of certain strike and dip measurements plotted on the map. The visualization could be rotated to observer the data from different angles. The visualization was developed on an Apple iPad2.

In each scenario the same questions were asked and participants wrote down answers. Apart from answers to the questions, time was recorded for each participant to answer the questions. Accuracy of the answers were assessed by an expert geologist. The questions and the scenarios were developed in cooperation with three experts in SEE.

6.2.1 Participants

Second year students were chosen who were familiar with the geological setting of Ingleton field trip from their first year, but not familiar with the other scenarios used in the study. Eight second-year students participated in the evaluation, four in each group. There were five males and three females, aged between 19 to 24 years.

6.2.2 Material

Four different structural geology scenarios were chosen from three different geological maps. This was done so that students would have a mix of scenarios from simple to more complex. Scenarios one and two were from the Ingleton field trip area (North Yorkshire) where all participants had been. Scenario three is a hypothetical example from a book and scenario four is from the second year student fieldtrip area near the village of Rhoscolyn, Wales.

For scenarios one and two, participants were shown the same map (Gordon 2009) which is the map used by SEE for Ingleton field trips (see Figure 52). Ingleton geology is discussed by (Soper & Dunning 2005) and other institutions have online material for the area such as (LJMU 2008).

In scenario one, participants considered the two strike and dip measurements in Figure 53, which is cropped from the bigger square in the map in Figure 52. This is the syncline formed by greywackes bedding planes to the south of Thornton Force waterfalls in Ingleton. A screen shot of the 3D visualization which the 3D group had is shown in Figure 54.

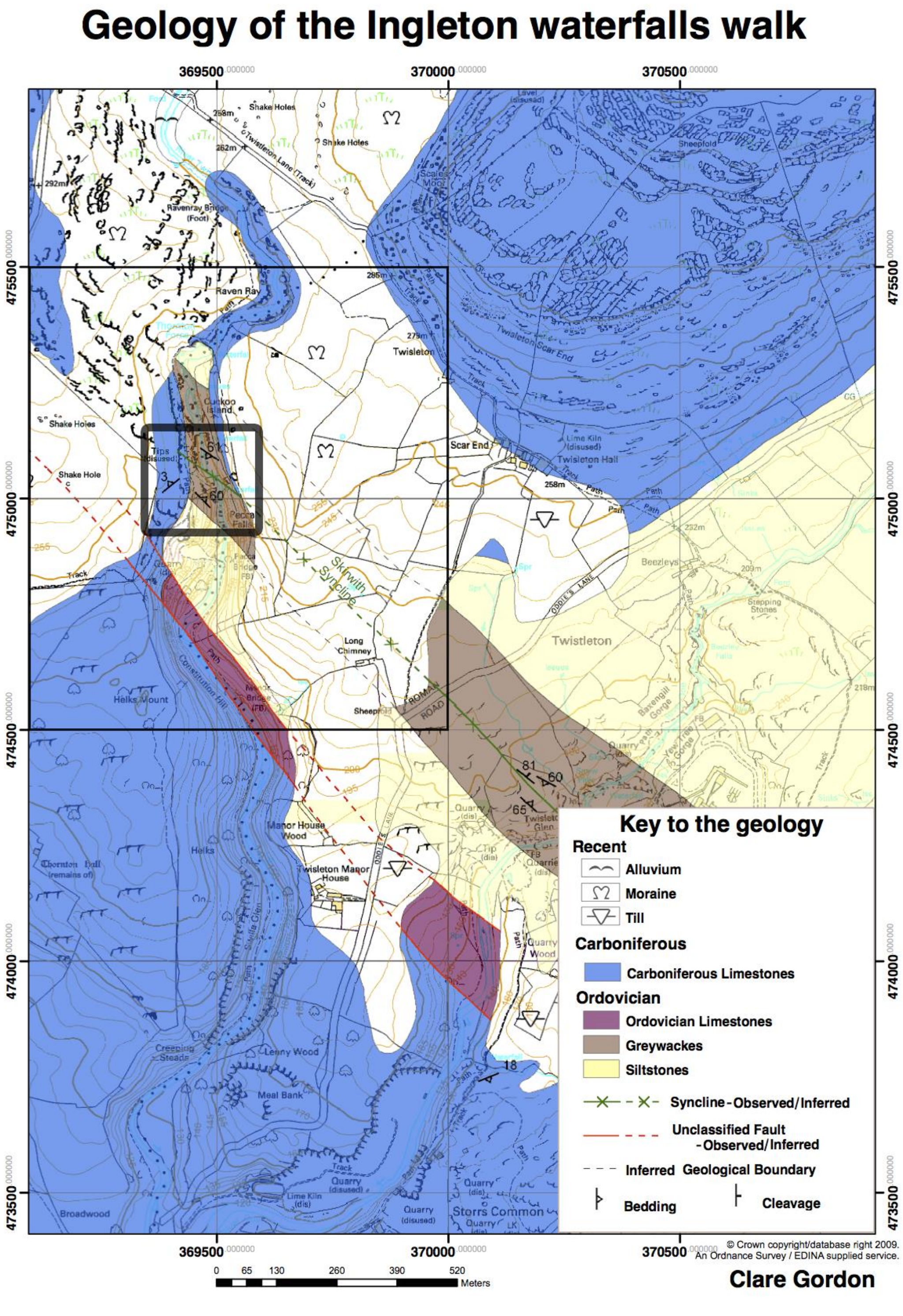


Figure 52: Geological map of Ingleton waterfall walks by (Gordon 2009). The bigger square shows the area used for scenario one, the smaller square shows the strike and dip measurements.

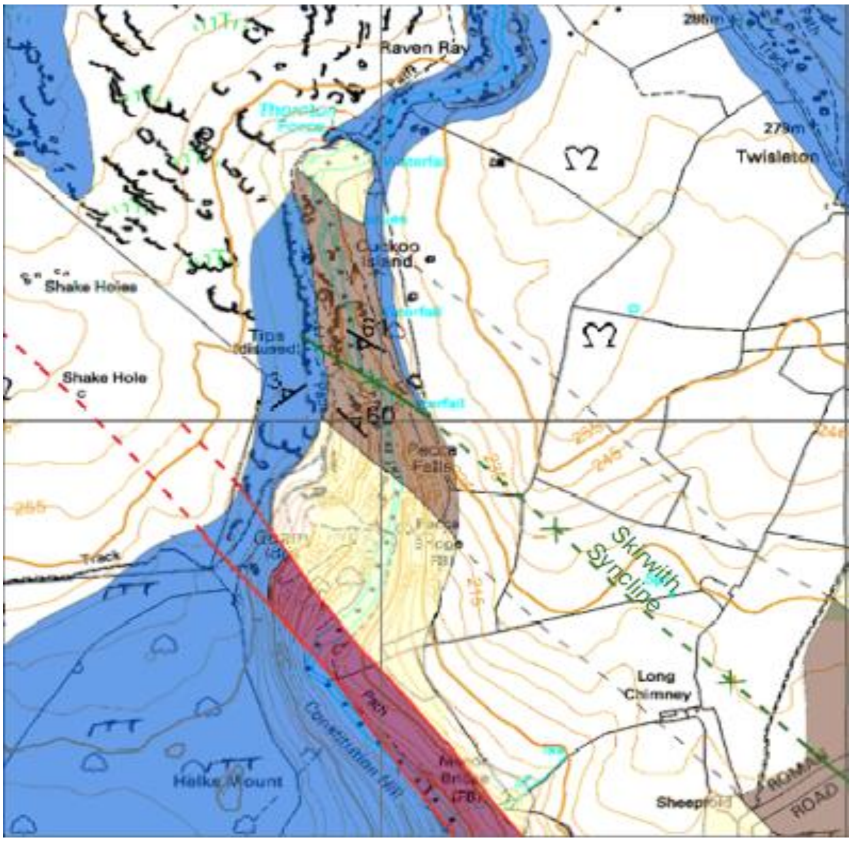


Figure 53: Screen shot of the 1km^2 of the map in Figure 52 to be used in scenarios one and two showing a section of Skirwith syncline. The image is the highlighted section of the map in Figure 52.

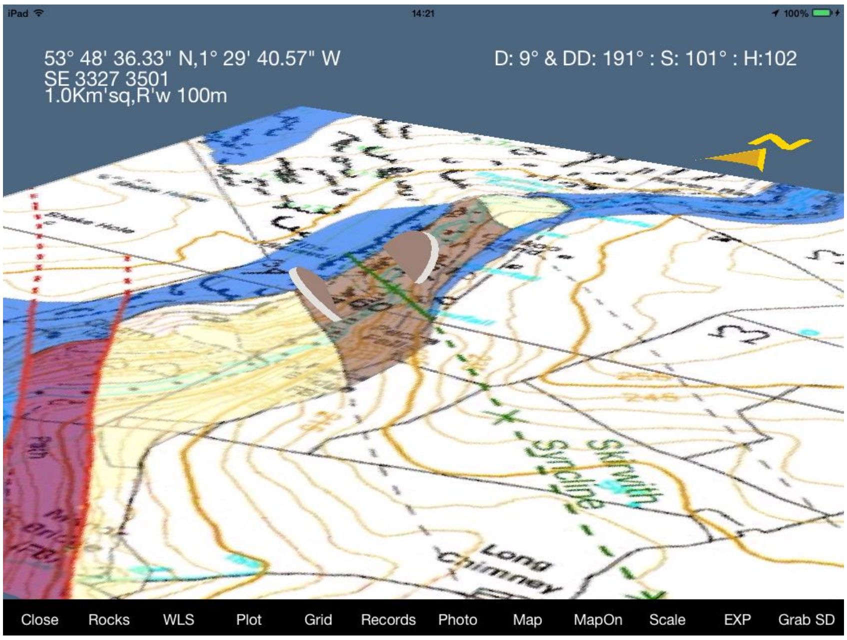


Figure 54: Scenario one, 3D visualization of the strike and dip measurements showing the syncline formed by the greywackes. The view is looking at the map from south east.

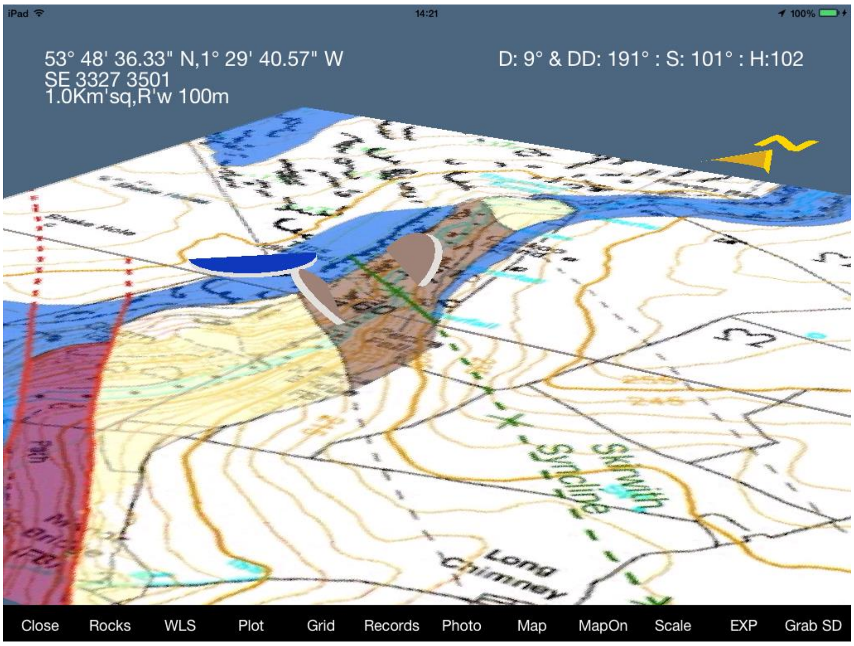


Figure 55: Scenario two the same Ingleton map. 3D visualization of strike and dip measurements for the unconformity formed by the *greywackes* and *limestones*. The view is looking at the map from south east.

In scenario two, participants considered the same area of the map as in scenario one. This time the bedding measurements from both the greywackes and the carboniferous rocks were taken into account. This forms the Ingleton unconformity with the steeply dipping greywackes beneath and the almost horizontal carboniferous limestone above. A screen shot of the 3D visualization which the 3D group had is shown in Figure 55, which shows three strike and dip measurements visualized in 3D plotted on the same map.

In scenario three, participants looked at a hypothetical fold from (Weijermars 1997, chap.9) shown in Figure 56. The figure shows a syncline-anticline fold pair that plunges towards the SW with a maximum limb dip of 30°. The 3D group participants could see the four strike and dip measurements visualized as shown in Figure 57.

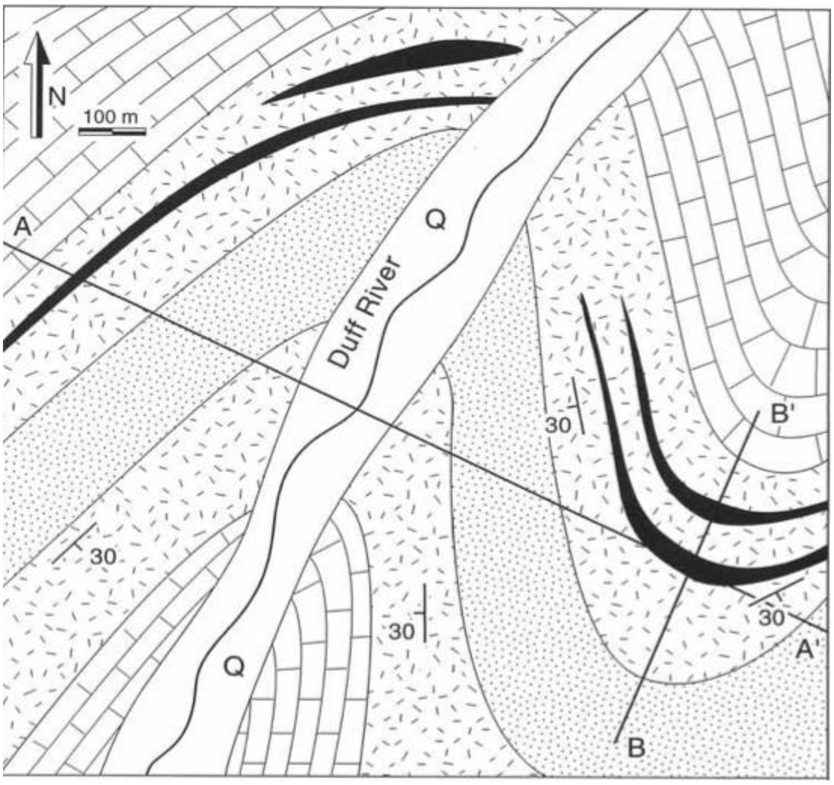


Figure 56: Scenario three, a screen shot of the hypothetical example for scenario three.

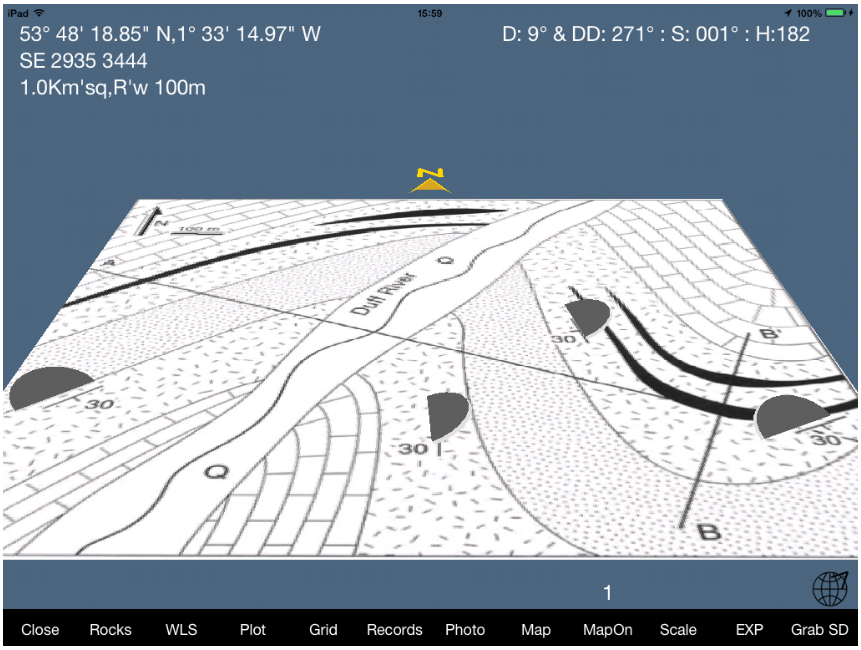


Figure 57: 3D visualization of the four strike and dip measurements of scenario three.

In scenario four, participants looked at the Rhoscolyn anticline. The geology of the Anglesey area of Rhoscolyn is described in detail by (Treagus et al. 2003) and briefly outlined by (Kabrnova 2012). Essentially the geological anticline fold near the village of Rhoscolyn has gone through two phases of deformation resulting in a refolded antiform that plunges towards the North East. The map shown in Figure 63 was obtained from a senior lecturer of SEE. A 1km^2 of the map was cropped, as shown in Figure 58, and used in scenario four.

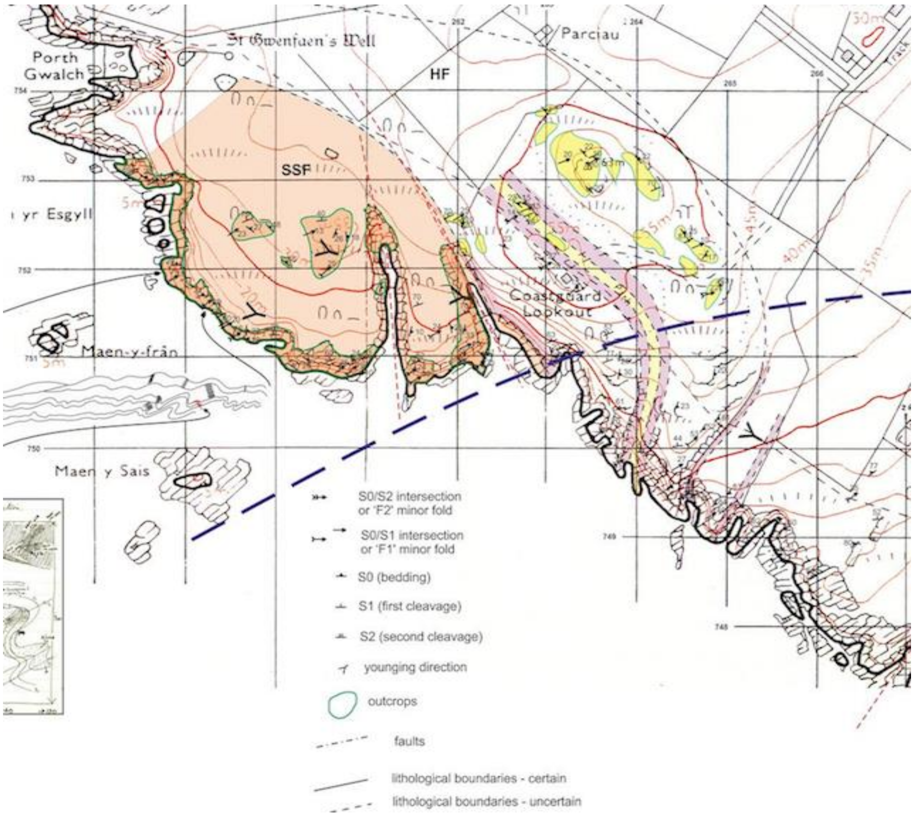


Figure 58: 1km^2 of the Rhoscolyn anticline fold map (Lloyd 2014).

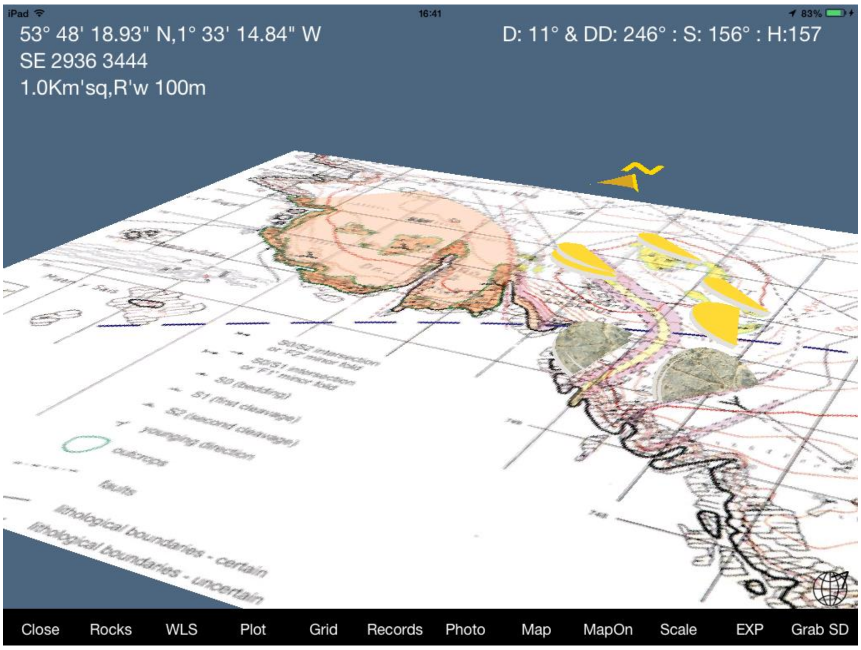


Figure 59: Rhoscolyn anticline with 8 strike and dip measurements visualized.

Given the complexity of the structure, not all of the strike and dip measurements of the bedding planes were visualized for the 3D group. From two different layers of the rather complex fold, only nine strike and dip measurements were visualized as shown in Figure 59.

For the purpose of this evaluation the relative elevation for the location of the measurements was ignored in the 3D visualization. Therefore, all bedding plane representations for the measurements were visualized on the same level (altitude). The visualization itself is part of the same prototype developed throughout the research. For this evaluation, standard Apple development APIs and the NinevehGL library for rendering on OpenGLES 2.0 were used.

The angle of view of the virtual world was set based on the calculations in Chapter five (33°, see 0). Using the camera movement of the NinevehGL library, a world rotation is simulated by moving the camera on a horizontal circle around the centre of the view (360° rotation). A birds-eye view is provided to give participants an orthogonal view of the visualization (see Figure 60). However, the vertical rotation is limited to 0° horizon view (0°) up to 90° axis rotation as shown in Figure 61 and in Figure 62 respectively.

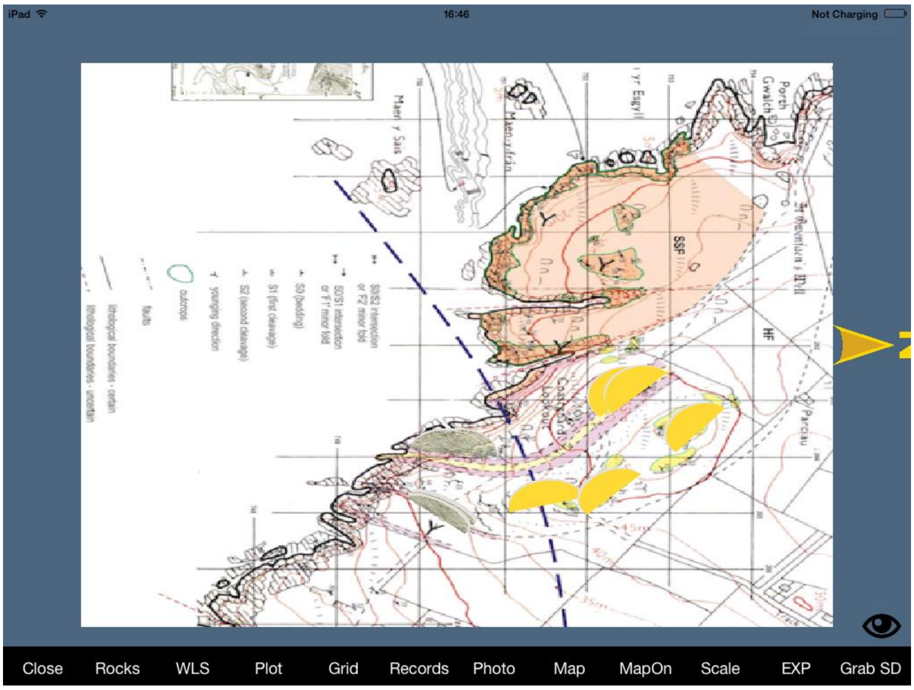


Figure 60: An orthogonal view of scenario 4.

Figure 61: View of scenario four when camera is level with ground view (the map).

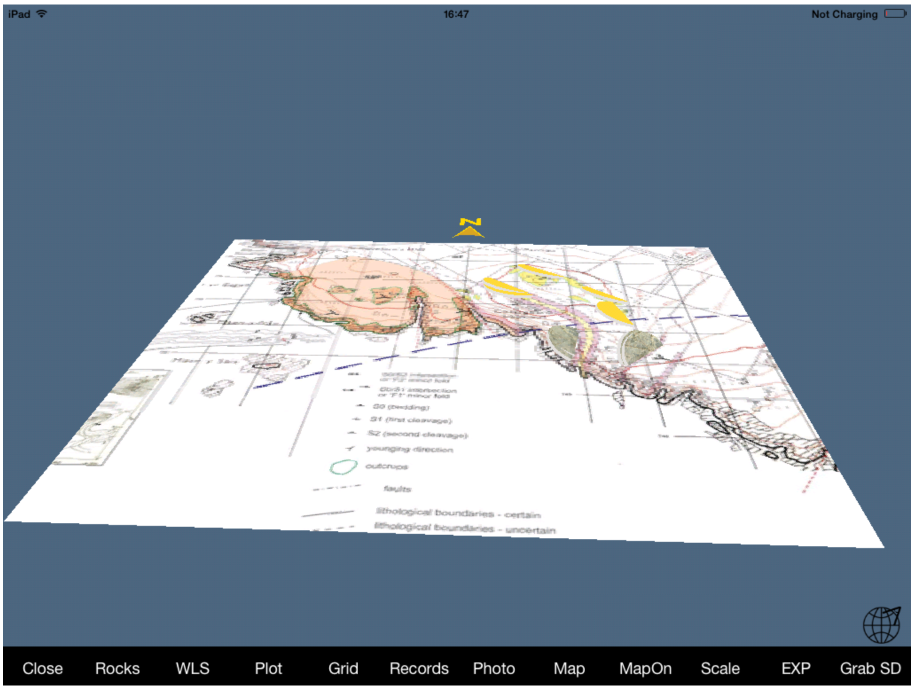


Figure 62: View of scenario four when camera is moved 90° from ground reference.

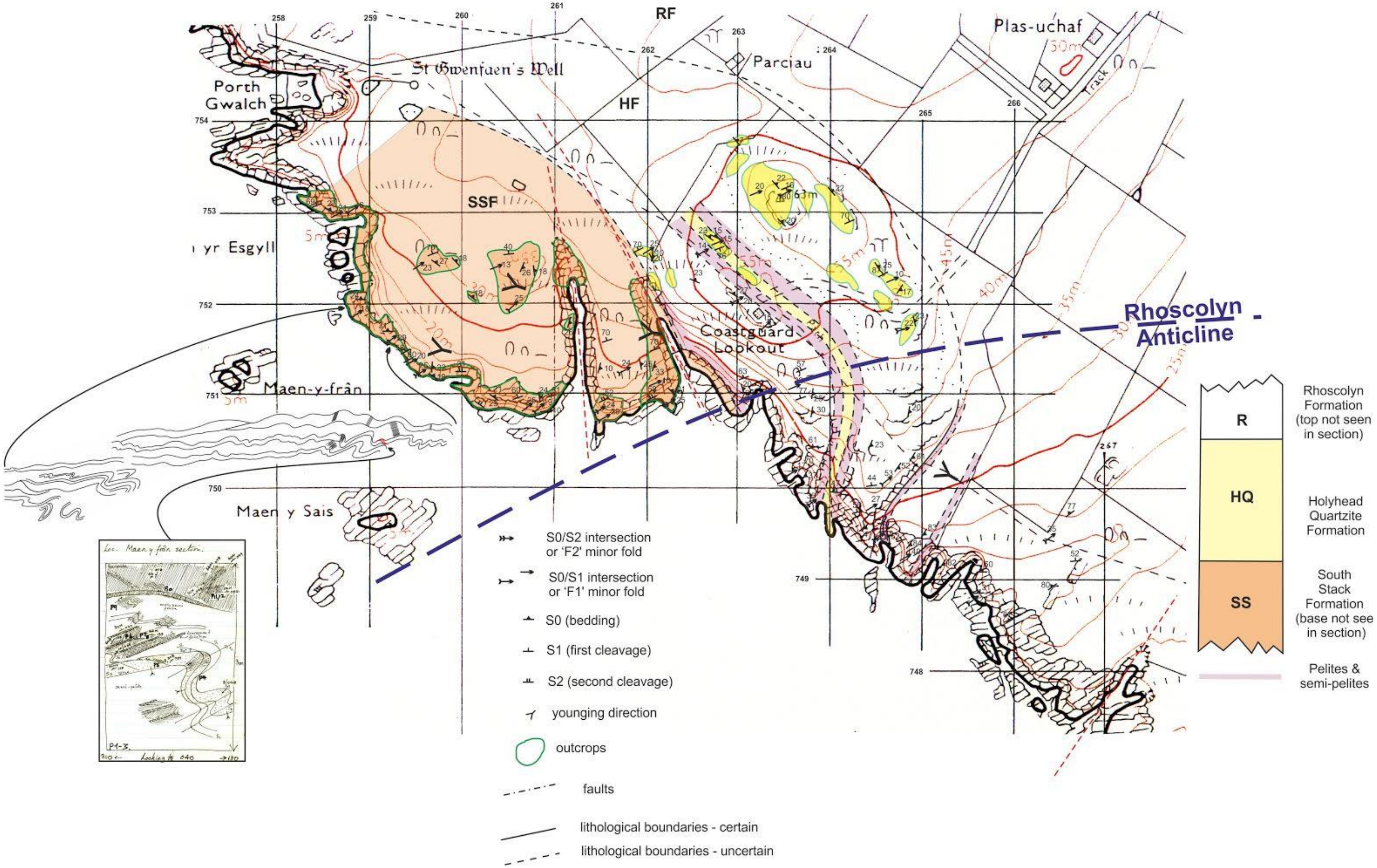


Figure 63: Rhoscolyn anticline fold, by Dr Geoff Lloyd. The original map.

6.2.3 Procedure

For the 2D group, in each scenario participants inspected the 2D map for a maximum of five minutes. They were then asked to answer the following two questions and write their answers down on a sheet provided:

Given the strike and dip measurements on the map:

- Describe the nature of the formation (3D structure)?
- Describe the nature of any contact (if any)?

The 3D group carried out the scenarios the same way as the 2D group. For each scenario, participants inspected the same map the 2D group had but were also allowed to use the visualization on the iPad2 with no extra time. They were then, like the 2D group, asked to answer the same two questions, by writing their answers on the sheets provided.

For both groups, given the complexity of the scenario four geological map, they were given a hint that the map contained an "anticline". Both groups carried out each of the scenarios then answered the questions before moving on to the next scenario.

6.3 Results

Participants wrote down their answers on the provided sheets for each of the two questions in each scenario. Three of the eight participants carried out the exercise and wrote down the answers in a quiet library environment with other people present nearby. The rest of them participated in a corridor of a relatively busy area at the SEE.

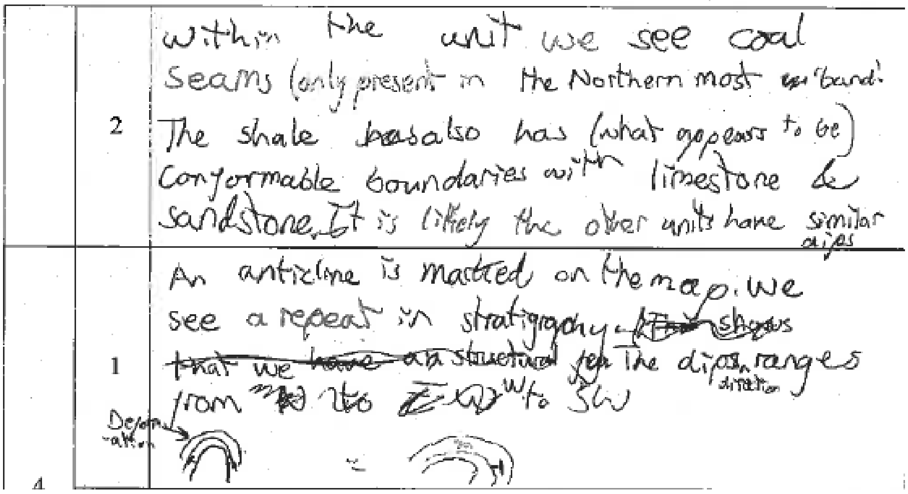


Figure 64: An example of answer to the questions where a participant uses sketching in the answer.

Participants replied to the questions and were engaged with the tasks. Two participants used drawings to answer the question, and one of the examples is shown in Figure 64. The other participant who also sketched as part of the answer was not able to see the anticline in scenario four, writing down "don't see the anticline" as the answer in response to the hint that the map contained an anticline structure. Although they were answering the same two questions for each scenario, writing down eight answers took them longer than anticipated.

Time spent on each scenario is shown in Figure 65, which shows average times for each scenario for each group with error bars being standard deviations. Both groups spent slightly more time on scenario one than two. On average, they spent least time on scenario three which was rather simple. Both groups spent the most time on scenario four which was the most challenging example. This indicates that participants were engaged with the experiment as hoped. From the graph, it is clear that the 3D group spent a little more time on average on the tasks compared to the 2D group which can be explained by the fact that they had the iPad to inspect in addition to the maps.

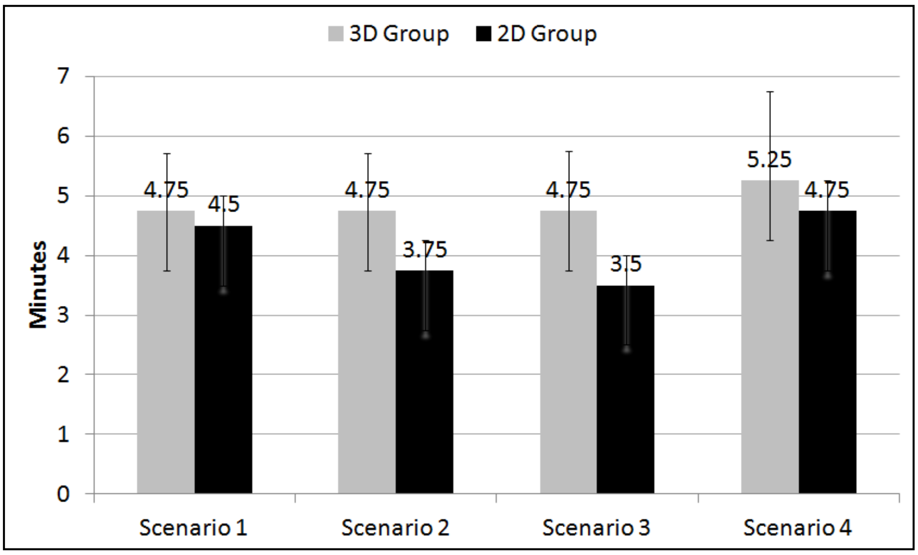


Figure 65: Mean and SD as error bars of number of minutes spent on each scenario by each group.

The answers were given to an expert geologist. The expert did not know which participant was in which group. The expert marked each participant's answer sheet for all four scenarios as either poor, OK or good. This was based on the level of detail indicating understanding of the structural formations.

All four participants from the 3D group were marked either OK or good, whilst three of the 2D group were either marked poor or OK and one was marked poor, as shown in Table 9. However, this difference in the results could well be explained by the possibility that the 3D group had the better students in it by chance.

Participant #	2D Group	3D Group	Participant #
5	OK	OK	1
6	Poor	OK	2
7	Good	Good	3
8	Poor	Good	4

Table 9: Expert marks for each participant in each group for all four scenario.

Participants in the 3D group were asked for any comments regarding the design regardless of their answers in the scenarios. There was replies such as "it is cool" and "useful".

6.4 Discussion

One of the observations was that, in general, participants in the 3D group inspected the printed maps longer than they spent looking at the 3D visualization on the iPad.

The other observation was that students wanted the ability to interact more with the visualization rather than the two directions of movement. For instance one participant said he wanted to pan and move around the scene and zoom into the measurements.

Due to the nature of the questions, the number of participants and the marking criteria (one expert and three categories of marking), the results are not comprehensive evidence. It is hard to say that visualizing strike and dip in 3D plotted over a 2D map would "definitely" help student comprehension. However, the evidence and the student feedback indicates that the design is novel and useful and the evaluation expectation has been met.

For a more conclusive answer to the extrapolation from a two dimensional representation to the three dimension issue raised by (Whitmeyer et al. 2009), further tests should be done including the "*determine spatial relationships with respect to the orientation of their own bodies*" described by (Linn & Petersen 1985). Although (Black 2005) states that it is the "mental rotation" category of spatial ability category that plays the more important role of understanding geological structures.

To alleviate these limitations, future experiments could include questions that would involve participant's orientation skills. Also the scoring should be made on a more quantitative method where there could be a benchmark and more statistical inferences could be made. Finally, more participants should be involved.

6.5 Summary

In this study a basic 3D representation of strike and dip measurements plotted on conventional maps was compared to the use of 2D printed maps only. Four different scenarios were used, two from a known location (Ingleton), one from a hypothetical location and another from one their future fieldtrip location (Rhoscolyn).

Data collected from a group of eight second year geology students were analysed. The evidence suggests that students *may* get a better understanding of the structural formations of the geology they study in the field if they have are able to see more than plan view/maps of the geology with structural measurements written down on them. Therefore it is assumed that such visualization may assist students "understand" 3D nature of geological formations.

Chapter Seven

7 An app for introductory fieldwork

7.1 Introduction

The experiment in chapter six was carried out as part of a design where strike and dip measurements could be plotted on the type of 2D maps used by students in field trips within a 3D simulation of the field. That way students can see measurements not in map symbols or digits but in a way that provides clues to the structural properties of the formations they belong to.

This chapter summarises a proof of concept app that has emerged out of the work outlined in the previous chapters. The work in chapters three, four and six was put together to create a proof of concept (PoC) prototype that could be used in the future. This chapter outlines this in the context of the problems discussed in chapter two. The PoC prototype here is not the code used in the studies outlined in each of chapters four, five and six.

7.2 Proof of concept app

The issues summarised in chapter two in section 2.5.4 and subsequent work outlined in the previous chapters have led to various iterations of a prototype used for this research. This is a work in progress prototype that is aimed to be a proof of concept (POC) for a field app on iOS powered devices. In order to show what can be done on today's tablets and smartphones, along with the work presented in the previous chapters it is necessary to outline the main functionality of the prototype.

The codebase is built on a sketching or drawing code repository called "SimpleDrawing" available from BitBucket (Woolls 2014), which is an open source package but also released on Apple app store as a drawing app (Woolls 2012). The 3D rendering is developed using the standard Apple APIs for OpenGL ES 2.0, using a library called NinevehGL version 0.9.3 (NinevehGL 2014). NinevehGL provides a range of functionality but was chosen because it enables importing 3D models in COLLADA and Wavefront formats.

A piece of functionality that is integrated with the sketching code is the ability to import pictures taken using the camera with GPS and compass data printed on them. Although the compass data is not complete, the basic idea has been implemented. This saves students using other apps such as the “Say Cheese” app that was used in the exploratory field study in chapter three. In the latest version of

FieldMove Clino, shown in Figure 66, it seems that it imprints compass direction of the camera on the image, though that cannot be seen after saving the image. A screen shot of the prototype is shown in Figure 67 showing how GPS and magnetic direction data could be imprinted on images taken.

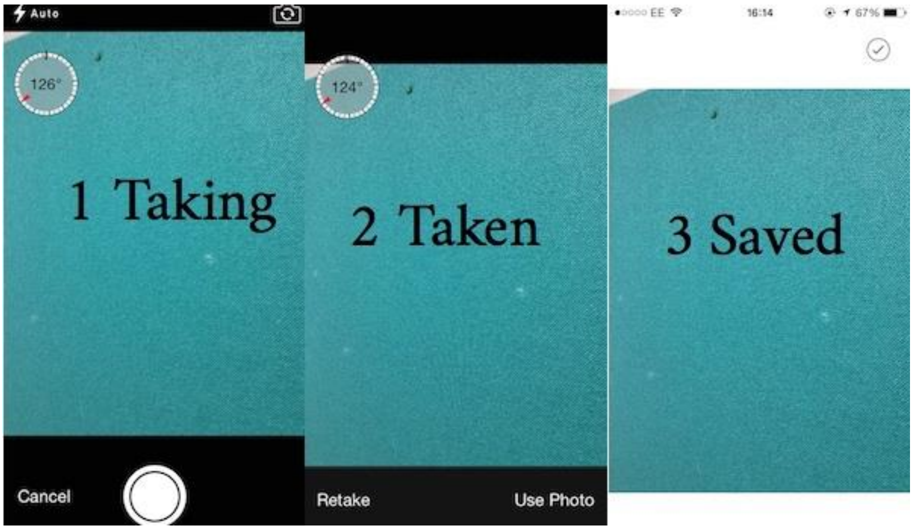


Figure 66: Three stages of a picture using FieldMove Clino, (1) shows camera before taking the shot, (2) shows preview of the picture taken where both shows the compass information.

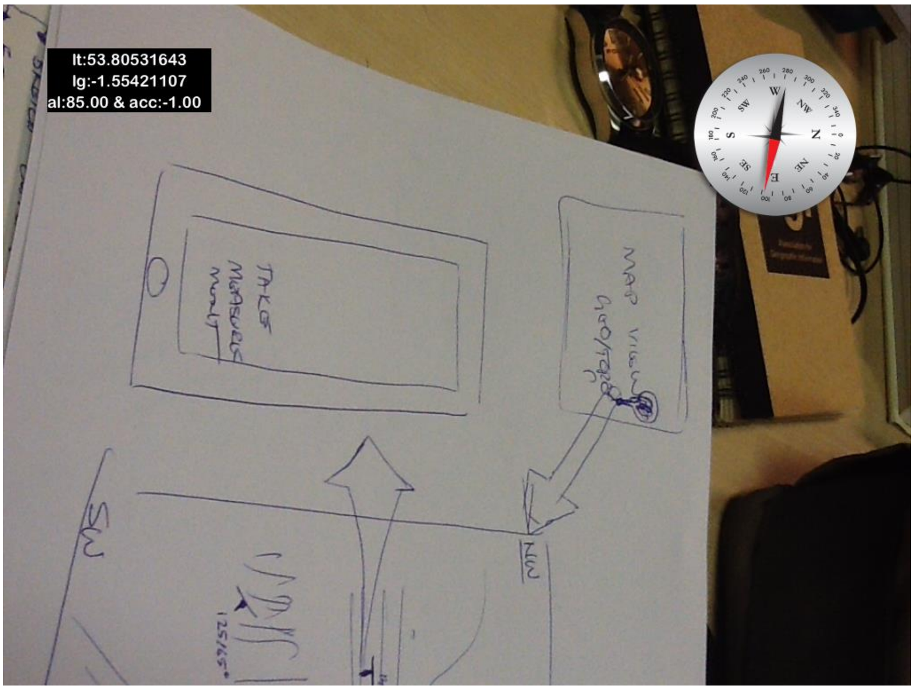


Figure 67: A screen shot showing GPS data on the top left and magnetic needle on the top right which shows the direction at the time of taking the picture.

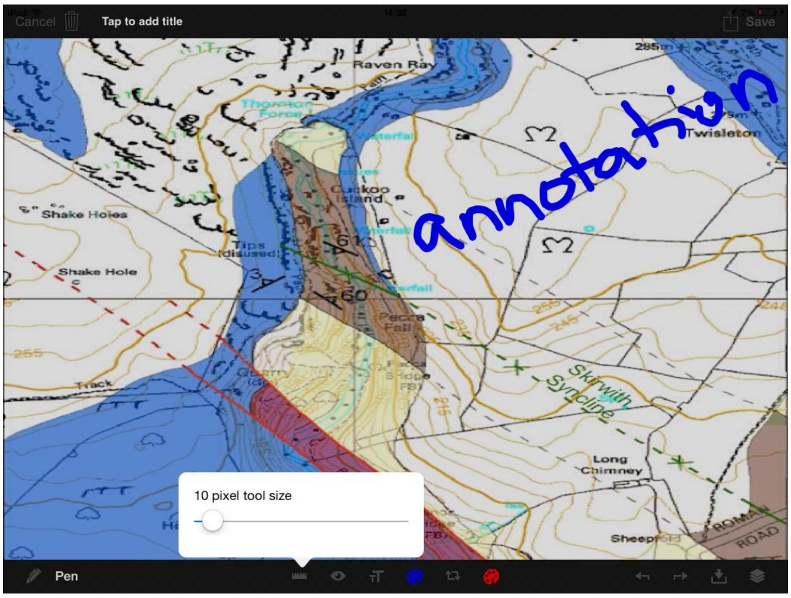


Figure 68: Screen shot of the drawing view of the prototype with Ingleton map section imported and annotation added.

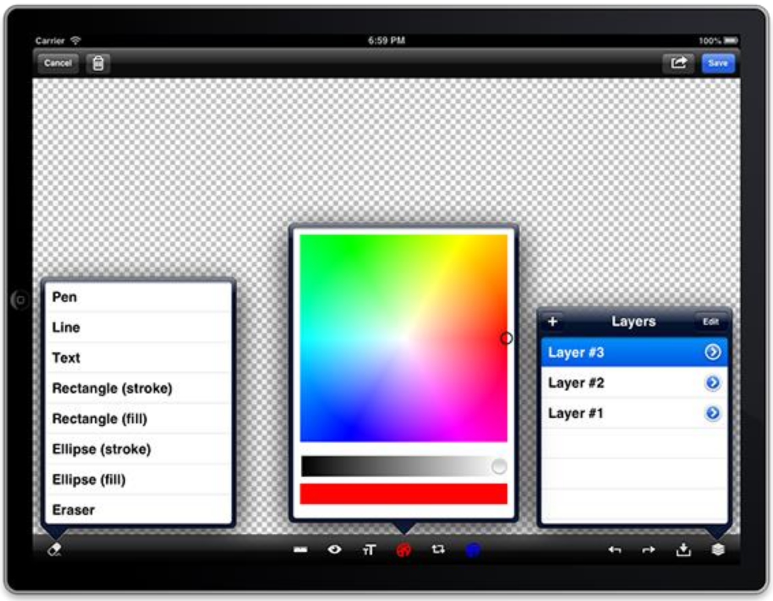


Figure 69: Simple drawing open source code base showing annotation, colouring and layers functionality at the same time.

Minor improvements are added to the code base such as ability to search through the map interface rather than depending on the GPS location only. The main drawing/sketching interface of the code is shown in Figure 68 where a section of a map is imported and annotation is added. The screen shot in Figure 69 shows multiple functionality.

The review of current apps in chapter two was based on the categorisation of the way data is handled: data collection, data viewing and analysis. Any field app, novice or otherwise, also needs to cater for all three categories of dealing with data. Therefore the next three sections outline what has been implemented based on this categorisation.

7.2.1 Capturing data

For novice geologists, as mentioned in chapter two, understanding the concept of strike and dip as well as recording them requires training and takes time (Kastens 2009). The current prototype contains an implementation of the widely used water level example, recommended by (Liben & Titus 2012) who mention an app that no longer exists on the app store. A screen capture of the simulation is shown in Figure 70. For the sake of simplicity let us refer to it as the water level simulation.

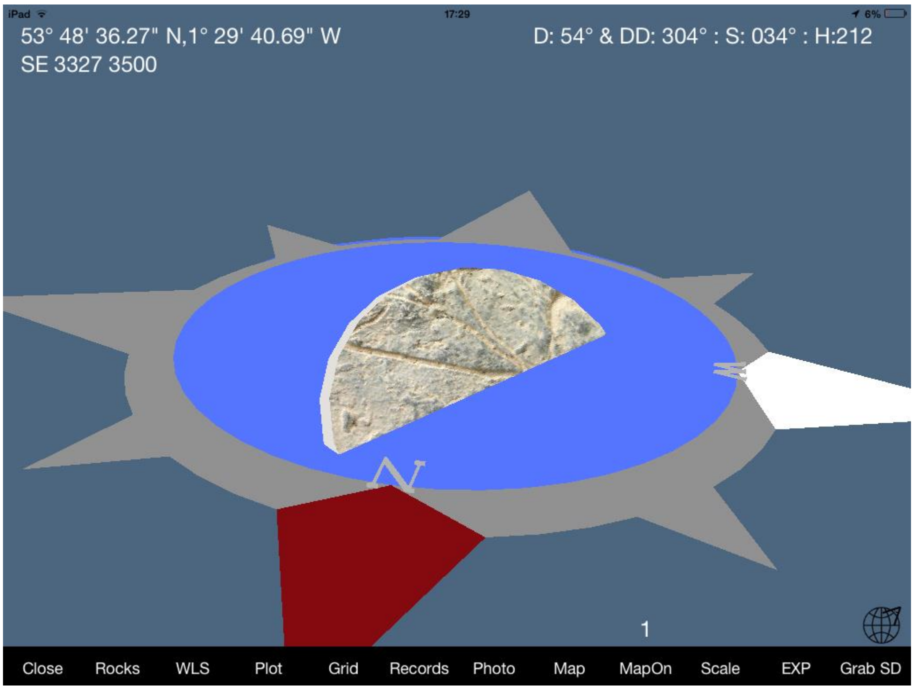


Figure 70: Water level simulation. The middle rock textured shape (half disc) represents a particular planar surface. The blue circle represents a water pool around the surface whilst the compass gives an overall geographic orientation of the surface.

The water level simulation is a basic 3D scene composed of three parts: a rock representation, a water pool and compass shapes. In the middle there is the rock which shows the dip angle in relation to a representation of the water pool, which remains horizontal as the device is rotated in space. The compass then indicates as the device is moved in space which way the direction of dip is and also both ends of the strike line directions. The strike line is formed where the bottom of the rock meets the water surface.

One way this simulation can be improved is to implement it in a mixed reality (MR) mode. This could be implemented by taking a measurement by placing an iPad or another tablet on an outcrop. Then a user holds the device away from the rock guided by the device to match the attitude of the rock then a water simulation is added to the rock via the device camera. The rock measurements such as strike and dip then can be added to the visualization.

The MR mode could lead to other areas of research. For instance, using image recognition rock composition data could also be offered from a database for this purpose. That way students will not just have structural data but also lithologic data as well. Then simply with a built in catalogue of rock types based on the rock type, more text or other information could be presented to the user.

7.2.2 Viewing data

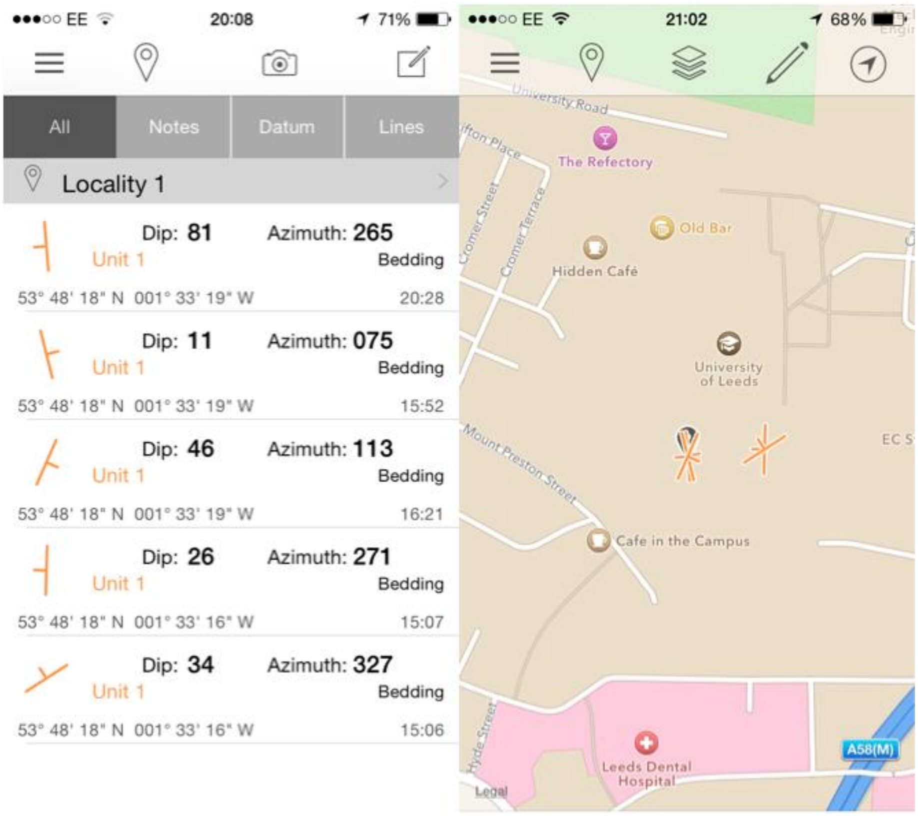


Figure 71: Two different screen shots from Midland Valley's FieldMove Clino iOS app. Left: list of strike and dip measurements in a table list. Right: strike and dip measurements plotted over a map view.

Viewing measurements or other data from the field such as notes, pictures and drawings (both digital and hand drawn sketches; scanned or photographed) are essential fieldwork data. Despite the fact that these were not the focus of the research, the prototype was built with these in mind. Viewing these and measurements taken using the device, GPS tracks or any of other types of data could be done in one of the following ways: list and other conventional alphanumeric formats, plotted on a map view or imported into the field simulation (discussed next).

For viewing data in alphanumeric formats on mobile devices, one way is using "table views". A table view is where data is viewed in a vertically scrollable table, which is a widely used method for at least iOS devices (Liu et al. 2011). The API from the vendors to support this is rich and recommended (AppleiOSAPI 2014b). Indeed, many applications such as FieldMove Clino rely on it, as shown in Figure 71 (left). The prototype too uses a list to show the list of strike and dips as shown in Figure 72.

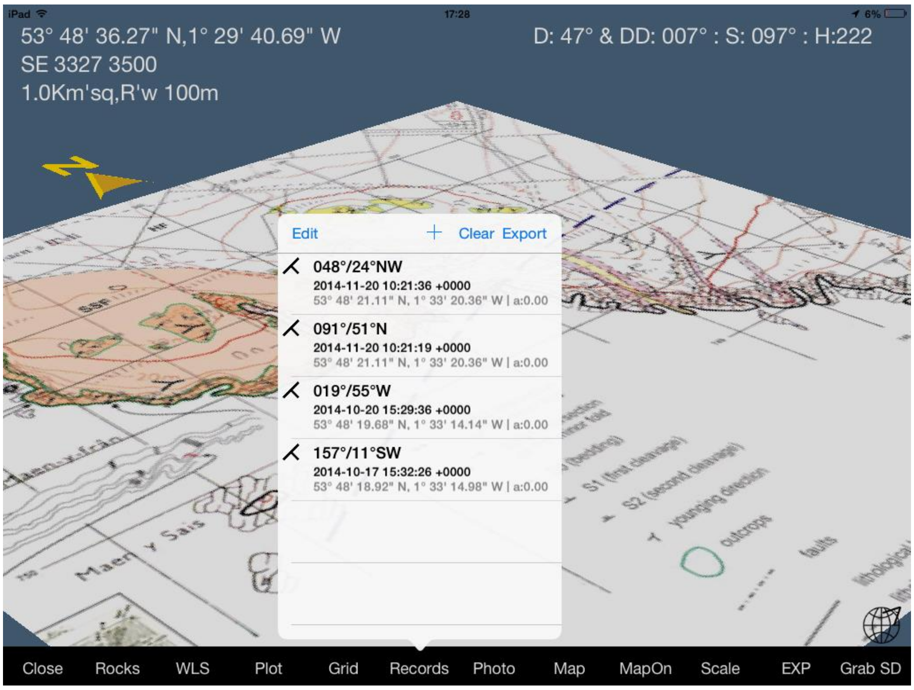


Figure 72: Screen capture from the working prototype showing a list of strike and dip measurements in a tablet list.

In terms of viewing maps, due to the lack of connectivity in the field these should be cached on the device. Despite the difficulties in reading maps by novice geologists mentioned in section 2.2.2, maps are still the foundation of teaching geology and therefore any field app should support them. During development of the prototype various SDKs (Software Development Toolkit) were tested such as MapBox which make caching map tiles easier on mobile devices including maps from the UK Ordinance Survey. Digital mapping functionality is slightly different than presenting data on maps, and applications targeting fieldwork such as Midland Valley's FieldMove Clino implement some. Future work on the prototype should also consider digital mapping too, as will be discussed in the next chapter.

Regarding other captured data such as structural measurements or GPS data such as tracking data, limited work has been done. GPX data (GPS Exchange Format) is currently supported via a third party library that creates a GPX file, and the Google Maps API for iOS was tested to show tracking of two points in a map. Screen captures of these can easily be exported from the app or used within the app for other purposes such as annotation or to be imported into the field simulator, as discussed next.

7.2.3 Analysing data

The idea of a 3D scene where users can add field data and other data from mapping API's on smartphones or imported from 3rd parties can be taken as far as a real scene replication. The aim, of course, is to make it easier for novice geologists to have a representation of the reality they study in their hands. For the purpose of this thesis let us call it a "field simulation". Some basic work has been done on the prototype to illustrate the idea.

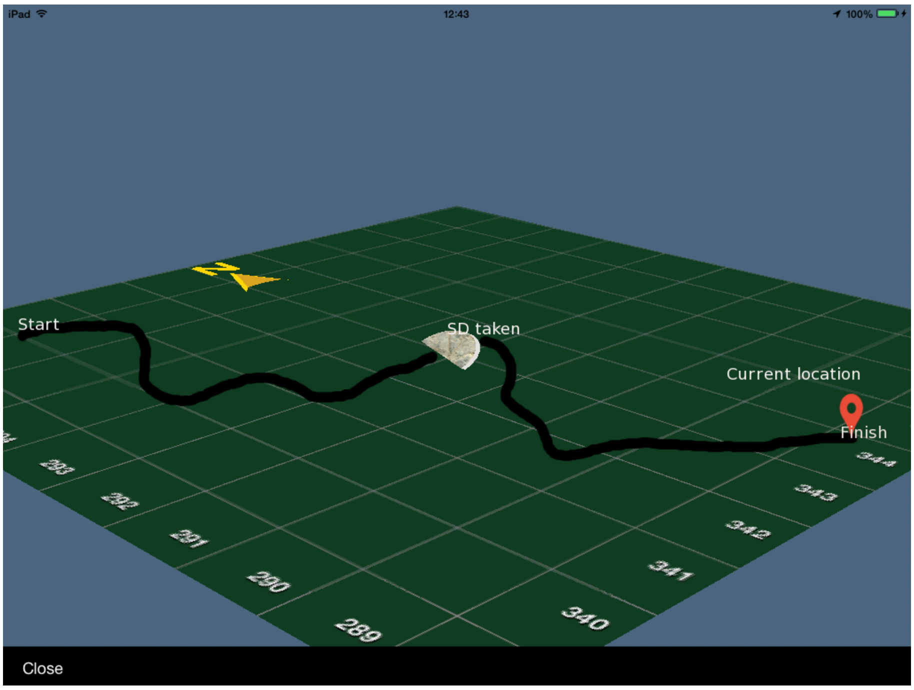


Figure 73: Visualizing current route, current location on a ground reference with measurements collected so far plotted on it. The ground reference is populated with UK grid three digit references, Easting towards the right and Northing towards the compass "N" sign. The location of the user is indicated by the red location symbol.

The current version of the prototype is designed to support two scales only: either 1 km^2 (1km by 1km area) or $0.01km^2$ (100m by 100m). The geographic correspondence between the simulation and reality is the first matter to solve.

Currently the simulation is user and device independent and the 3D world can be rotated by the user. However, the other scenario of matching the simulation to the real world was also considered and can be achieved, but was not implemented due to time constraints. For example, the direction of north in Figure 73 always aligns to the direction of the home button of an Apple device as the device is rotated in space.

In such a field simulation, the design also needs a way of matching the scene with reality, and this is currently done in few ways. The default method is by providing a reference grid either based on UK grid reference or UTM grid. To do this, currently the prototype converts latitude and longitude values from the GPS using a conversion by (Hankiewicz 2013). Having converted the GPS reading into the UK OS grid, the left column and bottom row of the 10x10 square shown in Figure 73 are populated with the corresponding grid references. This takes the current location as centre of the scene at the start of a session.

Having created a simple 3D scene with a geographic coordinate system, we can start thinking about possibilities of analysing geological data. The current prototype enables strike and dip measurements to be added (as they are recorded) to be represented with a half disc shape using the results from experiment in chapter five. Currently the shape is textured with a few built-in textures (a user can specify which one) with possibility of adding one's own texture or taking a picture and using it as a texture.

The simulation is designed to calculate the position of the first measurement, and then each subsequent measurement will be placed in the geographic grid (the green grid in Figure 73) or based on GPS readings from the measurements. This was tested in and around campus and requires other work to let the user know the accuracy of each GPS reading, which then allows possible manual correction of the measurements.

Part of the work implemented is visualizing current field routes as a line on a grid or lat/long ground reference with structural measurements plotted on it as shown in Figure 73. The basic elements of this requires drawing lines between GPS recording intervals. This is currently done using a built-in API map.

7.2.4 An ideal application

During the work on the POC one question was explored: “what is the ideal application for novice geologists?” Professional geologists use technologies such as a 3D PDF to achieve simulation of 3D geological models. An ideal application would integrate such models with applications like Google Earth. A 3D geological model of

Assynt in Scotland developed by (Leslie G., Krabbendam M. 2012) exists (see Figure 74), which made headlines (BBCNews 2013). The idea is more like Google Earth but with underlying geology available to be switched between the surface and the subsurface.

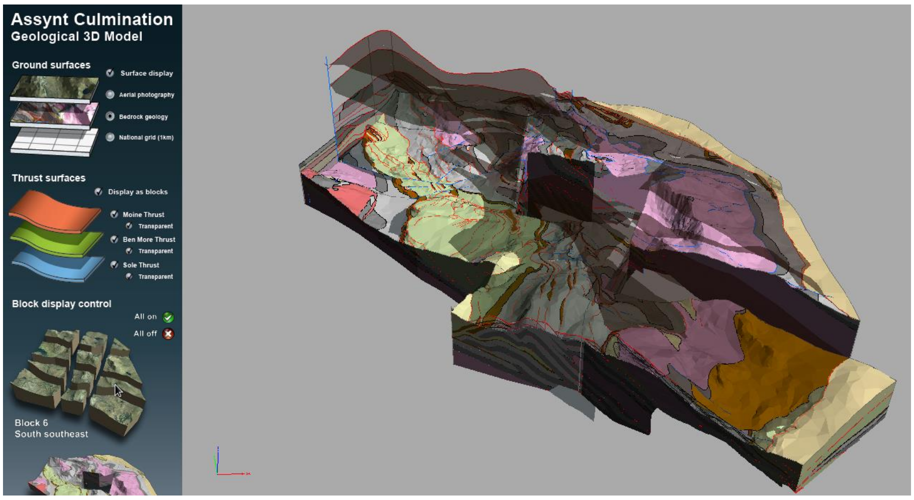


Figure 74: A screen shot from a 3D PDF of Geological model of Assynt Culmination, by BGS. The left side shows various controls such as adding and removing layers. The model itself is made of various blocks which can be highlighted and studied.

One inspiration for such an ideal application could be Autodesk's FormIt tablet app (Autodesk 2014), covered in chapter two. The iPad app allows engineers to design CAD engineering projects on the go and perhaps take their models out to the site. With the ability of integrating the smart devices such as the camera to import data into the project, a screen shot from the app store of the app is shown in Figure 75.

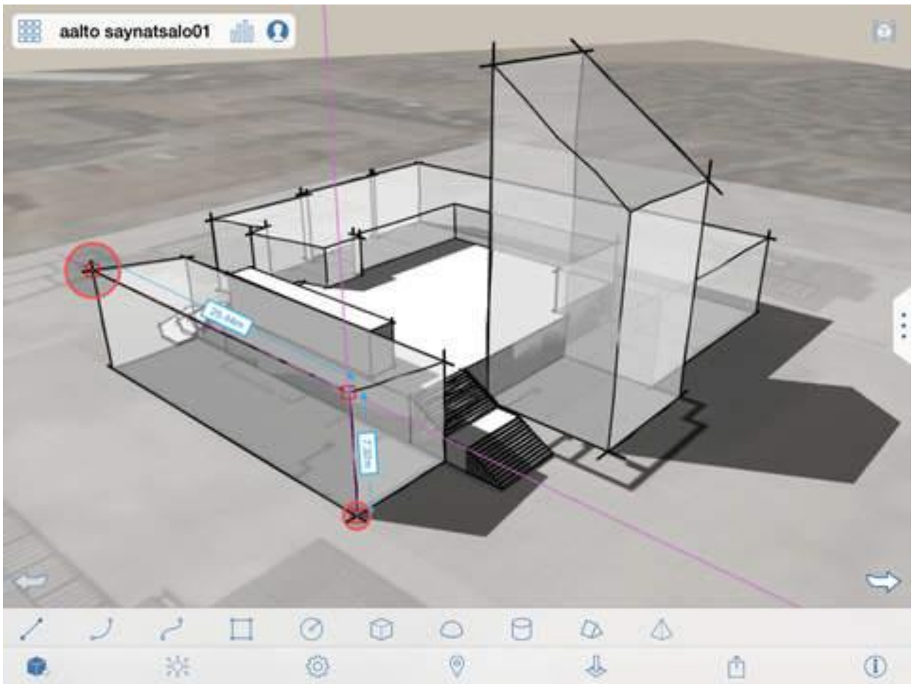


Figure 75: AutoDesk FormIT app for iPad screen shot. The image shows a see through model of a building built over satellite imagery within a geographical location.

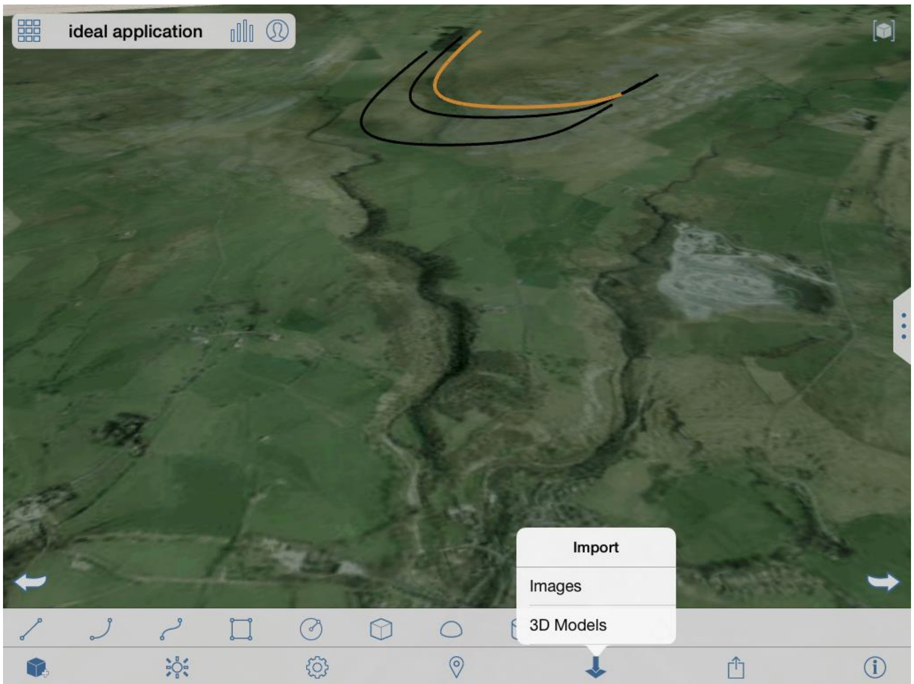


Figure 76: AutoDesk FormIT version 8.0 with satellite imagery of Ingleton area imported in as the ground of the scene, and possibility of importing 3D models into the scene too.

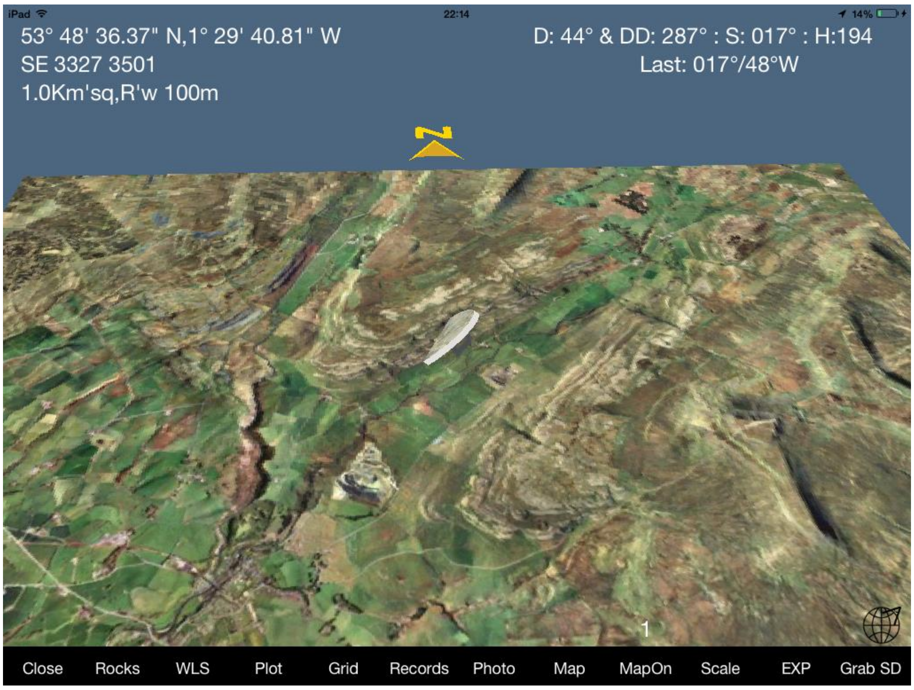


Figure 77: Screen capture from the working prototype. Satellite imagery from Apple Maps from Ingleton area is imported as the ground reference.

Although geological modelling is different from CAD models, the analogy is not bad. Given required funding and development capacity, a tablet application where real time modelling and earth surface DEM could be achieved. A screen capture of the app showing a satellite image of Ingleton area with some lines drawn around the ridge of the hill and possibility of importing 3D models is shown in Figure 77.

A similar scenario is shown in Figure 77 from the prototype where similar satellite imagery of the area is imported and a single arbitrary measurement is added. Further research is required as to how such a model could be used with the paradigm of virtual globes using currently available satellite imagery and DEM data.

7.2.5 3D structure contour generation

Other achievable work could be the implementation of “structure contour generation” functionality from Table 12. Structural measurements could be combined with GPS tracks obtained throughout the field. Using interpolation algorithms even the generation of contour lines of the measured structures could help the students start visualizing the geology of the field.

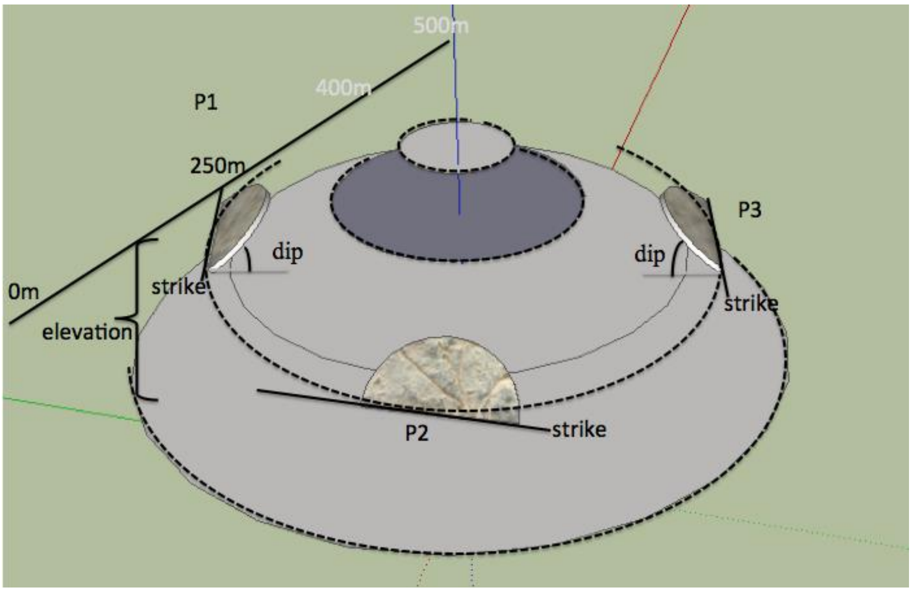


Figure 78: An imaginary scenario where an application can suggest 3D shape by generating a structure contour from three different strike and dip values of planar surfaces.

The mathematical rationale and interpolation algorithms are already described by (Groshong 2008, chap.2,3). It is assumed that this can be achieved from the attitude of the planes captured and GPS data from a smart device such as an iPad. However, this requires further research regarding data-format compatibility with those of mainstream professional GIS packages such as Midland Valley's Move.

A simple scenario would be where instead of triangulation, the application generates contour lines based on different measurements on the same or various elevations. A scenario is shown in Figure 78 where three separate measurements are taken with equal elevation and attitudes suggesting a hill structure. One way an application could aid students is to suggest different shapes based on the measurement attitudes and elevations including a hill structure. This is assumed to trigger and guide students to think in 3D rather than generating structure contours on paper in 2D only.

7.3 Functionality list

The last section outlined the implemented functionalities of the prototype. In light of the work contained in the last chapters a list of functionality was also generated. This section outlines the possible functionality in four different aspects for a novice geologist field app: measuring mode, modelling mode, sketching and conventional mapping. In each section for each of these modes, there is a table outlining the possible functionalities. In each table there is a column for categorizing the way data is handled, named "category" (see 2.6.1). The list is a broad list generated based on the work in Chapter two (see 2.5.3).

In the next four tables, FF stands for “future functionality”, C for “capture data”, V for “viewing data” and A for “analysing data”. Features are listed in no particular order or grouping.

7.3.1 Measuring mode

The functionality presented in Table 10 are considered those to be essential and needed for any data analysis or viewing mode of an app. Data compatibility is essential here as storing and exporting data has to be in formats supported by other applications used by the students.

Measuring Mode			
Functionality in brief	**Status in prototype**	**Category**	**Reason/Notes**
Capture measurement	Done	C	Only strike and dip measurements have been implemented and evaluated. Other planar and linear measurements are similar.
Water level example simulation	Done	C/V/A	Implementations of the water level example to aid users visualize the concept of strike and dip for planar structures.
Water level example simulation: change rock representation	FF	C	What graphical shape should represent the rock being measured and a colour code or texture to represent the lithology.
Water level example simulation: rock cantered	Done	C	The geographic coordinate system of the visualization, in this mode the device attitude is ignored.
Water level example simulation: user centred	FF	C	In this mode, as the device is rotated the simulation is done according to the device

Measuring Mode			
Functionality in brief	**Status in prototype**	**Category**	**Reason/Notes**
			rotation
Water level example simulation: MR mode	FF	C	Instead of representing the rock, holding a device towards a rock and adding visualization to the camera stream.
Export/import data (various and bearing compatibility in mind with other applications)	FF	C	Importing appropriate data formats such as CSV.

Table 10: List of functionality for the measuring mode of the prototype. FF stands for “Future Functionality”, C for “Capturing data”, V for “Viewing data” and A for “Analysing data”

7.3.2 Modelling mode

The field simulator design outlined in, as stated before is only a proof of concept. The list of functionality in Table 11 is based on the limited work carried out and outline only the major user tasks within a typical process of capturing software development requirements. For a real app the list is most likely to be even bigger.

Plotting/Modelling Mode			
Functionality in brief	**Status in prototype**	**Category**	**Reason/Notes**
Visualizing planar data in 3D: strike/dip	Done	A/V	For the purpose of the studies within the research only these two metrics have been implemented.
Visualizing other planar data	FF	A/V	Other planar measurements would be similar but needs implementation
Visualizing linear data: all	FF	A/V	
Viewing measurements	Done	A/V	Any application would need this to enable users to view

Plotting/Modelling Mode			
Functionality in brief	**Status in prototype**	**Category**	**Reason/Notes**
as a list			data and change/delete etc.
Edit/delete a measurement: strike/dip	Done	A/V	This is implemented because lack of GPS/precision issues requires manual entry or editing.
Update plotted measurement if a record is edited	FF	A/V	As a measurement is deleted from the list, if list is plotted, either re-plot all or sync plot with list.
Manual measurement entry	Done	A/V	General-purpose manual entry of measurements. Difficult places or guessed measurements for difficult geology.
Manual location data entry	Part Done	A/V	Lack of GPS reception or away from field modelling. User can set the centre of scene to their desired Lat/Long or UK grid
View measurements in 3D superimposed on image	Done	V/A	IF institution has the right image for the field area, can be given to students and data can be plotted on it.
View measurements in 3D superimposed on map	Done	V/A	A map section that matches the default field area scale of the scene can be imported and used as the base of the 3D scene. As was done in Chapter six.
Plotting scale (for now $1km^2$ & $0.1km^2$)	Done	V/A	Google earth, other maps are not made for geological

Plotting/Modelling Mode			
Functionality in brief	**Status in prototype**	**Category**	**Reason/Notes**
			fieldwork. The whole purpose of this is to create a new scaling.
Plotting in higher/lower scales	FF	V/A	Theoretically nothing should stop mapping in real world scales (no reference)
Change scale	Done	V/A	Changing between $1km^2$ and $0.1km^2$
Plotting grid Refs	Done	C/V	Dynamically adding grid refs to the scene to give students sense of location with real world or maps they might have.
Plotting lat. long.	FF	C/V	Students may not be trained on Grid references and may prefer latitudes and longitudes instead.
Conventional map location during plotting	Done	V/A	Inset map within screen to keep user aware of location. Depends on built in mapping detail & scaling.
Geological map location during plotting	FF	V/A	Inset geological map (for example using BGS API) to give wider area geological context to current analysis/viewing.
Change planar representation shape	Done	V/A	Staircase method study was carried out to determine this.
Change linear representation shape	FF	V/A	May require similar research to the staircase.

Plotting/Modelling Mode			
Functionality in brief	**Status in prototype**	**Category**	**Reason/Notes**
Generate structure contour	FF	A	Plotting single measurements within a 3D space is a step behind generating structure contour from those single measurements
Flexible rock representations	FF	V/A	Importing more models may always be needed
Adding other 3D objects to modelling	FF	A	Other ways to interact with the 3D model
Import 3D model in (COLLADA, Wavefront) formats	FF	A	This can be done, the library used in the prototype supports importing models.
Visualize current route as a line through the scene	FF	V/A	In the 3D space adding a line representing current field area route.
Import current route as ground reference	FF	V/A	Importing the field area from GPS track from a built in or custom mapping API
Indicate current location	FF	V/A	Given the 3D scene is synchronised with the field area, placing a moving indicator of current location.

Table 11: Implemented and future functionality list for the plotting mode of the prototype. FF stands for “Future functionality”, C for “Capturing data”, V for “Viewing data” and A for “Analysing data”

7.3.3 Sketching

Sketching Mode			
Functionality in brief	**Status in prototype**	**Category**	**Reason/Notes**
Import pictures with GPS and compass printed on.	Done	C/V	Take pictures & burn location & other data on the picture instead of other apps such as the ones used in Chapter three.
Import “map screen capture” for annotation	Done	A	Students may wish to draw on or annotate topographic or other map screen captures.
Annotate modelling mode screen captures	FF	V/A	Students may wish to use the field simulation functionality but may also wish to annotate them and save it.
Import field route map capture for annotation	FF	V/A	Having captured GPS track of current field reconnaissance, plotted on a desired mapping API, then import a screen capture of the route into the drawing application.
Various drawing and sketching functionality	Done	V/A	The SimpleDrawing, open source package integrated into the prototype has various drawing functionality. The list is too exhaustive for this thesis, can be found at the repository wiki.

Table 12: Implemented and future functionality list of the sketching mode of the prototype. FF stands for “Future functionality”, C for “Capturing data”, V for “Viewing data” and A for “Analysing data”

The list of functionality in Table 12 relies on the open source repository SimpleDrawing app's functionality list which is exhaustive for this thesis. Certain important functionality has been added to the list based on the fieldwork tasks in section 2.5.2.

7.3.4 Conventional mapping

Conventional Mapping Mode			
Functionality in brief	**Status in prototype**	**Category**	**Reason/Notes**
Record position (track)	Done		Third party code which is able to export GPX format tracking.
Draw route on map	Partly done		Partly implemented.
Plot measurements on built in map (Google or Apple)	FF	V/A	Google & apple
Plot measurements on custom offline maps.	FF	V/A	Rural connection is still a problem, also custom maps could have targeted data for teaching.
Importing sketch on map	FF	A	Integrating sketches from the field with custom or built in maps
Area & distance measurements	FF	A	Wider area (than modelling mode) geological interpretation
Conventional mapping use	Done		Google Maps API is preferred but any other map can be used.
Geological map (e.g. BGS UK geology viewer)	FF	V/A	Digital geological mapping integrated into the app.

Table 13: Implemented and future functionality based on conventional GIS usage for the current prototype. FF stands for “Future Functionality”, C for “Capturing data”, V for “Viewing data” and A for “Analysing data”

Due to the importance of GIS for fieldwork a list of functionality is required. The functionality presented in Table 13 is by no means a complete list. However, it is in the context of the field tasks discussed in 2.5.2 and also the way such functionality needs to interact with previous group of functionality presented in the last three tables.

7.4 Summary

This chapter summarises the functionality implemented as a code base for a field app on Apple's iOS. The prototype requires further work in order to be ready for use by students, these are outlined as well as the idea of an ideal application. There is no reason why with a limited amount of work the app would not be able to do what other apps does in terms of capturing, viewing and uniquely analysing structural data.

The water level simulation design is a novel design to assist students providing a visual representation of strike and dip alongside a compass clinometer. Although the design has not been evaluated, it is backed by literature (Liben & Titus 2012) and is meant to address the difficulty of learning strike and dip. The chapter also included a novel design for a 3D field simulation of geological data that can assist students with the difficult task of extrapolating 2D features to the third dimension.

The work carried out in the previous chapters have been combined and further developed into the proof of concept app with a list of functionality for a field app that is outlined in this chapter. The next chapter will outline the conclusions of the present work and directions for future research.

Chapter Eight

8 Conclusions and future work

The objectives of the present work are outlined in chapter one section 1.1. This chapter will summarise whether these objectives were achieved, the conclusions of the present work and the directions for future research.

8.1 Revisiting the Objectives

The work outlined in chapters three, four, five, six and seven provide the evidence that the objectives in section 1.1 have been met. The first objective was to understand the difficulties facing novice geologists. Chapter two, and especially section 2.5, shows that through both literature and first-hand work the issues were analysed and finally summarised in section 2.5.4. These were used as the basis for achieving the other two objectives.

The work in chapter three is put forward as evidence for the second objective, which was to understand the state of art in the use of smartphones in novice geological fieldwork and the use of visualization. Despite being an exploratory fieldwork study, it highlighted the limitations of tools such as Google Earth and iGeology3D. The accuracy study in chapter four is the most comprehensive study to date to show whether smart devices are reliable tools for taking basic structural measurements in the field.

The third objective was to put forward novel techniques for assisting with the issues facing novice geologists. The study in chapters five and six shows that this objective has also been met. The various aspects of the design of the proof of concept app in chapter seven is also presented as another piece of evidence that novel techniques have been proposed that will address the issues facing novice geologists in the field.

Overall, the contributions of the present work in light of the above objectives can be summarised as:

1. A systematic analysis of novice geologist tasks carried out during introductory fieldwork in chapter two.
2. Exploratory field evaluation of tablet applications for Android and iOS platforms up to October 2012 in chapter three.
3. The first published evaluation of the accuracy of an iPad2 as a measuring tool for strike and dip compared to measurements from a conventional compass-clinometer in chapter four.

4. Design and evaluation of new methods for portraying strike and dip in a 3D virtual environment, which users perceive more accurately than the conventional T symbol, in chapter five.
5. A user evaluation of how 3D visualization of field data can aid geological comprehension in chapter six based on the results from chapter five.
6. Design and implementation of a proof of concept for a 3D visualization mobile based app that can assist students overcome difficulties arising from conventional methods. This includes a novel design for water level simulation.

8.2 Conclusions

Regarding the first contribution, as discussed in chapter two in detail, there is a body of work regarding the difficulties and solutions of the issues facing novice geologists. However, this thesis has brought together published work and a first-hand systematic study of spatial and cognitive difficulties that arise from the use of conventional fieldwork tools.

Regarding the second contribution, the exploratory fieldwork study is a comprehensive look at apps used for introductory fieldwork with focus on analytical functionality. Chapter three presented evidence that apps developed up to the time of the exploratory study were generally not developed for novice geologists. Even data collection apps were found to be made for generic use, without focus on the tasks carried out by students in introductory fieldwork. This also confirmed the assertion in chapter two that limited amount of work has been carried out to address the difficulties students have in studying geology.

The third contribution stands out from other work because it presents the rationale and details of a comparison study between three methods of measuring strike and dip. The experiment in chapter four presented evidence that the gyroscope on an iPad2 tablet was accurate and consistent compared to a Silva ranger compass clinometers for measuring dip angles. However, the magnetometer failed to come anywhere near the expected error for measuring strike.

The fourth contribution is based on work outlined in chapter five which was the first study of its kind. The evidence presented in the study concludes that there is difference between 3D shapes to represent strike and dip. Participants in the study were worst in estimating strike and dip angles represented by the conventional T-shape model as expected.

Chapter six tested a hypothesis that, instead of looking at structural data on conventional geological maps, visualizing such data in a basic 3D visualization of structural data on maps could give more clues about structural formations presented in the maps. The results of the evaluation were in favour of the hypothesis. Therefore, based on the evaluation in chapter six, such a visualization could assist students with the difficulties of understanding or visualizing 3D nature of the structures on a geological map raised by (Whitmeyer et al. 2009) and discussed in section 2.5.1.

The last contribution is the design and implementation of the work in chapter seven which outlines a proof of concept prototype app. The novel aspects of this prototype including a water level example simulation which is recommended by (Liben & Titus 2012) can be developed into a novice geologist's field app.

8.3 Limitations

Overall, the nature of interdisciplinary research makes it more time consuming to carry out studies as it requires respective domain knowledge and expertise. As discussed in chapter two, novice geologists themselves struggle with basic geological concepts and this was also true for the researcher. It requires a non-geologist researcher considerable time to grasp the basic concepts which are, as discussed in chapter two, hard concepts to learn for those the research aimed at assisting.

The exploratory study in chapter three would have had better results had the researcher had better grasp of the nature of geological **novice** fieldwork. This is a limitation of time and the nature of interdisciplinary research. For more conclusive results, narrowing down the scope and the tasks carried out by the participants in the field. There were three tasks, and had the scope been cut down to only one task, more conclusive results could have been reached.

The accuracy study in chapter four is thorough. However, one can still find some limitations to the study. One of these could be the limited number of records for the ground truth in the case that better ground truth is needed for the iPad results to be compared with. Likewise, had there multiple devices, such as another iPad II been used to take more measurements, then more conclusive and robust evidence could have been presented.

The staircase method adopted in chapter five is, by definition, prone to limitations. Limitations such as the starting figures for the experiment, number of trials and number of participants. To address these limitations, the experiment was designed based on evidence from other experiments, and a pilot study was carried out before actual participants took part in the experiment. These measures can address these limitations but future work could also look at investing more time in more thorough pilot studies and bigger number of participants.

The user evaluation in chapter six, as discussed there, does not reach any conclusive results. The evaluation was carried out with a limited number of participants. The aim was to showcase the novel design of a 3D visualization of field data using 2D maps used by novice geologists. Therefore, even if the results of the evaluation would have gone against the design aim, it still provides a novel way of visualizing structural data in the field.

Focusing on the issues facing novice geologists in the field, due to the limited time and resources not many of the issues summarised in 2.5.4 were researched. The focus throughout the work in chapters five and six have been on assisting novice geologists with *visualizing strike and dip* (planar measurement). A more comprehensive research focus would also take into account other structural geological data, too. With more time and resources future work could focus on visualization of other fieldwork data, discussed next.

8.4 Future work

Overall, future research in visualization techniques to assist novice geological fieldwork could draw from the issues summarised in 2.5.4 that were not within the scope of the present work. These are the issues from literature and first hand work outlined in chapter two. Given the increasing processing and presentation power of smart devices, how can visualization assist novice geologists with less cognitive burden? Can visualization on smart devices assist students with visualizing the underlying structures with data captured in the field? If desktop techniques for generating structure contour were ported to smart devices, and novice geologists had the benefit of these contours in the field as they record measurements, would it be useful?

In chapter six, the evaluation showed that students who used the basic 3D visualization of strike and dip measurements plotted on a 2D map had a better understanding of the geology they studied. This shows that one way to assist students extrapolate 2D features into the 3D dimension is by adding 3D visualization to the widely used 2D maps. This is not new in the context of Google Earth-type digital globes. What is novel though is that the research has focused on the use of smart devices to assist novice geologists with difficult tasks such as extrapolation of 2D into 3D.

The designed prototype in chapter seven describes how a measurement taken in the field could be related to a point on the map using modern device capabilities. This is a step towards addressing "relating features from the map to the real world". The evaluation in chapter six was an attempt at testing how well visualization could help in perceiving the orientations of the structures better than looking at a 2D map. One way of taking this a step further could be testing novice perception of structural geometry using a mental rotation test or others described in the spatial cognition section 2.4.

The focus of the present work has been on the difficulties faced by novice geologists. It can be used for the purpose of developing solutions facing professional geologists, too. It is obvious that to so, there needs to be more work done to pinpoint the requirements. Also, to be able to achieve this, thorough knowledge of current desktop applications used by professional geologists is a must.

One of the areas of work for such requirements would be how far professional mainstream applications used by geologists could be replicated on a tablet application. So far, for example, only Midland Valley has created an app that is developed with focus on the needs of geologists in the field. Other mainstream vendors such as ESRI have only released what can be described as "viewing client" apps for data generated using their desktop applications.

The AutoDesk FormIT app for iPad can be a good example for this, too. FormIT presents a rich CAD environment and aids users by making use of the sensors such as GPS and camera to bring into the project data from the "site". Likewise, the field simulation described in section 7.2.3 is designed a step before 3D modelling can be supported, with no limitation with geological fieldwork workflow in mind. For example, if the shapes chosen in Chapter four is not deemed suitable for professional geologists, perhaps arrows or points could be used instead.

Finally, throughout the time dedicated to this research there has been little change in the available applications for novice geologists to use in the field. This is despite the fast moving pace of smart devices ecosystem. There is still a long way ahead in developing an app that is able to address the issues facing novice geologists in the field.

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Appendix I

INGLETON 2011

LOCATION

Thornton Force, in the R. Twiss Valley, ~2 km N of Ingleton, which is ~100 minutes' drive from Leeds. The site is accessed by taking the 'Waterfalls Walk', a very scenic trip up the gorges of the Twiss Valley (see over page). It is a ~2.5 km walk with an ascent of ~100m. The path is rough & slippery in places, requiring due diligence.

HAZARD ASSESSMENT – appended (see below – you will sign a copy also)

ESSENTIAL EQUIPMENT

Clothing: warm clothing (including hat & gloves) & waterproofs (jacket, over-trousers – NO jeans), appropriate footwear (boots); rucksack (hands must be free for the walk) – ***anyone inappropriately dressed will not be allowed to attend the field class!***

Field: appropriate field notebook; compass-clinometer; hand-lens; pencils (HB & coloured); pencil sharpener & eraser; A4 clip board + (thick) elastic bands; A3 (clear) plastic bag; tape measure; pen knife (or similar) – ***NO HAMMERS***

Safety: hard hat and high viz

Food: we will be in the field ***ALL*** day & there will be ***NO*** opportunity to buy lunch etc., so bring ***sufficient*** food & (warm) drink with you!

ASSESSMENT: although there is no formal assessment, the field class & debriefing exercise are part of the SOEE Skills Week & attendance at both is compulsory – any student that does not attend will be issued with a formal written warning as part of the University's '*Unsatisfactory Procedures*'

FEEDBACK – debriefing sessions on Friday 5th Nov (part of the Skills Week programme – check your group allocation)

WATERFALLS TRAIL, INGLETON

(http://www.ingletonwaterfallswalk.co.uk)

Introduction - The Waterfalls Trail has some of the most spectacular waterfall & woodland scenery in England. The whole trail is 4.5 miles/8 kilometres long (we do only the first 1.5 miles/2.7 kilometres). It passes through ancient oak woodland & magnificent Dales scenery via a series of spectacular waterfalls. Due to its rare & interesting plants & animals & its importance as a geological site, much of the Waterfalls Trail has been designated as a Site of Special Scientific Interest (SSSI) by English Nature.

History - The Waterfalls Trail in Ingleton opened to the public in 1885 & has continued to attract visitors ever since. In fact, Ingleton has been well-known for its caves & magnificent mountain scenery since the end of the 18th Century but at that time the waterfalls were hidden from view & people were unaware of their existence. A series of articles then appeared in the Lancaster Guardian & other newspapers on the scenery in & around Ingleton, which generated so much public interest that the idea of making the waterfalls accessible began to be developed & an 'Improvement Company' was formed. Pathways & wooden bridges were built & the trail was opened on Good Friday, 11th April 1885 at an entrance charge of 2d. Thousands of visitors arrived in Ingleton by train from Bradford, Manchester & other towns. Visitors bought souvenirs of photographs & paintings by local artists. The popularity of the trail at that time is shown by the fact that on one day in June 1888 there were 3,840 visitors to Ingleton. Today, over a hundred years since it first opened to the public, the Waterfalls Trail remains a beautiful and unique place to visit.

Swilla Glen - The first section of the trail follows the River Twiss through Swilla Glen, a deep valley cut into limestone with woodland of oak, ash, birch & hazel. A variety of wild ground plants are to be found here, such as bluebells & dogs mercury. Mosses & ferns thrive in the moist conditions of the area. After crossing the footbridge (Manor Bridge) the path leads towards Pecca Falls.

First Pecca Falls - After crossing Pecca Bridge is the first of the Pecca Falls. Here the vegetation changes from typical limestone to bracken & heather, which are associated with slate & sandstone & more acidic soils. There are five main waterfalls at this point, dropping 30 metres over sandstone & slate. The river tumbles over the sandstone steps into the plunge pools, which may be as deep as the falls are high.

Pecca Twin Falls - Pecca Twin Falls is the second of the Pecca Falls & an impressive sight! As before, the river tumbles over the sandstone steps into deep plunge pools The Waterfalls Trail continues then to Hollybush Spout.

Hollybush Spout - The path climbs steeply up a series of steps via Hollybush Spout, onto open moorland where the river then flows through a shallow valley leading to Thornton Force.

Thornton Force - Thornton Force is the most famous of the waterfalls on the trail, located 1.5 miles from the car park & not to be missed! Here the river falls 14 metres over limestone rocks in an impressive cascade of water. There is a viewing area which is also a suitable picnic spot.

AIMS/OBJECTIVES

To introduce basic concepts of geological field work by carrying out a small geological field investigation whilst developing the following skills:

- setting-up & keeping a geological notebook;
- use of compass-clinometer to measure lines & planes;
- introduction to field sketching;
- orientation: map location and taking bearings
- rock descriptions and outcrop observation skills
- basic introduction to geological mapping;
- developing a scientific investigation;
- risk & hazard assessment.

METHODOLOGY

You will be split into small groups. Each group will be led by an experienced field geologist & there will be also demonstrator support. Each group will visit a series of locations, which are in close proximity, where they will practice collecting & recording geological information, as well as practising appropriate risk & hazard assessments. Following the field day, a class-based debriefing exercise will be provided also.

Assessment:

*Those of you on the **Geological Sciences programme** will use the data you record and observations you make to write up a **field report as part of the SOEE 1590 module.***