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Digital geological mapping with tablet PC and PDA: A comparison

P. Clegg[a,*], L. Bruciatelli[b], F. Domingos[a], R.R. Jones[c,d], M. De Donatis[b], R.W. Wilson[a]

[a]*Department of Earth Sciences, University of Durham, DH1 3LE, UK*
[b]*Laboratory of Information Technology for Earth and Environmental Sciences, Universita degli Studi di Urbino, Campus Scientifico– Loc. Crocicchia, 61029 Urbino, Italy*
[c]*Geospatial Research Ltd., Department of Earth Sciences, University of Durham, DH1 3LE, UK*
[d]*e-Science Research Institute, University of Durham, DH1 3LE, UK*

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Abstract

Both the hardware and software available for digital geological mapping (DGM) have advanced considerably in recent years. Mobile computers have become cheaper, lighter, faster and more power efficient. Global Positioning Systems (GPS) have become cheaper, smaller and more accurate, and software specifically designed for geological mapping has become available. These advances have now reached a stage where it is effective to replace traditional paper-based mapping techniques with those employing DGM methodologies. This paper attempts to assess and evaluate two currently available DGM systems for geological outcrop mapping: one based on a Personal Digital Assistant (PDA) running ESRI "ArcPad", and the second based on a Tablet PC running "Map IT" software. Evaluation was based on field assessment during mapping of a well-exposed coastal section of deformed Carboniferous and Permian rocks at N. Tynemouth in NE England. Prior to the field assessment, several key criteria were identified as essential attributes of an effective DGM system. These criteria were used as the basis for the assessment and evaluation process. Our findings suggest that the main concerns presented by sceptics opposed to DGM have largely been resolved.

In general, DGM systems using a Tablet PC were found to be most suitable for a wide range of geological data collection tasks, including detailed outcrop mapping. In contrast, systems based on a PDA, due to small screen and limited processing power, were best suited for more basic mapping and simple data collection tasks. In addition, PDA-based systems can be particularly advantageous for mapping projects in remote regions, in situations where there is a limited power supply or where total weight of equipment is an important consideration.

Keywords: Digital geological mapping; Tablet PC; PDA; GIS; GPS

1. Introduction

Digital geological mapping (DGM) is the process of mapping and collecting geological data using some form of portable computer and Global

*Corresponding author. Tel.: +44 (0) 1913342338; fax: +44 (0) 1913342301.
E-mail address: p.clegg@durham.ac.uk (P. Clegg).

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Positioning System (GPS), rather than a traditional approach based on notebook and paper map. Digital mapping is rapidly becoming accepted and established as a valuable tool for geoscientists.

Over the past years there have been numerous papers discussing the methodology, software development, applications and the merits of DGM (e.g. Struik et al., 1991; Brodaric, 1997; Briner et al., 1999; Brimhall and Vanegas, 2001; Maerten et al., 2001; Edmondo, 2002; McCaffrey et al., 2003; Jones et al., 2004; Wilson et al., 2005; McCaffrey et al., 2005). These papers document the ongoing technological development, which has allowed relatively unwieldy computer equipment available to the early digital pioneers to be replaced by lightweight and user-friendly DGM systems. Most modern users favour a DGM setup based around either a palm-sized Personal Digital Assistant (PDA) or a larger Tablet PC. In this paper, we examine and assess the particular merits of these two types of DGM system. In addition, we briefly summarize the evolution and current status of DGM, and consider some of the more general issues that remain unresolved in digital mapping.

2. Overview of DGM

In recent years, technological advances and innovations in portable computing, GPS, and mobile Geographical Information Systems (GIS) software have permitted geoscientists to undertake digital data capture and mapping in the field. This process has been referred to as "born digital mapping" (Fitzgibbon, 1997) or primary digital mapping (McCaffrey et al., 2005), and is the main focus of this paper. Primary digital mapping contrasts with other digital tasks such as transcribing field data into spreadsheets or databases, and reproduction of field maps with cartographic or graphic software; these are post-fieldwork tasks related to secondary digitizing (McCaffrey et al., 2005).

Digital field acquisition has been used by surveyors and workers in the utility industries since the late 1980s to input data or to correct, modify, or create maps directly in the field. Generally the data collected by these user groups, although often varied, is in a relatively simple format, and can be input into a handheld computer relatively easily by an operator with limited computing skills using standard software containing simple data collection forms. In contrast, geological field mapping is an iterative process of observation, reasoning, and interpretation, which is strongly influenced by the geoscientist's prior knowledge, experience and expertise (Jones et al., 2004). In the field the geoscientist uses a combination of processes and scientific tools to gather the rich data provided by the field environment. These include; recording direct observations, collection of field samples, measurement of bedding and structure, field sketching, photography and mapping. This process therefore requires a more flexible approach and a broader range of recording media than that used to record basic types of utility data mentioned above. This level of flexibility is already met by traditional paper-based mapping methodologies, so geologists will need to be convinced of the added value offered by digital mapping over traditional methods before they are likely to adopt the new methods.

3. Advantages of DGM

DGM is not simply a direct replacement for traditional paper-based mapping methods; importantly, it gives the geoscientist the enhanced ability to collect geospatially georeferenced field data that can be analysed and visualized in ways that are impossible or very difficult to achieve using traditional techniques (McCaffrey et al., 2005). Pioneers of DGM (e.g. Struik et al., 1991; Brodaric, 1997; Briner et al., 1999; Kramer, 2000; Brimhall and Vanegas, 2001; Edmondo, 2002; McCaffrey et al., 2003; Jones et al., 2004; Wilson et al., 2005; McCaffrey et al., 2005) have discussed the many advantages offered by DGM over traditional methods, which include:

- GPS allows all data and their attributes to be geospatially referenced in x,y,z, space, i.e. latitude, longitude and elevation, (although data added freehand by drawing with the stylus will generally lack altitude values).
- There is a streamlined workflow from data collection to final map production without the need for disparate and separate data processing.
- Data derived using other geophysical and geographical systems can be easily integrated e.g. satellite imagery, gravity and magnetic surveys, geochemical sampling, Digital Elevation Models (DEM) etc.
- Data management and storage capability are enhanced.

- There is greater accessibility to data for a wider audience through data archives.
- A wider range of analytical techniques including 3D analysis, spatial analysis etc. can be applied.
- Accuracy and precision of GPS positional data can be tested and quantified. This is not the case in traditional mapping, where this possible source of error is largely ignored.
- Cost savings can be gained by reduction in the need for time-consuming data conversion and handling.

Despite these numerous advantages many field geologists are still reluctant to try the new technology, preferring instead to continue to use the old tried and tested methods of paper-based field mapping. For example, in a survey of twenty nine geological survey organizations in Europe, all utilized secondary digitization for data storage and the production of maps, however only two were actively investigating the use of primary digital data acquisition during geological mapping (Jackson and Asch, 2002). Consequently, field geoscientists practising traditional methods of mapping and interpretation of the complex geological structure and history of the Earth, do not yet derive appreciable benefit from the digital and information technological advances and innovations that have been made in other related fields of science (Brimhall et al., 2002). Of the reasons often given for a particular geoscientists' reluctance to embrace DGM, three main themes commonly arise: (1) cost and reliability of equipment; (2) time required to learn the new techniques required for DGM and (3) the complex nature of the mapping process and the flexibility required by any methodology.

4. Requirements of a DGM system

The technology involved in traditional field mapping is cheap, well-proven, flexible, has a familiar user interface, and is highly reliable. Geological mapping is a time consuming and often expensive process. Therefore, any DGM system not only has to be as efficient as traditional methods, but also in addition has to offer distinct advantages over them. An important definition here is "Fit for purpose" i.e. will the chosen DGM system perform the tasks required of it efficiently, accurately and consistently throughout the range of environmental conditions met during mapping e.g. extreme cold and heat, high humidity, very wet or dry? Prior to field assessment we identified several key criteria that we felt were critical to a well-designed DGM system regardless of its intended purpose (Table 1).

4.1. Assessment criteria

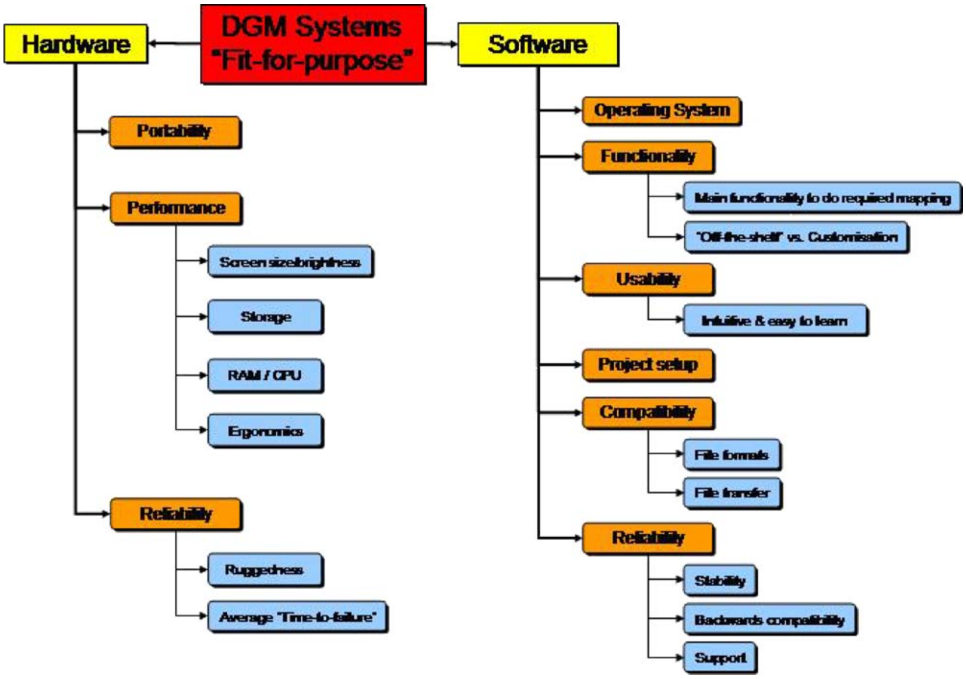
4.1.1. Hardware

- *Portability*: the portability of a DGM system is an important issue and not only concerns issues of weight and size, but is also related to ergonomics i.e. how comfortable the system is to carry and hold in use. The location of any individual mapping project can vary enormously from roadside cuttings where weight of the system is not an issue to extremely remote settings where all equipment must be carried by hand. In addition, peripheral equipment such as extra batteries, chargers etc. need to be taken into account.
- *Performance*: this covers aspects of screen size and brightness, storage capacity, RAM and CPU size/speed and the general ergonomics of each system. Of vital importance is that the screen should be clearly visible in bright sunlight. Transreflective screens are the most effective; these are relatively common in modern PDAs, but less so in Tablet PCs.
- *Reliability*: this concerns the ruggedness of each system and its suitability to carry out its task in a variety of environmental conditions e.g. rain, cold, heat and dust. Also under this heading is the average "time-to-failure" i.e. how long will the system (or its components) last under normal operating conditions?

4.1.2. Software

- *Operating system*: the operating system (OS) ultimately dictates which digital mapping software can be used. Some manufacturers provide different versions of their software for different operating systems whilst others only produce software for a single OS.
- *Functionality*: This criterion concerns two specific issues: firstly does the software require any setting-up or customization before even basic mapping can be carried out i.e. is it "out-of-the-box" ready? Secondly, does the software contain an appropriate range of tools and functions to carry out the required mapping, and can it be customized to the users specifications?

Table 1
Critical criterion for the design of a 'Fit-for-purpose' digital geological mapping system



- *Usability*: this can be a subjective issue and depends largely on the user's familiarity with Graphical User Interfaces, and in particular, previous experience with desktop GIS software. However, a well designed, clear interface will enable the user to utilize the software for maximum efficiency as quickly as possible and will also encourage them to continue to use the system.
- *Project set up*: the pre-fieldwork setup of any DGM project is critical and is typically a much more involved process than the preparation required for traditional paper-based mapping. Base maps, aerial photographs, satellite images etc. need to be scanned or downloaded. Scanned raster images must be georeferenced, shapefiles (or equivalent geographical objects) need to be created and data collection forms produced. The ability to be able to define levels of user control within a project at set up is highly desirable. This allows a project manager to establish a clearly defined set of forms, base cartography and symbols etc. that will be used by any particular group.
- *Compatibility*: DGM systems need to be able to import and export files from and to a wide variety of other applications which employ numerous different file formats e.g. ESRI shapefile, ArcInfo, MapInfo MIF, DXF, TIFF, JPG, GIF, MrSID. The range of file formats supported and/or the ease of conversion is a key issue.
- *Reliability*: issues of reliability are critical for any system that will be used in remote settings or to collect data that is not easily re-collected. Crashes in software lead to delays in progress, reduced confidence in the system and particularly important, possible data loss. "Backwards compatibility" (the ability of a system to open files generated with earlier versions of the software) is also an important consideration, particularly where archive data is more than a few years old. The level of support offered by a software manufacturer to its client is also important.

In general, good DGM systems:

- need to be reliable, rugged and not significantly bulkier than a field notebook and mapping board;

- should be fit for purpose and priced accordingly; i.e. a system designed for reconnaissance mapping at a scale of 1:250 000 need not be coupled to an expensive differential GPS capable of submetre precision;
- have a simple and logical visual interface in order to make the transition from traditional paper-based mapping to DGM easier;
- should require little prior knowledge of computer skills from the operator (with current students and recently qualified geoscience graduates this requirement is becoming less important because of their general high level of IT expertise);
- should be adaptable enough to allow users to easily configure the software to their particular requirements whilst in the field without the need for computer programming skills.

5. DGM hardware and software

Currently, many DGM systems belong to one of two types: those built around a Personal Digital Assistant (PDA), and those built around a Tablet PC. The systems shown in Table 2 are just a small selection of the many different PDAs and Tablet PCs available on the market, and simply represent those with which we have direct experience. The main focus of this paper is to review the pros and cons of both these types of DGM systems by focussing on two in particular (Table 3). The first is a PDA-based system comprising Trimble Recon PDA, a GPS, and ArcPad mapping software (Fig. 1a). The second system comprises an Xplore iX104R rugged Tablet PC, Haicom HI-204S GPS and MapIT$^{\text{TM}}$ software (Fig. 1b). We will also look briefly at the Trimble GeoXT, which is an integrated PDA and GPS receiver system (Fig. 1c).

5.1. GPS choice and testing

The GPS is an important and integral component in any digital mapping system and the choice currently available is large. However, the GPS is only required to provide positional information, which is then displayed via the DGM software. Therefore, more advanced features offered by some GPS models, such as colour screens, ability to store and display map data etc. are not required. What is important is that the choice of a particular GPS is determined by the mapping task to be undertaken and the levels of accuracy and precision required. Table 4 of McCaffrey et al. (2005), provides precision and accuracy information for a range of GPS units including the Garmin Geko 201 and the Trimble GeoXT.

5.2. Accuracy and precision

Although many users assume that GPS receivers give exact positions, it is important to understand that there is some amount of uncertainty, or error, inherent in these positions. Several factors contribute to this error including satellite clock drift, atmospheric conditions, measurement noise, and multipath (i.e. reflection of the signal off buildings etc. before being received by the GPS). Additionally, vertical accuracy (elevation) for GPS measurements is generally one and a half to three times worse than horizontal accuracy.

5.3. Differential GPS, WAAS and Egnos

The accuracy of GPS receivers can be improved by using differential correction (‘‘differential GPS’’, DGPS), to reduce some of the error. DGPS involves using a GPS base station, located at a known position, to calculate corrections for each satellite. The corrections can be derived by comparing the known location of the base station to the apparent location measured using GPS. This can increase the accuracy of the autonomous GPS position (i.e. one without differential corrections) from 5 to 10 m down to less than 1 m, depending on the system used.

There are two approaches to DGPS: real-time and post-processing. Post-processing corrections are stored on a disk and then applied to the field data after data collection is complete. Real-time corrections are broadcasted from the base station to the field GPS receiver almost instantly, so that you can begin to work with the more accurate GPS positions immediately. There are various sources of real-time DGPS signals, including Coastal beacons; Wide Area Augmentation System (WAAS, North America), and European Geostationary Navigation Overlay System (EGNOS, Europe only). The Geko 201 and Haicom HI-204S are capable of receiving real-time differential corrections using WASS and EGNOS, while the GeoXT can utilize both real-time correction using WAAS, EGNOS and beacon data, as well as permitting differential corrections via post-processing software.

Table 2
Some of the available digital mapping core devices grouped into PDA or tablet PC platform and their main features

System	Example	Type	Cost (approx.)	Weight incl. batteries (kg)	Battery life (manufactures data) (h)	Pros	Cons
PDA	HP iPAQ H3950	Standard windows pocket PC 2003 PDA	£350	0.185	4	Light and portable. Daylight readable screen.	Small screen size. Speed. Not ruggedised[a]. Short battery life.
	Trimble recon	Ruggedised PDA	£1200	0.49	8	Light and portable. Daylight readable screen. Ruggedised.	Expensive. Small screen size. Speed.
	Trimble GEOXT	Ruggedised, integrated PDA & GPS	£3500	0.72	8	Light & portable. Daylight readable screen. Ruggedised. Integrated GPS (no cables).	Expensive. Small screen size. Speed.
Tablet PC	Acer TravelMate C110 Tablet PC	Note book/tablet PC hybrid	£1200	1.4	0	Relatively cheap. Light weight. Large screen. Full PC specs.	Screen not visible in daylight conditions. Not ruggedised. Short battery life.
	HP Compaq tc1100 Tablet PC	Standard tablet, with detachable keyboard	£1600	1.4[b]	3[c]	Large screen. Daylight visible. Full PC specs.	Not ruggedised. Short battery life.
	Xplore iX104	Ruggedised tablet	£2700	2	6[c]	Ruggedised. Large screen. Daylight visible. Full PC specs.	Expensive.

Costs are approximate and are likely to change by time of publication.
[a]A rugged case is available.
[b]1.8 kg with detachable keyboard.
[c]Depends on operating system, power management and applications in use.

Table 3
Technical specifications of the DGM systems compared in the present work.

Features	Rugged PDA and GPS	Tablet PC and GPS receiver unit	"All in one" handheld
Hardware	Trimble Recon	Xplore iX104R	Trimble GeoXT
Processor	40 MHz Intel PXA255 XScale	866 Mhz Intel PentiumIII M	206 MHz Intel Strong ARM SA-1110
Physical memory	64 MB RAM	512 MB RAM	32 MB RAM
Display	240 × 320 pixel full outdoor colour display, with backlight	10.4″ XGA TFT colour (1024 × 768) 48 MB shared RAM	240 × 320 pixel full outdoor colour display, with backlight
Battery	Removable internal lithium-ion (all day)	Internal Li-ion (up to 6 h[a] operation)	Internal lithium-ion (all day)
Storage	128 MB internal flash disk and 2 user changeable compact flash slots	40 GB 2.5″ shock & vibration damped HDD	512 MB internal flash disk
Weight	0.49 kg with battery	2 kg with standard battery	0.72 kg with battery (including antenna)
Dimensions	16.5 × 9.5 × 4.5 cm	28.4 × 20.9 × 4 cm	21.5 × 9.9 × 7.7 cm
Chassis/casing	Rugged water-resistant, shock-resistant, and dustproof (MIL-STD-810F)	Rugged magnesium, Patented industrial bumper system, sealed and protected from the environment (MIL-STD-810F)	Rugged water-resistant, shock-resistant, and dustproof Wind-driven rain and dust-resistant as per IP 55 specifications
User Interface	TFT touch screen, 10 hardware control keys	Hi-Resolution active screen; 8 key backlit keypad–tablet pc keys and programmable; 5 way navigation joystick	Anti glare touch screen; 2 hardware control keys; 4 programmable permanent touch buttons;
Communications	USB, DE9(M) RS-232 serial port	Wireless radio bay; 1 × USB; 1 × IEEE 1394; LAN (RJ-45); 1x mic/spk; 15-pin D-SUB connector for external VGA monitor	USB connectivity via support module, serial communications via optional DE9 serial clip adapter; integrated Bluetooth for wireless connectivity
Operational system	Widows Pocket PC 2003	Windows XP Professional Tablet PC Edition	Windows CE 3.0
GPS receiver	Garmin Geko 201	Hicom HI-204S GPS	Trimble
Channels	12	12	12
Integrated real time	WAAS/EGNOS	WAAS/EGNOS	WAAS/Egnos & Beacon[b]
Protocol	NMEA-0183, Garmin, Garmin DGPS, RTCM	NMEA-0183 (GGA, GSA, GSV, RMC, VTG, GLL)	NMEA (GGA, VTG, GLL, GSA, GSV, RMC) and TSIP (Trimble Standard Interface Protocol)
Update rate	1 Hz	1 Hz	1 Hz
Weight	88 g without batteries (2 × AAA)	120 g	N/A (integrated)
Accuracy	5–25 m (standard); 2–5 m (DGPS)	5–25 m (standard); 1–5 m (DGPS)	Sub metre (real-time DGPS) No autonomous data given
Acquisition time	warm 15 s; cold 45 s	hot 8 s; warm 40 s; cold 50 s	30 s. (typical)
Mapping Software	ArcPad 6.03	MapIt Version 1.3 (now 2.0 is available)	ArcPad 6.03
Price	Trimble Recon £1200 Garmin Geko £90 PDA-GPS cable £25 ArcPad 6.03 £75 (educational) ArcPad £450 + vat (non educational) ArcGIS 9 £1495 + vat (non educational) ArcStudio £1495 + vat (non educational) ArcGIS £100 + vat (educational) ArcPad Studio £250 + vat (educational)	Xplore iX104R US$ 2723 = £1540 (Sept 05) Hicom HI-204S GPS receiver £70 Map IT €1050, £750	Trimble GeoXT £3150 ArcPad 6.03 £75 (educational) ArcPad £450 + vat (non educational) ArcGIS 9 £1495 + vat (non educational) ArcStudio £1495 + vat (non educational) ArcGIS £100 + vat (educational per year) ArcPad Studio £250 + vat (educational)
Total cost of system	£1810—£4833	£2360	£3645–£6960

[a]Battery life is dependent upon operating system, power management and applications in use. All prices are approximate and likely to change by time of publication.
[b]Optional extra.

Fig. 1. PDA and tablet PC systems compared: (a) Trimble Recon PDA running ArcPad software with Garmin Geko 201 GPS; (b) Xplore tablet PC running Map IT software with Hicom HI-204S GPS receiver and (c) Trimble GeoXT integrated PDA and GPS receiver running ArcPad software.

5.4. Testing accuracy and precision

Accuracy is the closeness of a measurement to the actual value of the measured quantity, whereas precision is the repeatability of a particular measurement method. It is possible to be accurate and not precise, and vice versa (Fig. 2). The precision or error in a GPS position may be estimated by repeated observations at the same location over a given length of time (McCaffrey et al., 2005). Accuracy can be determined by making observations on a known survey point (e.g. http://users.erols.com/dlwilson/gps.htm). Wilson (2006) has tested the accuracy of a variety of GPS units including the Garmin Geko 201 and Trimble GeoXT GPS (the Haicom HI-204S was unavailable at the time of testing). For the test the position of a known surveyed location was recorded daily over a fifty day period. Fig. 3 provides the results for the Geko 201 and GeoXT. The accuracy observed for the Geko and GeoXT is sufficient for a wide range of typical field-mapping scales e.g. 1:250,000–1:5000.

Table 3 summarises the manufacturers' specifications of all the GPS units evaluated. Predictably, the more expensive GeoXT is more accurate than the Geko, however, this difference is marginal and would generally not be noticeable when mapping at scales greater than 1:10,000. Although the Haicom HI-204S was not tested, the manufacture's accuracy figures imply that it should have a similar accuracy than that of the Geko and should therefore be suitable across a similar range of mapping scales.

5.5. DGM system 1

5.5.1. Hardware

This DGM system is based around the Trimble Recon PDA (Fig. 1a, Table 3). The Recon is a ruggedised PDA, and is water, dust, and shock-proofed to military standards (MIL-STD-810F). The battery is user changeable, and provides the PDA with approximately 8 h of operation in normal conditions. The unit is bright yellow, which gives it high visibility, and has black rubber bumpers on each end that provide protection and cover the battery and compact flash slots. The PDA was connected to a Garmin Geko 201 via a serial/Garmin cable, which provided a lightweight, accurate, digital mapping system.

5.5.2. Software

The mapping software installed on the PDA is ArcPad, part of the ESRI suite of GIS products.

Table 4
Summarized evaluation of the DGM systems assessed in the present work

		Pros	Cons
Hardware	Xplore Tablet	Large data storage capacity.	Relatively heavy.
		Processing power.	The supplied case is poorly designed for field mapping purposes.
		Large screen size.	Battery life (4.5 h ave.) requires additional batteries to be carried.
		Full PC specs.	Screen needs dedicated digital pen- loss could be disastrous.
	Trimble Recon PDA	Light weight.	Small screen size- requires lots of scrolling.
		Portable.	Generally slow processor speeds- long refresh times for displays containing large raster mages.
		8 h + battery life.	Needs PC and Active Sync to upload/download data.
Software	MapIT	Fully specced GIS e.g. georeferencing, spatial analysis, coordinate conversion etc.	Polyline data cannot be added manually when using GPS (continuous streaming time or distance only—this has been rectified in v2).
		Designed for digital pen input including direct drawing onto map/photographs.	Polygon data cannot be entered using GPS (this has been rectified in v2).
		Fully field editable projects.	
		Easy-Note function is extremely useful.	
		Automatic correlation of digital images with geographical object.	
	ArcPad	Easy user interface- particularly to those familiar with ArcGIS.	Some operations are difficult to locate & help files are limited.
		Part of the ArcGIS suite.	Needs ArcGIS for full capability.
		Full customization with ArcStudio (e.g. data entry forms, toolbars etc.)	Needs ArcStudio for full customization.
		Wide range of scripts, applets & third party plugins available.	Requires a high level of IT skill for customization.

This GIS mapping application is designed specifically for PDAs and integrates almost seamlessly with ESRI's desktop GIS application ArcGIS as a front-end data-capture solution. It cannot be considered as a standalone mapping software as it needs to be used in conjunction with ArcGIS and ArcPad Studio to provide the full range of GIS functionality. ArcPad Studio is a separate software development package for building custom ArcPad applications.

5.6. DGM system 2

5.6.1. Hardware

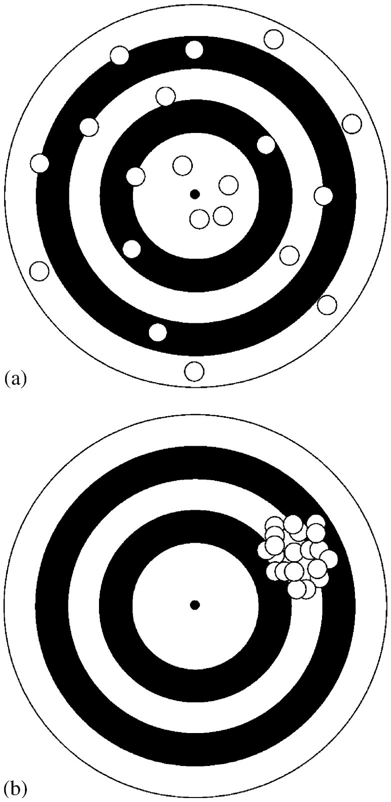
This system is based around the Xplore iX104R (Fig. 1b, Table 3). Like the Recon this Tablet PC conforms to MIL-STD-810F standards for water, dust, and shock resistance. Battery life is specified at approximately 8 h; although in our experience under normal mapping conditions with the GPS connected the average battery life is 4.5 h. The GPS receiver used in this system is a Haicom HI-204S, which is WAAS/EGNOS enabled and has a specified accuracy of 1–5 m (DGPS) (Table 3). The GPS draws its power from the tablet via the USB port.

5.6.2. Software

The mapping software installed on the iX104R tablet is Map IT^{TM}. This is a bespoke DGM software application which has been developed in collaboration with Terra Nova (De Donatis and Bruciatelli, 2006). Unlike ArcPad, Map IT^{TM} is a fully functioning, stand-alone GIS mapping package with all the functionality and capability of a desktop GIS such as ArcGIS. It has been designed specifically for the Tablet PC and thus makes full use of the "digital pen".

5.7. Trimble GeoXT

The GeoXT is an integrated GPS and PDA unit ruggedised to IP54 standards of water, dust and

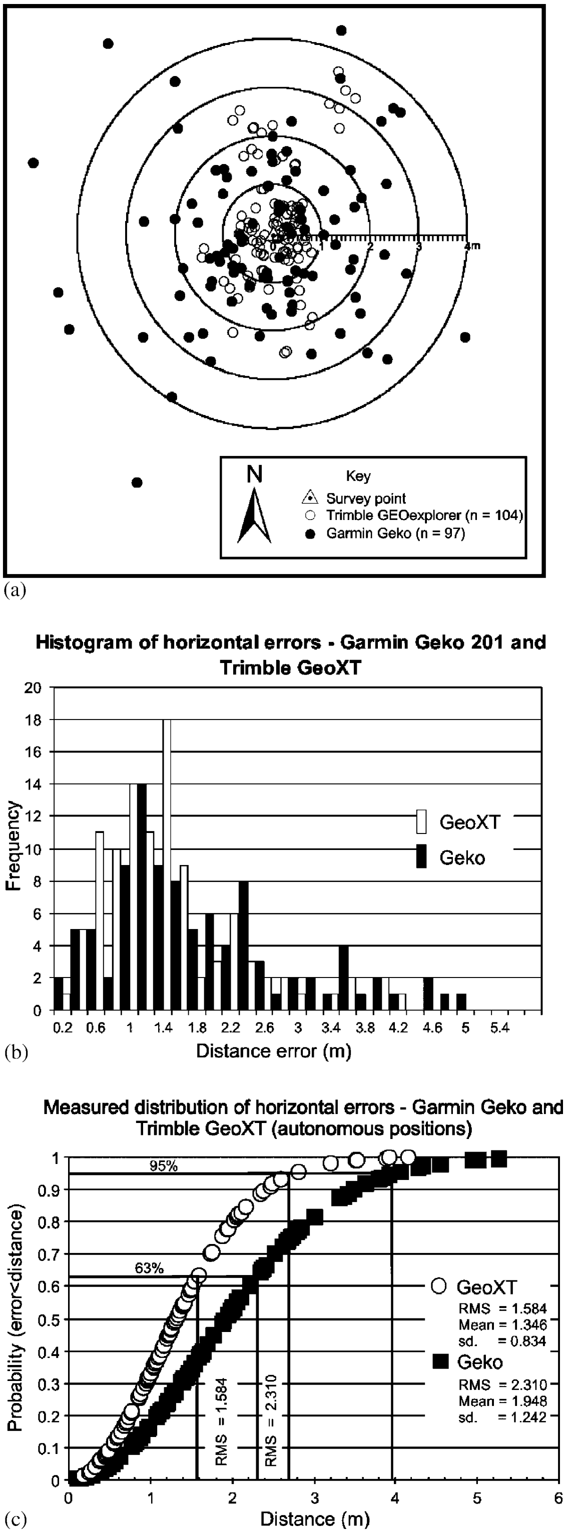


(a)

(b)

Fig. 2. Accuracy versus precision: (a) GPS positions relative to true location (centre of target) show high accuracy and low precision and (b) GPS positions relative to the true position show high precision, but low accuracy.

shock resistance (Fig. 1c, Table 3). Autonomous positions have an accuracy of 1–3.5 m, while DGPS accuracies of <1 m are achievable (Table 3). In addition, an external beacon receiver (“Beacon-on-a-Belt” or “BoB”) can be attached which will provide correction data that can be post-processed to achieve an accuracy of 10–20 cm. This requires the installation of GPSCorrect™ software on the GeoXT and post-processing of the data using Pathfinder Office™ on a PC. If these levels of accuracy and portability are required this is an excellent system. However, it is a relatively costly alternative (Table 3) and the speed of the processor is slower than that of the Recon. This can cause



(a)

(b)

(c)

Fig. 3. Accuracy plots for the Garmin Geko and Trimble GeoXT: (a) plan view of recorded GPS positions relative to a known point collected over a fifty day period, (b) histogram showing horizontal errors in metres of GeoXT and Geko GPS positions and (c) probability vs. distance plot for GeoXT and Geko GPS positions.

quite long delays while the screen updates, especially when mapping onto raster images such as base maps or aerial photographs. In this respect, it is probably more suited to simple data collection tasks where accurate GPS positioning is required rather than a full DGM project.

6. Field assessment

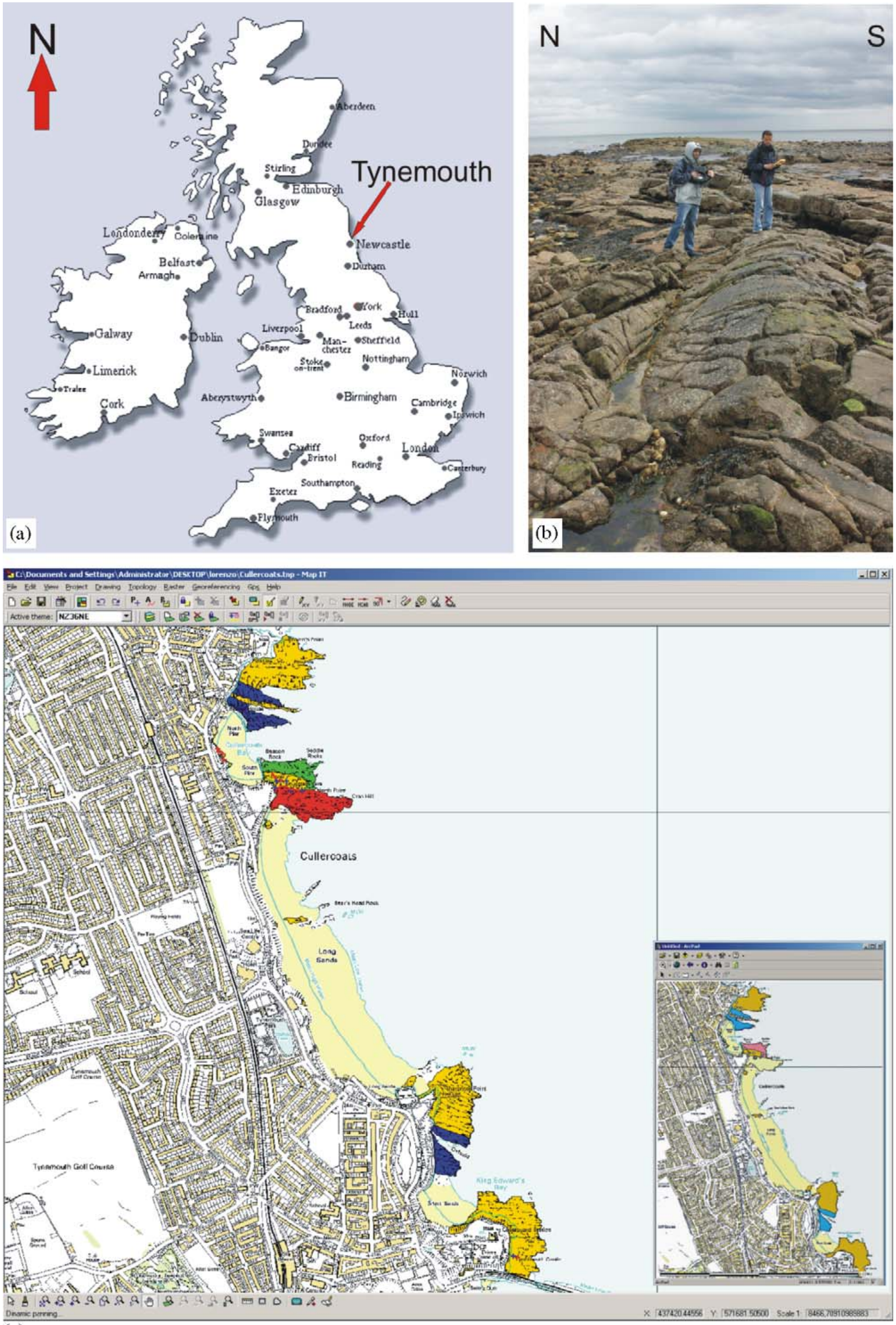
We tested the suitability of each system using the criteria given in Table 1 by mapping a section of well-exposed outcrops of deformed Permian and Carboniferous sedimentary rocks at N. Tynemouth on the coast of NE England, near to Newcastle (Fig. 4a–c). Here, the outcrops offer a sequence of easily identified, distinctive lithological units which are deformed by a number of different structures (e.g. faults, folds and fractures), which we felt would serve as a suitable test of system performance, and provide us with the necessary user-experience and personal impression of each system. The findings of the field assessment are presented below and summarized in Table 4.

6.1. Hardware

- *Portability*: The extra external and internal protection required to meet the MIL-STD-810F standards have added both weight and bulk to both units when compared to more conventional PDAs and tablets (Table 2). Despite this, both are well-designed and relatively easy to carry in the field. The relatively small size of the Recon allows it to be stowed easily when not required or when both hands are needed on difficult terrain. The iX104R tablet is by necessity larger and heavier than the Recon. The carrying system provided by the manufacturer, though adequate, is not particularly well suited to outdoor work, and is not well designed for mapping, where the user may make regular measurements and often needs both hands free for security on steep ground.
- *Performance*: The two systems are vastly different where it comes to performance. The iX104R tablet is a fully specified PC, which can be purchased in a variety of configurations depending on the available budget and or the requirements of the user. The Recon, although relatively well specified for a PDA, lacks the processing power, memory and storage capacity compared to the iX104R. This becomes apparent when attempting to view large files such as aerial/satellite images and raster maps. The iX104R handles these with ease whilst the Recon may take several minutes to initially display an image, and redraw times are slow. This, coupled with the small screen size of the Recon can be very frustrating for the user while waiting for data to load and display during scrolling of the screen. The large, bright screen of the iX104R is comfortable to use and feels more like mapping onto a traditional paper field map. The buttons on both the Recon and the iX104R are well laid out and can be used while wearing gloves. One important issue concerns the use of the digital pen for operating the iX104R. The screen on this particular model is not touch sensitive but uses a special digital pen. Without this, the system is useless, thus the loss of the pen can be catastrophic. With this in mind it is important that a spare pen or pens are carried. In contrast the Recon uses a touch sensitive screen that can be operated by any pointed object (e.g. a pencil).
- *Reliability*: Potential problems with hardware reliability are often cited by those promoting the continued use of traditional geological mapping. Both systems are built to MIL-STD-810F standards and should therefore be suitable for all, but the most extreme conditions. In our test both performed perfectly in typical British spring conditions of rain and wind. The longer-term reliability of each system could not be tested in the short duration of our test period, although both systems are over a year old and have not suffered failure in any of their components.

6.2. Software

- *Operating system*: Map IT and ArcPad are designed to be used with Windows operating systems. Specifically, Map IT runs on Windows XP whilst ArcPad runs on Windows XP and Pocket PC/Windows CE. Neither can be used directly with Macintosh or Linux. An advantage with ArcPad is that although it is specifically designed to run on a PDA it will also run on any PC running Windows XP or XP Tablet. This is a consideration if a combination of PDA's and Tablet PC's will be used during a mapping project.
- *Functionality*: Map IT is a fully functional stand-alone GIS and offers all of the tools available in



(c)

Fig. 4. (a) Map of UK with location of Tynemouth arrowed, (b) inset photograph showing the general appearance of the foreshore outcrops mapped and (c) screen shot of the area mapped displayed using Map IT and the Xplore tablet PC. Inset bottom right shows equivalent area viewed on the Recon PDA running ArcPad.

other desktop GIS such as ArcGIS. In addition Map IT has been specifically designed for *geological* mapping. Therefore it is ready to use "straight-from-the-box" for DGM purposes. Map IT offers the user two levels of operation. The first as a *manager* where all the characteristics and parameters of a project can be set up, and the second as a *surveyor* who physically carries out the mapping. The surveyor works within the bounds of the project interface prepared by the manager. This can provide a simplified user interface for novices or a specific set of data collection tasks, symbology etc. for group use. ArcPad on the other hand is a generic mapping package and requires a degree of customization to optimize it for geological mapping. Although there is a limited degree of customization available within ArcPad itself, to fully manage and customize a geological mapping project requires the additional resources provided by ArcGIS and ArcPad Studio at a considerable cost (Table 3). From this point of view ArcPad is less "straight-from-the-box" ready than Map IT. However, for the advanced user, the combination of ArcPad and ArcPad Studio allows a high level of customization to be undertaken to create a highly tailored mapping system.

Both ArcPad and Map IT allow the user to create point, polyline, and polygon data either manually or using the GPS. For polylines and polygon data GPS vertices can be added individually or in a continuous streaming mode. Both mapping packages allow feature editing in the field. ArcPad supports a limited degree of feature editing; points and vertices on polyline and polygon features cannot be dragged to new locations, but can only be moved to a new position by entering the x,y,z values of the new position or by the using the current GPS position. Feature attributes e.g. strike and dip etc. can be edited quickly and simply within the appropriate features attribute table. As would be expected from a fully functional GIS Map IT allows full editing. The use of specific feature symbology is an important issue when mapping. It is possible to define and use specific feature symbols within Map IT and ArcPad, however, a number of problems occurred where symbols failed to be correctly shown in ArcPad. User defined forms for the rapid

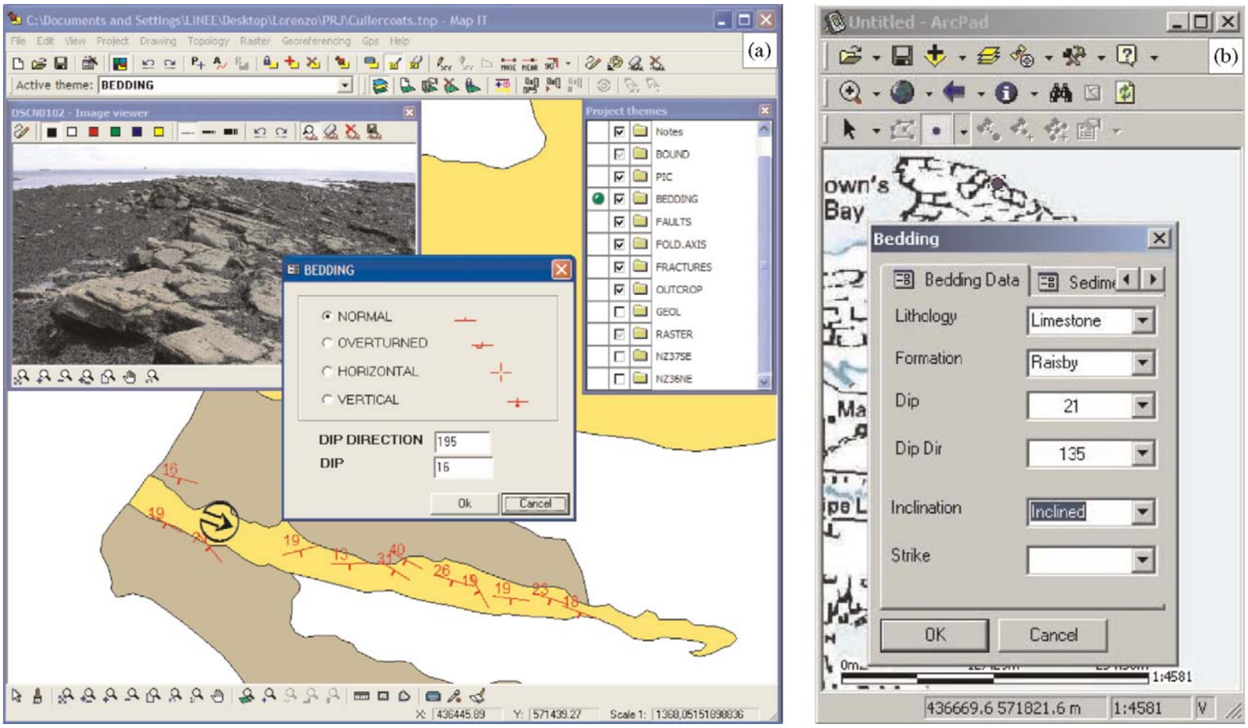


Fig. 5. Screen shots of (a) Map IT and (b) ArcPad showing general layout of working area and customized forms used for recording feature attribute data.

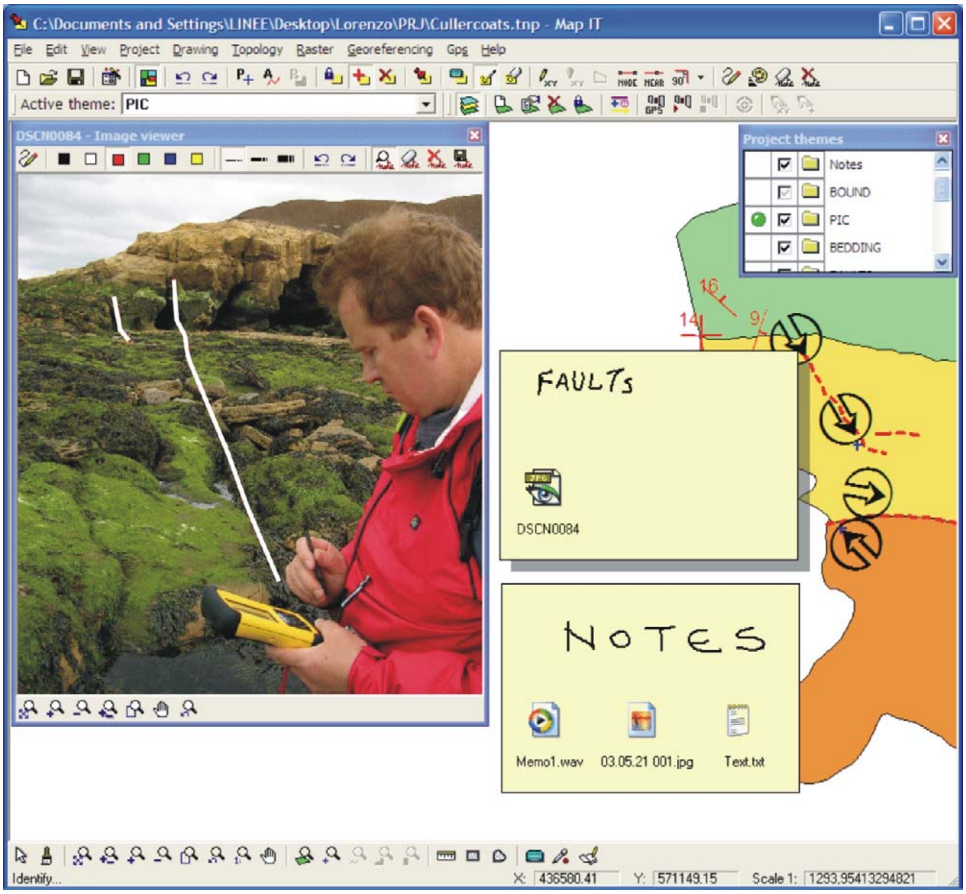


Fig. 6. Screen shot of the "Easy Note" resource available in Map IT. Two "Easy Notes" labelled "faults" and "notes" have been linked to the recorded feature. The note labelled "faults" contains a .jpg image file (shown on the left). This image has been annotated to show two faults (highlighted). The note labelled "notes" contains a video .wav file, a .jpg file and a text file. All are fully georeferenced within the project.

recording of feature attribute data can be created in both packages (Fig. 5).

Several innovative features within Map IT allow the user to map in a more traditional way than is possible with ArcPad. Easy-Note is a georeferenced, electronic version of a Post IT note. The geologist can create an Easy-Note at any time during mapping (Fig. 6). Any type of file can be attached to the note using "drag and drop". Digital photographs of outcrop features etc. can be annotated using the digital pen. The software uses the time and date stamp from the exif file of each image to synchronize it with the GPS location at the time the image was taken, and thus georeferences the image. Sketches and annotations using the digital pen can be made on any other raster data within the mapping project. Whilst it is possible to perform similar tasks within ArcPad, there are no dedicated tools for these tasks and the limitations imposed by the storage capacity and screen size of the PDA make this a more difficult operation.

- *Usability*: Map IT and ArcPad both use an icon-based system for most commonly used functions and thus will be familiar to the majority of users. The Map IT user interface is generally well set out although the large number of buttons on the screen may be daunting for new users. However, it is designed to be used with a digital pen without the need to open menus or use a keyboard, and toolbars can be hidden as required. The digital pen also allows the user to write and draw as they would on a conventional paper map or notebook. ArcPad on the other hand, due to the reduced screen area compared with the Tablet PC, has fewer buttons, but utilizes drop-down menus. Toolbars can be edited to show those buttons, which are most frequently used, and can be hidden when not needed. Although the ArcPad interface is generally good, some functions can be difficult to find, and the installed help files are very limited.

- *Project setup*: This is a crucial stage in any digital mapping campaign. As a stand-alone GIS package the advantage of Map IT is that the entire project set up, management and final map production is undertaken in a single application. ArcPad requires that the greater part of the project set up and management is undertaken in ArcGIS, with additional customization carried out using ArcPad Studio. All the required project files are then transferred to the PDA to run within ArcPad for data collection. Once mapping is complete the files are then transferred back to ArcGIS for display, analysis and map production. This is quite a cumbersome process and can lead to errors during transfer, such as overwriting newer files with older ones. The full GIS capability of Map IT also allows the user to add additional material to a project without needing to return to base e.g. non-georeferenced raster images can be georeferenced in the field and added as a new layer in a project, something which is not straightforward within ArcPad.
- *Compatibility*: Map IT supports a wide range of vector and raster formats including: ESRI shapefile, UNGENERATE, ArcInfo, AutoCad, DWG/DXF, MapInfo, NTFcadastral, Tiff, BMP, JPG, GIF, PNG, MrSID and ECW. ArcPad on the other hand is much more limited in the file formats it supports. ESRI shapefiles are the only vector data format that is supported, while raster files are limited to JPG, MrSID, BMP and CADRG. File formats that are not directly supported by ArcPad must be converted into usable formats by the wide range of tools available in ArcGIS. This reliance on conversion within ArcGIS places severe limitations on which data can be added to an ArcPad project whilst in the field.
- *Reliability:* During the test both ArcPad and Map IT performed well, with no crashes of the software. However, ArcPad has a tendency to ''hang'' occasionally. This appears to be due more to the limitations of the memory in the PDA rather than a problem with the stability of ArcPad. On such occasions it is necessary to perform a ''soft'' reset on the PDA. Although not an issue directly related to the reliability of the software, those involved in digital mapping should save their data regularly. In the case of ArcPad running on a PDA, data should ideally be saved to non-volatile memory so it is protected in case of power failure. On some PDA's (not the Recon) the default folder for the ArcPad software is not non-volatile. In these cases, battery failure will lead to loss of the ArcPad software, which will need to be re-installed. Another important component when looking at reliability is the support and backup package offered by the manufacturer. ArcPad and the associated suite of Arc products are produced by ESRI. They provide a wide range of support services including user forums, discussion groups, software updates and online training for many of their packages. This provides the user with a vast resource, although at times it can prove time consuming to locate the required information. Map IT on the other hand lies at the opposite end of the support spectrum. As a new and small company it is possible that any problems or questions are likely to be answered more quickly. In addition the greater likelihood of direct contact with users may provide an enhanced environment for software development and evolution.

7. Conclusions

From a broad general perspective based on the critical criteria listed in Table 1 both the systems assessed in this paper performed extremely well and dispel many of the issues raised by DGM sceptics. The Recon PDA and Xplore iX104R tablet are well built, rugged and easy to operate. Map IT and ArcPad are well designed, generally stable and offer the user a broad range of mapping tools and functions. However, for the specific purpose of outcrop (''green-line'') mapping, the combination of iX104R tablet and Map IT was found to be the most suitable and most capable DGM system of the two. The iX104 tablet with Map IT software provides the geoscientist with a mapping experience, which most closely matches that provided by traditional paper-based mapping. The ''Easy Note'' facility and the ability to annotate photographs, draw sketches and make handwritten notes which are all georeferenced is not only extremely useful, but importantly provides the user with a familiar environment within which they can make the transition from paper to digital mapping.

Additionally, the greater processing power and storage capacity of the tablet allows the user to store and carry large volumes of supplementary data in the field, where it can be consulted as required. The functionality, usability and flexibility provided by Map IT combined with the processing and storage capacity of the Tablet PC allows the iterative process of observation and interpretation crucial to good geological field mapping to be followed in DGM methodologies.

Despite the fact that the Recon/ArcPad system was at times frustratingly slow, and the smaller screen required much scrolling to see the whole map, it was still possible to use the system for outcrop mapping, albeit in a less flexible manner than when using the tablet. The lightweight and compact size proved particularly beneficial when moving on difficult ground, as the unit can be easily slipped into a pocket or carrying pouch. Therefore, although the PDA-based system can be used for outcrop mapping, it is generally more suited to relatively simple mapping tasks such as sampling surveys. Where portability is critical (e.g. very remote areas where equipment must be carried in), the lightweight and small size of the PDA-based system may outweigh the limitations mentioned above.

From a software point of view, although the out-of-the-box usability of Map IT is superior to that of ArcPad, by using ArcPad Studio it is possible to develop fully customized mapping packages designed for specific user groups and tasks. This provides the user with a highly flexible development package that possibly makes it more suitable for large organizations where there are a broad range of tasks to be undertaken and dedicated IT development staff are available.

One critical factor, which may be the greatest influence on choice for some users is cost. Both the systems assessed are relatively expensive (Tables 2 and 3). It is possible to use cheaper hardware options (Table 2), particularly PDA's, but it should be remembered that these cheaper options are not designed nor intended to be used in hostile environments. The cost of the equipment has to be carefully weighed against the often much larger cost of repeating fieldwork due to equipment that has failed because of the rigors of fieldwork.

Although there is a general trend for consumer electronics to become progressively cheaper, this does not necessarily apply to more specialised equipment. While laptops, PDAs and Tablet PCs have all dropped in price over recent years, ruggedised systems remain expensive. In addition, upgrades in performance are relatively slow to reach the market when compared with un-ruggedised off-the-shelf systems. Nevertheless, developments in computer technology advance at a rapid pace. What was considered to be state-of-the-art can quite quickly become ordinary or obsolete. What was once very expensive, becomes increasingly less so as newer models are introduced. Therefore, the information and conclusions presented here are just a snapshot in the continuing development of DGM technology.

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