MODERN GEOLOGIC MAPPING

THE CONCEPTUAL DEVELOPMENT AND PRACTICAL REVIEW OF A DIGITAL GEOLOGIC MAPPING APPROACH

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Tilmann Jenett

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Für meine Eltern und meine Brüder

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KURZZUSAMMENFASSUNG

Die Geologie hat in den letzten Jahrzehnten eine starke Entwicklung und Modernisierung erfahren. Verbesserte analytische Methoden und die Entwicklung von fortschrittlichen flugzeug- und satellitengestützten Technologien erlauben, die Erde heute wie niemals zuvor zu beobachten und zu studieren. Hingegen sind die Methoden und die Ausrüstung für die geologische Geländearbeit annähernd unverändert geblieben (McCaffrey et al., 2005), wenn man von der weit verbreiteten Nutzung von satellitengestützten GPS-Empfängern absieht.

Folglich gibt es oftmals eine klare Diskrepanz zwischen dem Sammeln von Geländeobservationen und der Möglichkeit, diese mithilfe von neuen Entwicklungen und Technologien – z.B. durch die Integration in ein GIS – zu interpretieren. Diese verzögerte Integration der Geländedaten in einen effizienten Interpretationsablauf ist nicht nur sehr zeitaufwändig, sondern vermindert auch gravierend die Qualität der finalen Ergebnisse, da Unklarheiten bezüglich der Geländearbeit oftmals nicht mehr vom Schreibtisch aus beantwortet werden können.

Obwohl das Potential von verschiedenen mobilen GIS-Ansätzen für die Modernisierung der geologischen Geländearbeit zunehmend in wissenschaftlichen Publikationen untersucht wird (Soller, 2000-2012; McCaffrey et al., 2005; Clegg et al., 2006; De Donatis and Bruciatelli, 2006; Jones et al., 2009), bleibt dies doch ein neues wissenschaftliches Feld, das sich kaum auf Langzeit-Tests unter realen Projektbedingungen stützen kann und dem daher erfahrungsgemäß eine Zahl von Geowissenschaftlern mit Skepsis gegenüberstehen.

Um diesem Defizit entgegenzuwirken und die Diskrepanz zwischen traditioneller Geländearbeit und neuen digitalen geologischen Kartiermethoden (DGM) im Sinne von Clegg et al. (2006) zu verringern, präsentiert diese Doktorarbeit einen neuen DGM-Ansatz. Dieser ist, ausgehend von einem in den Grundzügen vorhandenen System, das Ergebnis der kontinuierlichen Analyse und Auswertung von verschiedenen geologischen Großkartierungen der letzten acht Jahre. Die unterschiedlichen Voraussetzungen dieser Kartierungen und die verschiedenen Entwicklungs- und Anpassungsstadien des Ansatzes bilden dabei eine praktische Basis für die sachdienliche Beurteilung von DGM-Methoden im Allgemeinen und – im Hauptteil dieser Arbeit – für den beschriebenen Ansatz im Speziellen.

Diese Arbeit beinhaltet die konzeptionelle Weiterentwicklung eines maßgeschneiderten, mobilen geologischen Informationssystems, das GIS-Funktionen mit einem GPS-gestützten digitalen Feldbuch kombiniert. Durch die Verwaltung von Datenimport und -export einer relationalen Datenbankstruktur kann das System mehrere Nutzer verwalten, die mit mobilen und stationären Geräten Geländedaten aufnehmen. Die Möglichkeit, iterativ Geländedaten zu erheben und diese direkt vor Ort in einem zweckdienlichen mobilen GIS zu interpretieren, erlaubt eine effiziente Nutzung der Zeit im Gelände. Durch den Zugriff auf zusätzliche Informationen während der Geländearbeit wird nicht nur die Qualität der Interpretation erhöht, sondern auch die digitale Datenintegration für die spätere Weiterverarbeitung verbessert.

Neben einer Erhöhung der Interpretationsqualität zeigt die vorliegende Arbeit außerdem, dass sich in Abhängigkeit von der Kartierungsdauer auch die benötigte Zeit und die Kosten im Gegensatz zu konventionellen Kartierungsansätzen reduzieren lassen.

Es wird festgestellt, dass der entwickelte DGM-Ansatz im Sinne von McCaffrey et al. (2005) zu einer deutlichen Verbesserung des gesamten Ablaufs von geologischen Kartierungen beiträgt und dass DGM-Methoden im Allgemeinen ein hohes Potential haben, die geologische Geländearbeit zielführend zu unterstützen.

ABSTRACT

Geology as a science has seen a strong development and modernization over recent decades. Improved analytical techniques as well as the interpretation and the development of more advanced airborne and satellite techniques now allow scientists to observe the Earth as never before. At the same time the techniques and equipment for geologic field work have largely remained unchanged (McCaffrey et al., 2005). Here, the widespread use of satellite GPS receivers probably constitutes the only exception.

Consequently, there is often a clear gap between the collection of observational data in the field and the interpretation of these data with new GIS developments and technologies that are available today. The postponed integration of observational data into an efficient interpretation workflow is extremely time-consuming – even worse, it reduces the quality of the final results as questions coming up after fieldwork frequently cannot be answered anymore from back in the office.

Although the potential of various mobile GIS solutions for the modernization of geologic field mapping has already been discussed in several publications (Soller, 2000-2012; McCaffrey et al., 2005; Clegg et al., 2006; De Donatis and Bruciatelli, 2006; Jones et al., 2009), it remains a relatively new scientific field with just a few long-term tests under realistic project conditions and is, thus, often viewed skeptically by geoscientists.

Responding to this deficit and narrowing the gap between traditional fieldwork methods and new digital geologic mapping (DGM) techniques as defined by Clegg et al. (2006), this thesis aims to present a new DGM approach. Developed from an already existing basic system, the approach is the result of the analysis and assessment of various geologic mapping campaigns carried out over a period of eight years. The changing preconditions of these projects and the various development and adaptation stages of the approach form a practical basis on which a pertinent review of new DGM methods in general – and the presented approach in particular – is built as the main part of this thesis.

The thesis describes the further conceptual development of a tailored mobile geologic information system merging desktop GIS functionalities with a mobile GPS-linked digital field book. The system can handle multiple users collecting field data

with mobile and stationary hardware units by managing the data input and output of a relational database. The possibility to iteratively collect observation data and interpret them with a convenient mobile GIS system directly on the spot allows for a very efficient use of field time: The access to additional information during field work considerably raises the quality of the interpretation. In addition, the digital integration of data into further processing steps is improved.

The presented study also points out that, apart from quality improvements, time and cost efforts of geologic mapping can be reduced in direct comparison to conventional mapping methods as a function of the survey length.

In concluding, it is stated that the developed DGM approach improves the overall workflow of geologic mapping campaigns as defined by McCaffrey et al. (2005) and that DGM methods generally provide a high potential to support geological field work in a fast and efficient manner.

1 INTRODUCTION

1.1 Background and Scope of the Study

"No geologist worth anything is permanently bound to a desk or laboratory, but the charming notion that true science can only be based on unbiased observation of nature in the raw is mythology. Creative work, in geology and anywhere else, is interaction and synthesis: half-baked ideas from a bar room, rocks in the field, chains of thought from lonely walks, numbers squeezed from rocks in a laboratory, numbers from a calculator riveted to a desk, fancy equipment usually malfunctioning on expensive ships, cheap equipment in the human cranium, arguments before a road cut (Gould, 1987)."

This aptly put quote not only reflects the need of geologic science to go beyond one-dimensional working approaches, but further shows up the necessity of an efficient and convenient approach that allows the organization and interpretation of manifold scientific information from various origin in support of geologic mapping. Today developments in the fields of advanced GIS and mobile computing offer a variety of possibilities that could theoretically cope with this task, but their efficient implementation into extensive geologic mapping campaigns remains isolated. In this context the motivation of the submitted thesis is to analyze the potential of DGM techniques and to present a developed new DGM working approach that should help to overcome the needless barriers between new technology and traditional geologic working methods.

The thesis was made possible by the author's involvement in geologic mapping projects carried out between 2003 and 2011 by GAF AG, a Munich based consultancy and provider of geo-information services and products. When the author joined GAF AG in 2004, the company had already recognized the potential of digital methods used in classic geologic mapping. At that time GAF AG was developing a mobile GIS solution for geologic applications called GeoRover XT. In theory the software was designed for being used in any type of geologic mapping project, but until then only short-term tests during small mapping campaigns had been realized.

During his studies at the Freie Universität Berlin – an university that had been active in conducting extensive geologic mapping projects supported by remote sensing and GIS techniques (List, 1999) – the author already gathered some experience in mobile

GIS, remote sensing and digital field work techniques. Therefore, with a strongly developed personal interest in this modern scientific field, the author gladly took the challenge and opportunity to further develop and maturate the existing DGM system conceptually, to maximize its usability on extensive geologic mapping projects and to establish a streamlined working approach built around it, as part of a thesis.

To realize this thesis, the participation in several mapping projects was used to study and analyze the requirements of involved experts, to evaluate and consider the interactions between all participating groups and to further develop the DGM system concept accordingly. The advantage of being directly involved in all working steps of these geologic mapping campaigns, in the field and in the office, made it possible to obtain first-hand information that was used for the design and the final assessment of the approach under practical working conditions.

Three selected mapping campaigns played a major role in the development of this thesis as they represent milestones in the further development of the DGM system and working approach: A geologic mapping campaign in Oman in 2003/2004 can be seen as an initial phase, whereas extensive field work campaigns in Madagascar between 2005 and 2008 were used to adapt the approach to large teams and challenging terrain conditions. An extensive geologic mapping survey carried out in Uganda between 2009 and 2010 was used to further enhance and maturate the approach.

To substantially review the developed DGM working approach, the thesis compares and evaluates in its main part the qualitative and quantitative differences to conventional geologic mapping techniques.

The main objectives of the thesis and the specific work of the author can be summarized as:

1) The **presentation** of accepted modern working methods and tools in extensive geologic mapping surveys *(chapter 1.2).*

2) The **preparation of a catalog of requirements** for a DGM approach considering the needs of all experts involved in modern geologic mapping surveys *(chapter 2.1).*

3) The conducting of several **field work studies** *(chapters 2.3, 2.4 and 2.5)* carried out to:
    a) analyze the **general potential** of DGM techniques.

    b) **test and evaluate the capability** of an existing DGM system to cope with realistic conditions of variable geologic mapping campaigns.

    c) **further develop and improve** the DGM system concept according to the evaluated new requirements.

    d) **organize** the DGM field work of geologists in an efficient way.

    e) **establish a streamlined working approach** built around the improved DGM system, taking all stages of modern geologic mapping into account.

4) A detailed description of key development steps with focus on **specific problems and the identification of solutions** *(chapter* 3*).*

5) The in-depth **review and analysis** of the potential and practical use of the new DGM approach, with strong emphasis on the requirements of field geologists and GIS experts in direct comparison to conventional geologic mapping methods *(chapter 4.1and 4.2).*

6) A **time and cost analysis** of the DGM approach juxtaposed to conventional geologic mapping methods *(chapter 4.3).*

1.2 The Status of Conventional Geologic Mapping

Naturally geologic knowledge is strongly built on observations made in the field. However, the quality of the conclusions drawn from these observations has always been influenced by auxiliary information gained from other disciplines (e.g. chemistry, biology). Additionally, today a tremendous amount of new earth observation data is available from rapidly evolving remote sensing sensors and the last decades have seen numerous new developments in the fields of computer science, computer based information systems, and the internet. All these new possibilities affected the working methods of all geoscientists to some degree and influenced the overall process of geologic mapping already and independently from new DGM methods. Therefore the author prefers the term “conventional geologic mapping” (hereafter abbreviated CGM) to the term “traditional geologic mapping” when referring to modern geologic mapping surveys that do not include DGM methods.

1.2.1 Common Digital Tools and Methods

In the digital age the processes of data acquisition, -processing, -administration and -exchange, being fundamental to all scientific studies, offer numerous new possibilities. As did the industrial revolution 200 years earlier, the digital revolution set a widespread innovation process in motion that is still affecting nearly all spheres of life (Toffler, 1980). Consequently, combined with the coinciding rapid evolution of computer technology, scientific working methods and approaches have repeatedly undergone radical changes.

As analog systems represent information defined by physical quantities that consist of a continuous sequence of values with unlimited intermediate stages *(Precht, 2004)*, a digital system uses discrete values to typify the same information. Although almost all processes in nature can be characterized as analog, discrete values are the major pre-condition for binary sequences and a requirement of any computer-supported system. In practical experience analog data describes information that exists in printed, written or drawn format. This includes for example text pages, maps and photographs. In contrast digital data describes information that has already been transferred into binary code and is editable with a computer system. In order to take advantage of computer technology, information that is not acquired directly in a digital format – which describes the vast majority of older scientific data - has to undergo the process of digitization.

When transferring data from a continuous analog dataset to a digital one limited to discrete values, the quality of the result is a function of the sample rate, which is in turn proportional to the size of the digital output (Figure 1). Although this issue is less problematic when digitizing simple information such as text, it is an issue for raster imagery, particularly when subjected to more complex image enhancement techniques.

The advantages of maintaining data in a digital format are obvious. The data can easily be duplicated, shared without loss of quality and archived without degradation over time with little storage space needed. In combination with the internet it is possible to get instant access to a continuously growing amount of information and powerful research capabilities.

Although the use of digital data is today relatively common in the first world, in many developing countries the data structures date back to the first half of the 20th century and remained in analog format till today. Recognizing the fragility of analog data archives, many countries understand the need to implement a process to compile and digitize their analog data inventory. Therefore this process is often a part of extensive geoscientific projects that developing countries are putting out to tender. Another part is capacity building in the utilization of digital archives and their integration into the World Wide Web, facilitating the integration into the international scientific community.

One of the major developments in the field of geoscientific, computer-based information technology is the establishment of spatial information systems that allow the simultaneous interpretation of geometric information and thematic data (Bill, 1991). In a more generic sense a geographic information system (GIS) can be seen as a tool to manage, edit and visualize digital geospatial data by combining traditional spatial datasets, such as maps, geophysical data and satellite imagery with a database and a data layer editor with geo-referenced coordinates.

A GIS always deals with the processing of three basic types of geographic information and their mutual conversion: Analog data, raster data and vector data (Figure 1). As analog data is the initial non-digital data type, raster data consists of a matrix of numeric values for which each matrix value is related to a rectangular extent with a certain spectral information (Albertz, 2009). Each of these picture elements (pixel), is organized by its unique row and column value and coordinates inside the matrix. This data type is the standard of remote sensing information today. Remote sensing imagery has become a major contributor to the modern geologic mapping data inventory. According to Albertz (2009) remote sensing data is defined as the measurement of reflected or emitted electromagnetic waves at a distance to the measured object. It is primarily linked to subsequent advancements in photography and sensor platforms. The first documented implementation of modern remote sensing techniques into geologic studies dates back to 1940 (Pandey, 1987), whereas first near infrared photographs (VNIR) were already available at the beginning of the 20th century, followed by the active RADAR technique and the recording of thermal infrared imagery (TIR) (Drury, 1987). A major breakthrough was the successful launch of the ERTS-1 satellite in 1972. It gave rise to a series of other satellite launches allocated to the Landsat missions (Elachi and Van Zyl, 2006). Landsat imagery was ever since used in extensive geological mapping, e.g. campaigns in north east Africa carried out by a DFG financed Berlin university consortium (List et al., 1978; List et al., 1990) and the imagery of Landsat 5 and 7 are still broadly used in geologic remote sensing interpretation. The evolution of digital image sensors contributed greatly to the development of new space-borne remote sensing platforms that include modern platforms such as QuickBird, IKONOS and

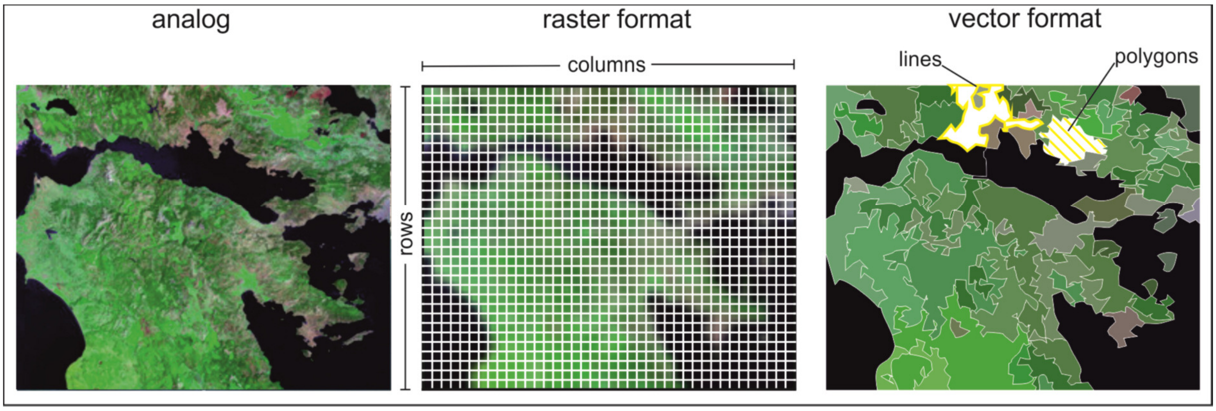


Figure 1: Conversion of an analog information into raster and vector format.
By applying a grid of digital numbers with definable cell size (number of columns and rows equivalent to sample rate); the transfer into vector format (points, lines, polygons) is today done by on-screen drawing from raster images but can be done from the analog original with a digitizing tablet/pen; points, lines and polygons are commonly attributed with text.

WorldView. The success of global digital globes like Google Earth made remote sensing imagery widely accessible and has raised public awareness to the potential of these techniques. It can be assumed that the supportive use of remote sensing data in the geosciences will increase to a great extent in the near future.

Vector data – the third type of data used in a GIS – are normally represented by points, lines and polygons. Points are connected to form lines and lines can be connected to form areas or polygons. The easiest underlying model for the creation use of vector data is known as the "spaghetti model" (Bonham-Carter, 1994), not considering any topology. However, in geologic studies more complex topological relations are needed to define commonly used features such as lithological boundaries belonging to two bordering polygons or an intersection point of two fault planes.

The evolution of GIS up to the end of the 20th century has been divided by Bartelme (1995) into five phases: a phase of pioneers (1955-1977), a phase of public authorities (1970-1985), a phase of companies (1982-1990), a phase of users (1988-1995) and a phase of an open market for geoinformation (since 1995). This evolution runs parallel to developments in computer technology and the society's acceptance and use of it. The emergence of web-based GIS can be seen as a new, sixth phase that has increased in importance during the last years (Figure 2). This modern phase deals with the transition from an expert technology, mainly restricted to government and industrial agencies, to a public technology (Goodchild, 2007). Whereas the software applications and data processing were initially limited by the capacity of the computer hardware, the rapid expansion of computing power means that today complex processing can be done at home and even on mobile devices by public users and distributed via the internet.

Recently introduced terms in literature and the internet like "neogeography" (Turner, 2006) or "volunteered geographic information" (Goodchild, 2007) that are exemplary discussed in Elwood (2009), describe a phenomenon that is affecting particularly the geosciences but society's understanding and use of the internet in general, combined under the keyword "web 2.0" (Hendler and Golbeck, 2008). A huge amount of data can nowadays be created, but standards are lacking and it is difficult to evaluate the data quality. Where this route is taking the modern geosciences is currently the subject of many discussions (Elwood, 2009; Goodchild, 2009; Hudson-Smith et al.,

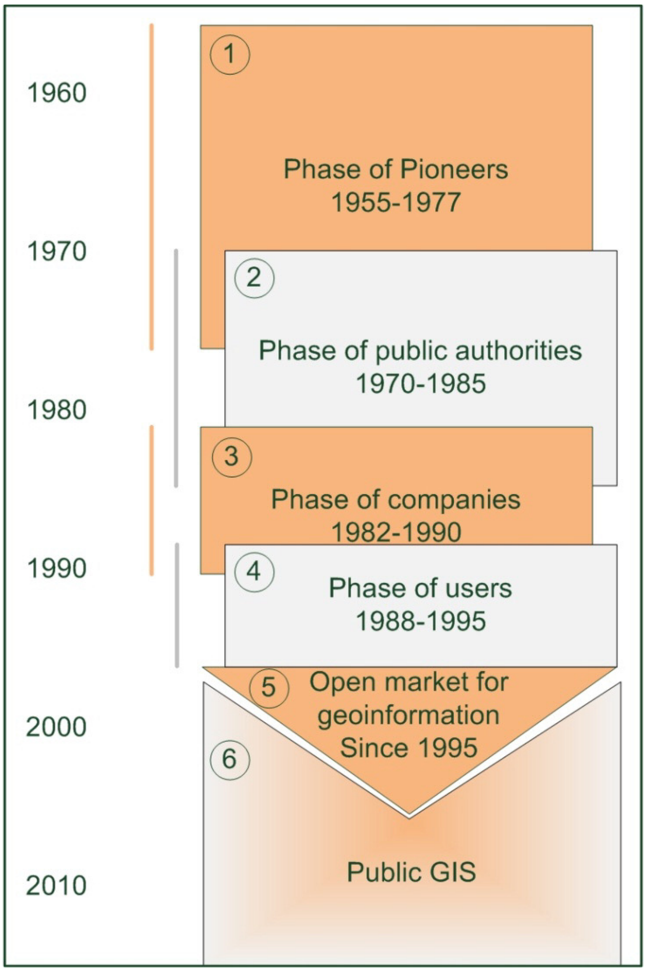


Figure 2: Five phases of GIS evolution (Bartelme, 1995) with a sixth phase of GIS as a public technology usable by anyone (Goodchild, 2007).

2009; Schuurman, 2009) and it seems evident that there is still a need for GIS applications in which the quality of the input can be controlled and evaluated in order to be able to work scientifically substantiated. One step in this direction is the aim of geologic surveys and agencies to homogenize their geologic data portfolio by the use of database management systems (Van Gasselt and Nass, 2011) like the National Geologic Map Database Project (NGMDB) described by Soller and Stamm (2008).

Digital Geologic Mapping Techniques

Digital geologic mapping (DGM) as “the process of mapping and collecting geologic data using some form of portable computer and Global Positioning System” (Clegg et al., 2006) has been the subject of discussions in numerous recent publications by the geologic society over the last fifteen years (Williams, 1997; Soller, 2000-2012; McCaffrey et al., 2005; Clegg et al., 2006; Athey et al., 2008; Jones et al., 2009; Whitmeyer et al., 2009; Whitmeyer et al., 2010). Whereas the advantages of GIS are widely accepted, the establishment of digital field work techniques is still in its infancy without developed hardware and software standards. The most important publications dealing directly with mobile digital geologic mapping are those of Carver et al. (1995), McCaffrey et al. (2005) and Clegg et al. (2006) who describe studies from the UK, while the relevant publications from the USA and Italy are those of Whitmeyer et al.(2009; 2010), Clegg et al. (2006) and De Donatis and Bruciatelli (2006). In addition the topic forms a central theme of the Digital Mapping Techniques workshops (DMT), held yearly by the United States Geologic Survey (Soller, 2000-2012) (chapter 4).

Most of these publications deal with very specific tests of unique hard- and software combinations under various conditions. Whereas Carver et al. (1995) discussed the advantages and disadvantages of digital geoscientific field work, Clegg et al. (2006) specifically contrasted the usability of PDAs and tablet PCs in combination with various software solutions in geologic field work. De Donatis and Bruciatelli (2006) focused on detailed insights into digital geologic mapping work with particular reference to the workflow of the MAPIT software. The main interest of Mccaffrey et al. (2005) was the streamlining of a digital work flow in geologic projects and additionally the provision of an outlook on possible future developments, including for example the possible use of 3D applications. Whitmeyer et al. (2009) highlighted new digital possibilities that emerged from various student projects and evaluated the links between professional requirements and the developments of virtual globes and other new public domain tools (Whitmeyer et al., 2010). Particularly in the actual proceedings of the DMT workshops since 2008, the need for digital mapping technology is discussed more often, e.g. Athey et al. (2008) critically discussed the advantages of digital techniques for a modern geologic survey.

All authors point out the big advantages of modern DGM techniques in relation to their specific test environments and strongly support the new methods in general. Especially the fast and easy integration of field observation data into a GIS environment is seen as an improvement as is the availability of additional information in the field, an increased spatial accuracy and the streamlined digital project workflow (McCaffrey et al., 2005). Specific tests of software and hardware solutions show that a lot of the geologic working methods can be directly transferred into a digital work flow, helping to improve the data management significantly (De Donatis and Bruciatelli, 2006).

However, some disadvantages are laid open that are mainly in the nature of a digital work approach. For most authors the hardware systems are critical regarding battery lifetime, screen size and readability, complex data entry without mouse and keyboard and the costs. The latter is also discussed in combination to the time needed to get used to a new working method (Whitmeyer et al., 2010).

In general DGM methods are seen as the next logical step in the development of modern geoscientific work and in that context this thesis is meant to provide the community with the DGM experience of various projects and with work flow solutions that are born and improved by practical experience.

1.2.2 Modern Geologic Mapping

Geologic mapping is normally composed of three principle working steps, which in the "Guidelines for the Compilation of Geologic Maps" (Schwarz et al., 2004) consist of a) a preparation or compilation phase, b) a field work phase and c) a final production phase. All phases have seen a remarkable change over the last decades, not so much affecting the general workflow of geologic mapping as such, but the technical status of it. As described in chapter 1.2.1, today a huge amount of digital tools and ancillary data is at hand and widely used in all phases. Based on the experience gathered during the collaboration with international geologic surveys, the most commonly accepted modern procedures and datasets are briefly presented in the following paragraphs.

Scientific Data Preparation

Data compilation covers today a mix of digital and analog data (Figure 3). In many cases analog data, for example paper maps, written reports and scientific papers and field notes form the bulk of the material at the start of any project. To manage these data within a GIS environment the analog data has to be digitized and stored in a useful database format. In this environment these data must be geographicly referenced to take advantage of the GIS technology. Although a lot of national surveys can nowadays provide this digital information off-the-shelf, the quality, completeness and overall usability vary strongly over the world. Especially in developing countries analog data often forms the vast majority of an archive. Therefore the digitization process can use up a serious amount of time and produce remarkable costs during the scientific preparation of a project. In addition to the collation and preparation of analog and digital data, one must also consider the selection and preparation of suitable remote sensing data. This could include for example aerial photographs, or satellite and geophysical data. Raw satellite and geophysical data often need further processing to yield useful images but can strongly contribute to the geologic understanding of a working area. Satellite data is recorded either with optical passive sensors or active RADAR sensors that are able to collect data over a wide range of wavelengths. Once the right spectral data are selected the image products undergo enhancement techniques to deliver the best results for the specific working area.

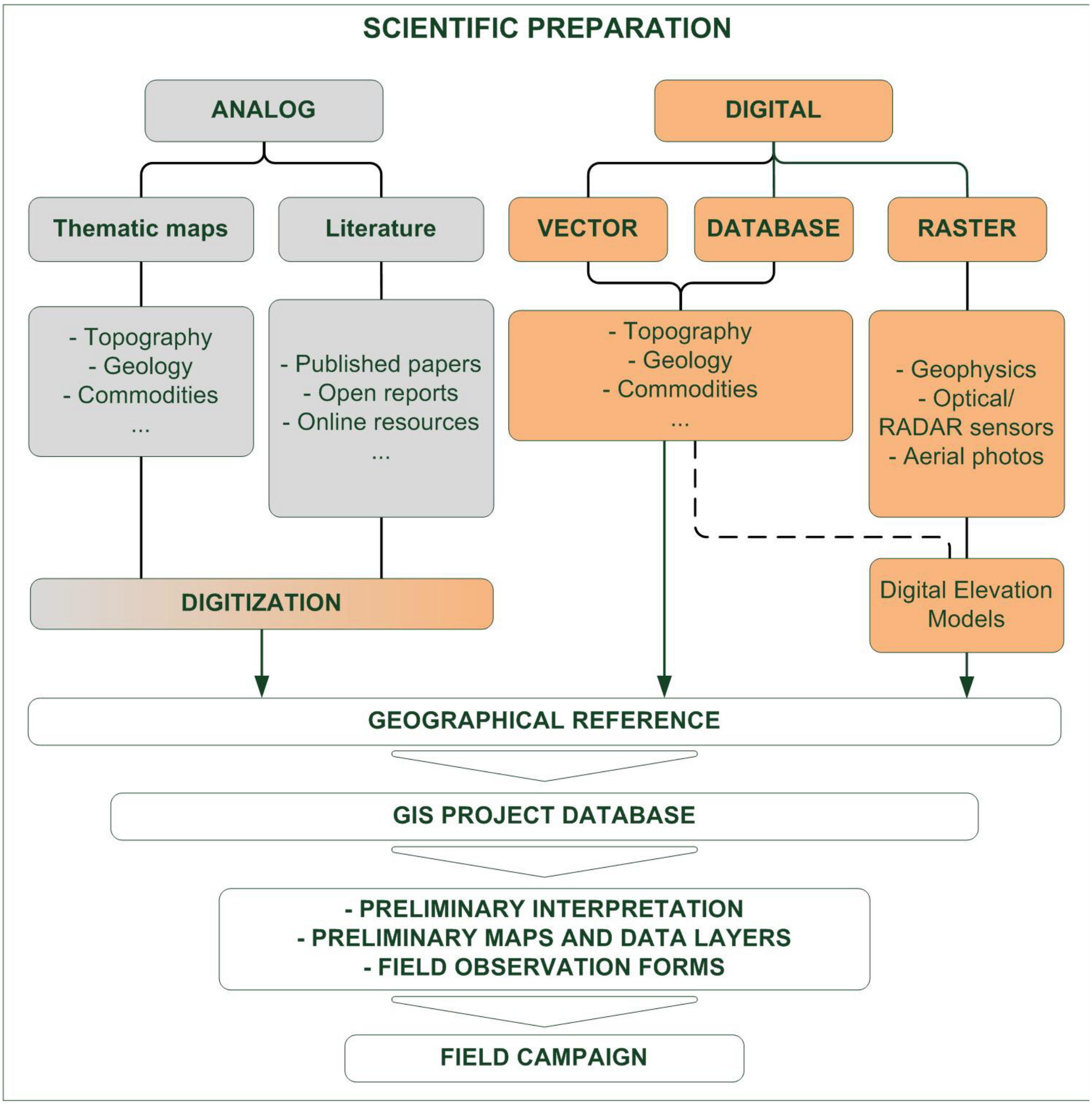


Figure 3: Scientific preparations of modern geologic mapping projects.
Combination of analog (grey) and digital data (orange) in a GIS database is followed by interpretation and preparation for field work.

Depending on the mapping scale aerial photographs in addition to satellite imagery can be of use although often not available for large areas in extensive mapping campaigns. The high requirements to precision can be met today with digital photogrammetric methods and the stereoscopic, three-dimensional interpretation of photos through computerized anaglyphic imagery has advanced.

Geophysical data is of high value for geologic mapping and has seen a huge increase in its extensive acquisition over the last decade. The data are collected from airborne surveys and commonly magnetic and radiometric data are used for geologic interpretation. Magnetic datasets reflect rock magnetite composition and can be used to define lithologic units, but given the penetrative nature of these data, they are equally useful to measure particularly structural trends of rocks covered by more recent sediments. Radiometric data reflect the U-TH-K composition of the surface and can be related to the composition of the surface units. Geophysical imagery is normally delivered in grid format and commonly needs further treatment to get the most visually useful product.

Topographic data is another fundamental dataset for geologic mapping. Apart from classic land survey maps, topographic information can be obtained today from digital elevation models (DEM) generated for example by the Shuttle Radar Topography Mission (SRTM). Depending on the spatial resolution, these datasets can provide a detailed virtual preview on the field area by creating digital terrain models (DTM). DTMs are excellent datasets for observing geomorphologic features.

Structural data – or any other geo-referenced information layer – can be draped over a virtual surface defined by the DTM. This provides a 3 D visual basis from which to view the study area. GIS technology further grants the possibility to intersect various thematic overlay layers and to merge useful information (e.g. a geologic map and radiometric signal) to create the best basis for interpretation and discussion.

A preliminary interpretation of the available data is a common output of the preparation phase of many projects. Such an interpretation provides ideas as to the geologic setting of the study area, and to particular areas that may need more attention. In this context provisional maps are normally produced that show specific useful combinations of data that can be updated during field work. These preliminary interpretation maps provide a basis of discussion and are used as a common basis of interpretation for the field teams, from where to start the field mapping campaign.

Technical and Logistical Preparation

Logistical preparation refers today as it did in the past, mainly to the facilitation of the transportation and accommodation needs of the project (Figure 4). However, it also includes facing security and local judicial concerns, issues closely connected to the communication with local officials and administrative authorities. Whereas the transportation, accommodation and safety issues have always been part of a survey's preparation, there are a few things that have to be considered additionally in modern projects. Apart from standard geologic equipment modern mapping campaigns commonly require additional equipment. For orientation in the field, hand-held GPS devices became common, as arguably did cell phones become a standard for communication in the field. In most parts of the world a mobile network exists in the more populated areas. However, when mapping in remote areas, satellite phones are more applicable. Like mobile phones, they can be also used to transfer a reasonable amount of data nowadays directly or when used as a modem on a laptop.

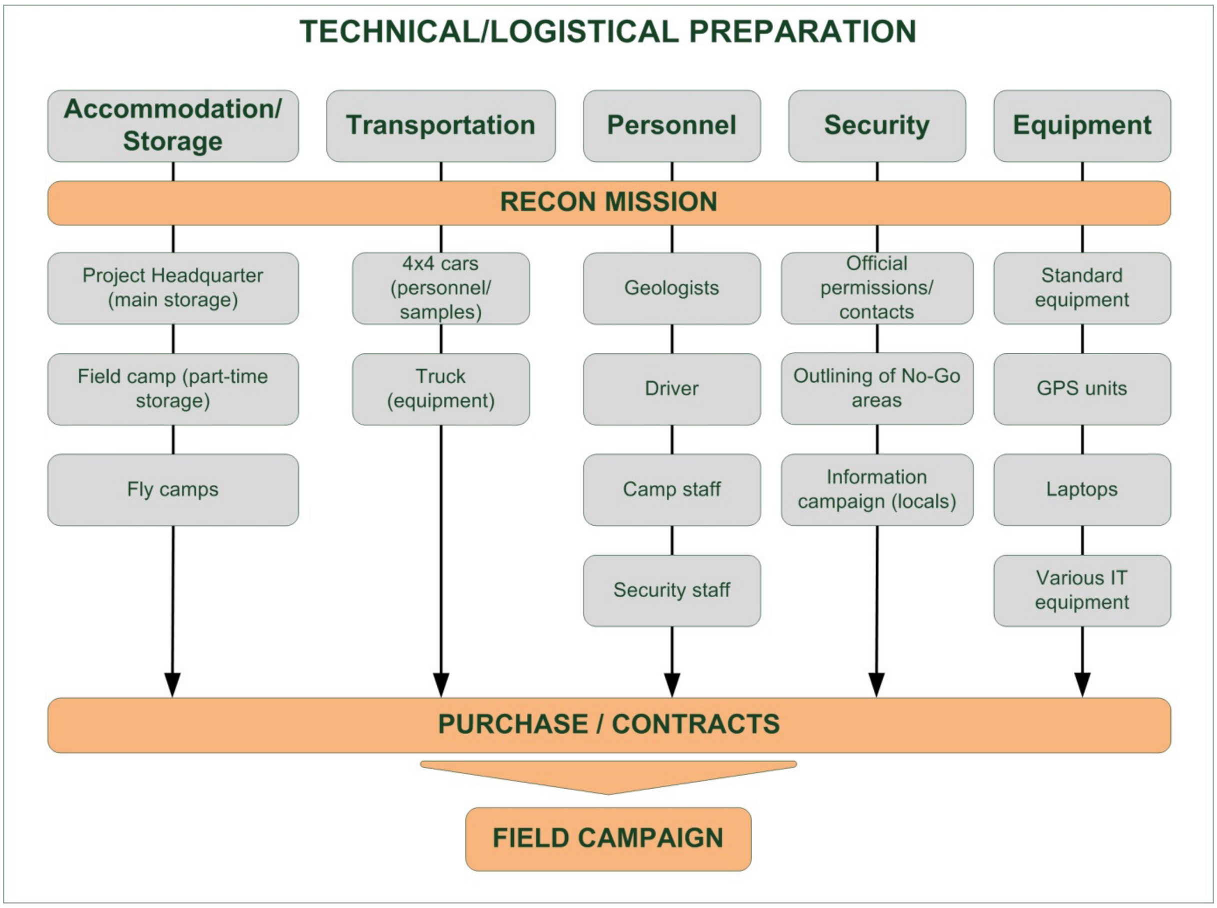


Figure 4: Exemplary list for technical and logistical preparations of modern geologic mapping projects.

Field Work Data

Various advancements in satellite and computer technology also affected the field data collection of the geologist, most impressively GPS technology, GIS software and digital photography.

To best describe the different effects on field data collection, three basic categories are used, according to Schwarz et al. (2004): First-order observation data describe direct observations and sampling of in-situ rocks. Older data that is directly comparable in terms of quality and methodology (e.g. existing observation points from published geologic maps) falls into the same category. Second-order observation data relate to observations of in-situ or nearly in-situ material such as boulders, cobbles or soil types that reflect the underlying but widely unexposed strata (Figure 5). Finally, third-order observations are gathered from other disciplines such as geomorphology, geophysics or remote sensing (Figure 6). Whereas the first two orders of observation data are undoubtedly the most important basics of geologic mapping, third-order observations are often the only type available in areas with little or no outcrops.

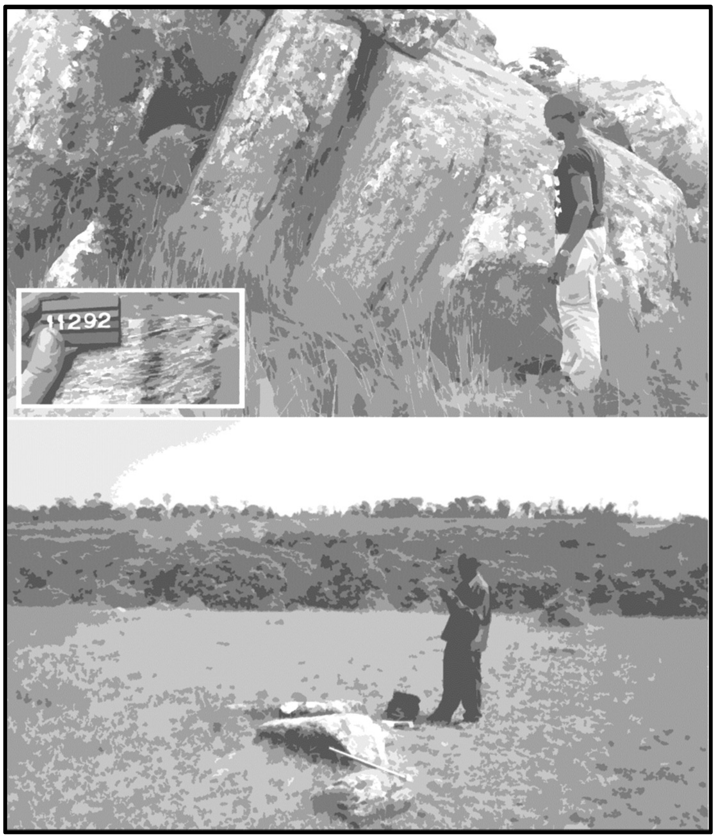


Figure 5: First- (top) and second-order (bottom) observations according to Schwarz et al. (2004).

First-order observations are reflecting direct observations on the outcrop or hand specimen; second-order observations are referring to nearly in-situ material that reflect widely unexposed underlying strata (boulders, soils).

Methods of handling first- and second-order observations still remain relatively conventional in most geologic mapping campaigns. However, when earlier geologists had to mark first and second-order observations on a paper map manually, the field geologist today is supported in most cases by a GPS handheld device, helping to provide those observations with precise coordinates. The observation points are commonly entered into a project database at some stage, making them easier accessible and shareable. Therefore the data must follow certain entry standards that are defined by geologic sciences as such or project specifics. To maintain these standards, the preparation and use of predefined field observation forms is common practice, either in analog or in digital format. The entries are normally made by using a unique coding that is clearly recognizable and comparable, limiting free text entries to a minimum.

Figure 6: Third-order observations according to Schwarz et al.(2004).
Third-order observations describe any additional information that is not directly observed in the field, e.g. thematic maps, scientific publications and satellite imagery.

The integration and interpretation of third-order observations has seen an enormous change over the years, as they can be based on a rapidly growing number of information layers today. Apart from just “helping out” when no first- or second-order observations is available, third-order information today contributes largely to the orientation and organization of the field teams. Their use for the geologic interpretation – especially of large mapping areas – has become widely accepted. In most cases selected and combined third-order information is put onto a GIS map prior to field work and then taken into the field as a hardcopy map. Although maps were always taken into the field, today the great variety of useful remote sensing data and geo-referenced GIS map products can improve their efficiency.

Concerning the general work flow of field campaigns, post-processing work in the camp after each day in the field is an accepted procedure amongst geologists (Schwarz et al., 2004) ever since. It helps to reconsider the observations from the field and develop theories. Nowadays this post-processing work is supported by entering the first- and second-order observation data into a computer system manually or semi-automatically (GPS download) and, if possible, visualizing them as simple points on a laptop screen.

Interpretation and Presentation

The final production phase combines all compiled and gathered data from the preparation and field work campaigns and lead to the conclusive visualization and description of the results. Whereas the description is likely to be in the form of a written report or explanatory map sheet notes, the visualization is today presumably a digital product. Although classical printed geologic map sheets are still generated and delivered as final products in most projects, the digital data can be presented in many ways, for example on virtual globes. Therefore an increasingly important issue is the archiving of all project data in extensive digital databases, granting the possibilities to prepare and select data quickly for various purposes, such as client-friendly web-GIS applications, national database systems, or scientific publications.

2 THE CONCEPTUAL DEVELOPMENT OF A DIGITAL GEOLOGIC MAPPING APPROACH BASED ON METHODICAL FIELD WORK STUDIES

The approach of the thesis considers all phases of geologic mapping campaigns, with a strong focus on geologic field work as the most challenging part between preparatory phase and final presentation of the results. As the demanding requirements and changing conditions of geologic field work are not sufficiently predictable in a theoretical concept, intensive field work studies have been carried out as part of this thesis, in order to put the approach iteratively to the test and adjust it according to practical restraints. These studies were conducted along with international geologic mapping project to guarantee a practical relevance. The particular character of the studies and the study areas, specific and general problems of the approach and subsequent improvements are presented in the following chapters. The technical status of the software system is described separately from the DGM work approach in the field, whenever possible.

2.1 Requirements of an Efficient Digital Geologic Mapping Approach

As part of this thesis, the author's evaluation of requirements is based on the discussion and interaction with all involved experts participating in many geological mapping projects carried out in the last eight years.

When analyzing modern geologic mapping campaigns it gets obvious that computer technology found its way into a lot of working aspects. Especially the scientific preparation of a mapping campaign and the final production of thematic maps and reports (chapter 1.2.2), are today strongly interwoven with geoinformatics and digital cartography. Thus the work of the individual geologist gets more and more interlinked with new disciplines. As in most international geologic mapping campaigns GIS, remote sensing image interpretation and digital database systems are used on a high professional standard today, the geologist faces the need of collaborating with an increasing number of experts in these fields. In addition, as almost the complete working process apart from field work is digital by now, the analog observations and interpretations of the geologists need to be digitized at some stage, in co-work with the GIS and digital cartography experts. This strong interdependency longs for a work approach that lets the geologist make use of the new technologies in an easy, goal-oriented way – in the office and the field – and at the same time streamlining the integration process of the geologists observation and interpretation results.

The most important basis of any new DGM approach must be its practical usability for all participating groups and the streamlining of the complete mapping process as such. The approach must consider the specific requirements that reflect the exceptional conditions under which geologists, GIS/remote sensing and database experts have to co-operate today, during all phases of a modern geologic mapping project. That would be best realized in combination with a software system that can be used by all participating experts in every aspect of their work and that is able to deal with all their specific requirements in an effective way. Therefore a strong involvement of software engineers would be advisable as it gives the possibility to adapt the digital system efficiently to upcoming needs.

The general focus ought to be put on simplicity as for obvious reasons it doesn't seem rational to create a highly sophisticated system that isn't used due to a high complexity or time requirement. Only if the approach is distinctly improving the working conditions of all involved groups right from the beginning, it will find broad acceptance amongst the users. Moreover it seems logical that the time of a geologist in the field should not be spent on tedious computer work but on making high quality observations; likewise the time of a GIS cartographer is not well spent on digitizing hand-written field book entries but on compiling a map.

However, a successful approach must count to a certain degree on the users' motivation to try new methods and accept extra efforts for the benefit of the improved work flow and final results.

Specific Needs of the Geologist

Huge amounts of ancillary data and modern technical equipment affect the work of geologists today and their efficient use must be considered in a DGM approach (chapter 1.2.1). Already during the preparation phase of a field work campaign, the approach should ensure the handling of digital datasets and basic GIS functionalities directly by the geologist, preferably independent from another expert or extensive training. The geologist should not only be able to compile and interpret available digital and analog datasets self-reliantly in the office but also to produce digital thematic layers and maps that can be taken into the field for verification.

In the field traditional geologic field work methods and challenging working conditions must be taken into account when thinking about a digital solution. Geologists must not be slowed down when visiting outcrops in the field but ideally be supported by new technology and digital data that help to boost the quality of any new observation. In this sense, granting easy access to a multitude of location-based ancillary data while literally standing on the outcrop would be a major asset. To put this into effect, a GPS-compliant device of some sort needs to be carried by the geologists, that is preferably small and light enough to be carried around, big enough to visualize additional information in an adequate format and reliable enough to endure field conditions, especially concerning robustness and power supply. Apart from a GPS-connected data viewer this device must also manage database entries and edits for field observations. When entering new observation data, this digital field book database must be intuitively and efficiently usable by individual geologists but likewise sophisticated enough to handle complex geologic interpretations of multiple users with minimal error-proneness. In order to maximize the advantages of a digital system, the data entries need to be digitally comparable by following certain input standards.

All digital field book entries should be visible and editable directly on the outcrop in order to cross-check interpretations and problems directly, not from a distance in the office. Naturally, as the geologic understanding of an area keeps evolving over field work time, the digital field book structure should be easily adaptable to changing field work conditions and needs.

Apart from managing point observations in the field, the whole system should motivate geologists by its simplicity and convenience to further develop field interpretations by digital mapping in the field office, before heading back home. It would help to interpret field observations on a bigger screen, where lines and polygons could be drawn and the results be presented in preliminary digital and analog field maps. To be able to take these revised map layers repetitively into the field, cross-checking and using them as a basis for discussions with other geologists, while still in the field would be a great improvement of the observation quality as such.

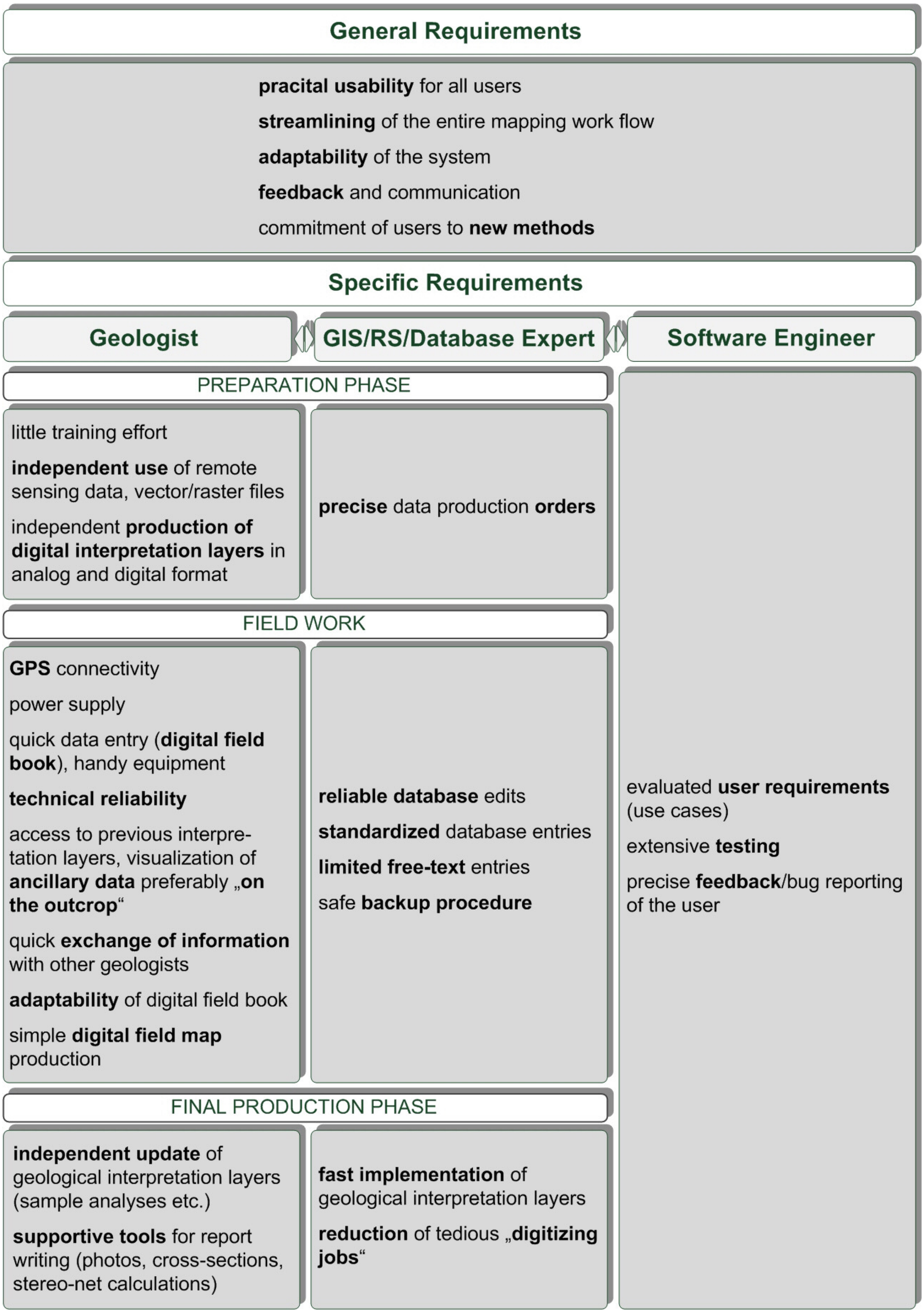
During the final map production phase back in the home office, the geologist should be able to update the geologic interpretation independently, whenever new information becomes available (e.g. rock sample analyses, new publications). These updated layers could be much easier integrated into the final map by the GIS and cartography experts. Additional digital tools that could help the geologist in final interpretation and report writing like cross-section and stereo-net calculations would be another asset.

The general requirements and the needs of the involved experts are displayed in Figure 7.

Specific Needs of GIS-, Remote Sensing- and Database Experts

Modern geologic mapping projects today need the support of a range of technical experts. They help to prepare and edit digital information layers needed for the interpretation, assist in organizing field observations in digital databases and manage the transfer of field results onto final digital and analog maps. All these supporting technical measures are dependent on precise scientific input of the geologists. Clear-cut production orders of digital data and the possibility to integrate the scientific contributions correctly and smoothly into the production workflow must be seen as the key requirements of technical experts involved in geologic mapping projects and they should be kept in mind particularly when designing any DGM approach. During field work the integration of observation data into a digital database by the geologists must be reliably designed in order to avoid laborious post-processing. To get the most out of a digital database it would be useful to plan the data entry whenever possible by standardized selection lists and by minimizing freetext entries. Doing so, the entries are digitally comparable and extractable with data queries, helping in an efficient analysis during and after field work.

Finally after a field work campaign the approach would ideally allow for the geologist to deliver interpretation results in digital thematic layers that could be integrated directly into a final digital map by the GIS and cartography experts. This would minimize transfer inaccuracies when digitizing hand-drawn maps and field book entries as it would help to reduce the tedious and inefficient digitizing double shifts of GIS experts and geologists.



General Requirements

pracital usability for all users

streamlining of the entire mapping work flow

adaptability of the system

feedback and communication

commitment of users to **new methods**

Specific Requirements

	Geologist	**GIS/RS/Database Expert**	**Software Engineer**
PREPARATION PHASE	little training effort **independent use** of remote sensing data, vector/raster files independent **production of digital interpretation layers** in analog and digital format	**precise** data production **orders**	evaluated **user requirements** (use cases) extensive **testing** precise **feedback**/bug reporting of the user
FIELD WORK	**GPS** connectivity power supply quick data entry (**digital field book**), handy equipment **technical reliability** access to previous interpretation layers, visualization of **ancillary data** preferably „**on the outcrop**“ quick **exchange of information** with other geologists **adaptability** of digital field book simple **digital field map** production	**reliable database** edits **standardized** database entries **limited free-text** entries safe **backup procedure**	
FINAL PRODUCTION PHASE	**independent update** of geological interpretation layers (sample analyses etc.) **supportive tools** for report writing (photos, cross-sections, stereo-net calculations)	**fast implementation** of geological interpretation layers **reduction** of tedious „**digitizing jobs**“	

Figure 7: Basic requirements of key experts involved in modern geologic mapping projects.

In general the much-feared loss of digital data due to technical problems in all project phases must be faced with a solid backup procedure.

Specific Needs of the Software Engineer

As the ideal setup would involve a software solution that is open to new ideas for improvement, the management of update requests must be assured. An evaluation and pre-selection of the requests seems necessary as in practice the programming feasibility and effort must be checked against the potential benefit. Successively the next step for any evaluated software update must be the precise definition of use-cases to face the needs with an adequate technical conversion and to use the time of software engineers efficiently. These use-cases should be prepared preferably by someone familiar with geology and software engineering to mediate competently between all participating groups and to maximize the benefit of any update.

Finally all updates of the software system must be thoroughly tested and a precise feedback of the users concerning functionality and improvement is essential to maintain a reliable system.

2.2 Selection of Study Sites

The field work studies were conducted by the author as part of three successive international geologic mapping projects in Oman, Madagascar and Uganda between 2004 and 2010 (Figure 8). The experience gathered in other projects, e.g. Ghana and Morocco further influenced the approach but the selection of these specific three projects is based on the strong variety of their general setup, geologic framework and field work character, forming a broad basis for the assessment and evaluation of the approach under different typical mapping conditions. The evaluation itself as another part of this thesis (chapter 4), is based on the author's involvement in all various stages of these presented projects, from preparation to field work and final production. This involvement made it possible to gather and analyze first-hand information on the requirements, the potential and the limits of digital geologic mapping techniques in practice.

The existing DGM setup comprising of a basic geologic information system was tested during a geologic mapping project in Oman carried out in 2003. The planned field work campaign was relatively small compared to the following study sites and gave the opportunity to test completely new DGM methods in a manageable framework. Field work was carried out by two geologists working in one team and outcrops were well accessible with only small distances to cover on foot. The study resulted in a first catalogue of improvement requirements used as a basis for the following study.

After improving the initial approach according to the newly identified requirements the second study dealt with a much more complex type of geologic mapping in order to test its suitability. Carried out during the geologic mapping campaign in Madagascar 2004 to 2008, the study challenged the DGM approach with large groups of geologists working simultaneously in a field work area of over 130 000 km^2. To maximize its significance the test was subdivided into three parts, each one characterized by specific geologic and logistical conditions. The author's analysis of these tests led to a major reformation of the approach. It further maturated during the third study realized in Uganda that allowed for a direct comparison with CGM working methods, as two teams worked with different methods.

The DGM approach as a result of the three field studies and the comparison with conventional geologic mapping surveys is finally analyzed and evaluated in chapter 4.

Figure 8: Selected countries in which the DGM potential was studied as part of the thesis. The DGM studies were in all three cases integrated into geologic mapping projects of GAF AG.

2.3 Study Phase I – Implementation and General Potential

The presented digital geologic mapping concept evolved initially around a geologic information system called GeoRover XT, that was developed by GAF AG in the late 1990's prior to the author's involvement. It was mainly used as a simplified GIS alternative to ArcView at that time. The primary intention of the software was to give geologists the opportunity to efficiently visualize and interpret raster and vector information, without profound GIS knowledge. The setup allowed the mobility of the system, to be taken into the field for ground verification of interpretation layers produced in the office. The first testing phase of the system under real field work conditions with the involvement of the author was carried out during the Uplift Probability Mapping project in Oman between 2003 and 2004.

Main objectives of the test study addressed the following basic topics:

- ***Support*** of traditional geologic mapping routines
- Accessibility and utilization of ***ancillary data*** during field work
- Transferring geologic field observations into a ***digital database***
- ***Implementation of field work results*** into the overall mapping project workflow
- ***Usability and reliability*** of digital equipment and software in the field

2.3.1 Study Framework and General Procedure

The study was conducted as part of the "Uplift Probability Map Project" (UPM) that had been a result of research activities in the field of newly evolving hydrocarbon exploration techniques combined with modern remote sensing and GIS developments. Based on the possibilities for uplift detection described by Berger (1994) – mainly related to topographical inversion (Figure 9) – the project was dealing with new methods in the specific field of RADAR and optical imagery merging techniques, highlighting anomalies in relation to the surface roughness.

The basic principle of the UPM approach is the correlation of surface features with the uplift of the underlying geology. A set of defined indicators is used to verify the potential of an uplift structure and its relation to a possible hydrocarbon reservoir. Laid open by inverted topography structures (in the sense of Berger, 1994) the uplift indicators most likely found in sediments are circumferential bedding traces and specific marker horizons in the center of semi-circular depressions. These indicators are overlain in a GIS intersection and the potential is weighted according to the number of indicators and their geologic importance at a specific point. Zones of ranked potentials for uplifts can be pointed out, acting as possible hydrocarbon traps. All these factors are derived from satellite imagery and map interpretations and built the preparatory work for ground verification. The ground verification missions into Oman's Interior from 2001 to 2004 and finally the direct comparison of the UPM results with already existing seismic cross-sections showed a strong correlation ratio of more than 70 per cent.

The project was financed by Petroleum Development Oman (PDO), the largest oil & gas producing company in the Sultanate of Oman, with the intention to test the potential of simple and fast "top down" remote sensing techniques (Steiner, 2004) when planning extensive seismic surveys. Preliminary studies for the UPM approach were carried out for PDO in 2002 with promising results. The UPM project launched in 2003 and 2004 dealt with the whole concession area of PDO roughly covering 114 000 km^2 in central Oman.

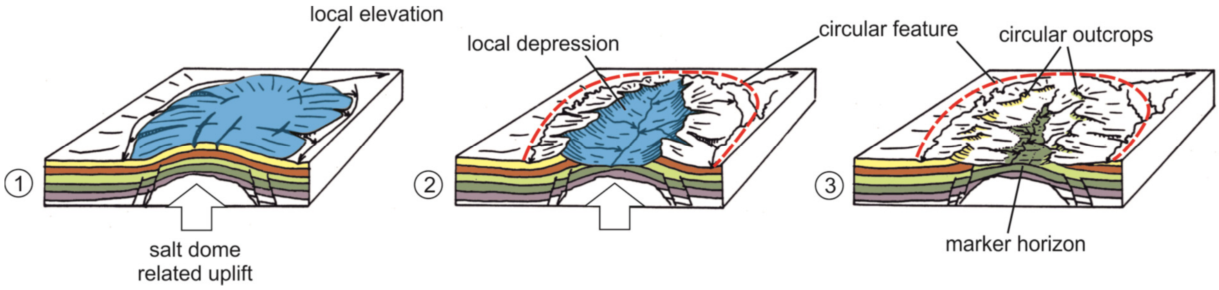


Figure 9: Schematic stages of topographical inversion (modified from Berger, 1994). Erosion ideally leads to uplift indicators such as circular features, circular outcrops and local depressions with a marker horizon in its center – all detectable in remote sensing imagery.

Following the project setup the DGM assessment study and the further development of the approach is split into three parts (Figure 15, page 45), with focus on the field work:

A) An inception phase including data compilation, production and interpretation of tailored optical and RADAR satellite imagery.
B) A ground verification phase comprising of two field campaigns separated by intensive office interpretation work.
C) The production of a final digital map showing the results.

Regional Geographic Overview

The study area (Figure 10) borders the southern flank of the Oman mountains, covering the Ghaba-, Fahud- and South Oman Salt Basins in interior Oman. It is bordered to the south by the Quara mountains and to the east by the Huqf-Haushi-Uplift area. It shares a further border with the Rub-al Chali desert to the west.

Whereas the south is subtropical and affected by monsoon periods, the climate of interior Oman is hot and dry with temperatures of more than 50 degrees Celsius in the summertime. North of the Oman Mountains and along the coast line the climate is hot and fairly humid.

Vegetation only exists in the coastal areas and the Salalah region in the south, where most of Oman's agricultural production is located. In the study area only sparse vegetation is found in and close to the wadis. Mainly due to the needs of the oil & gas industry the infrastructure in Oman is generally good with freeways around the capitol Muscat and sufficient paved main roads throughout the country. Apart from that a lot of graded roads do exist and are in good condition. With 4x4 cars off-road driving is in most areas unproblematic.

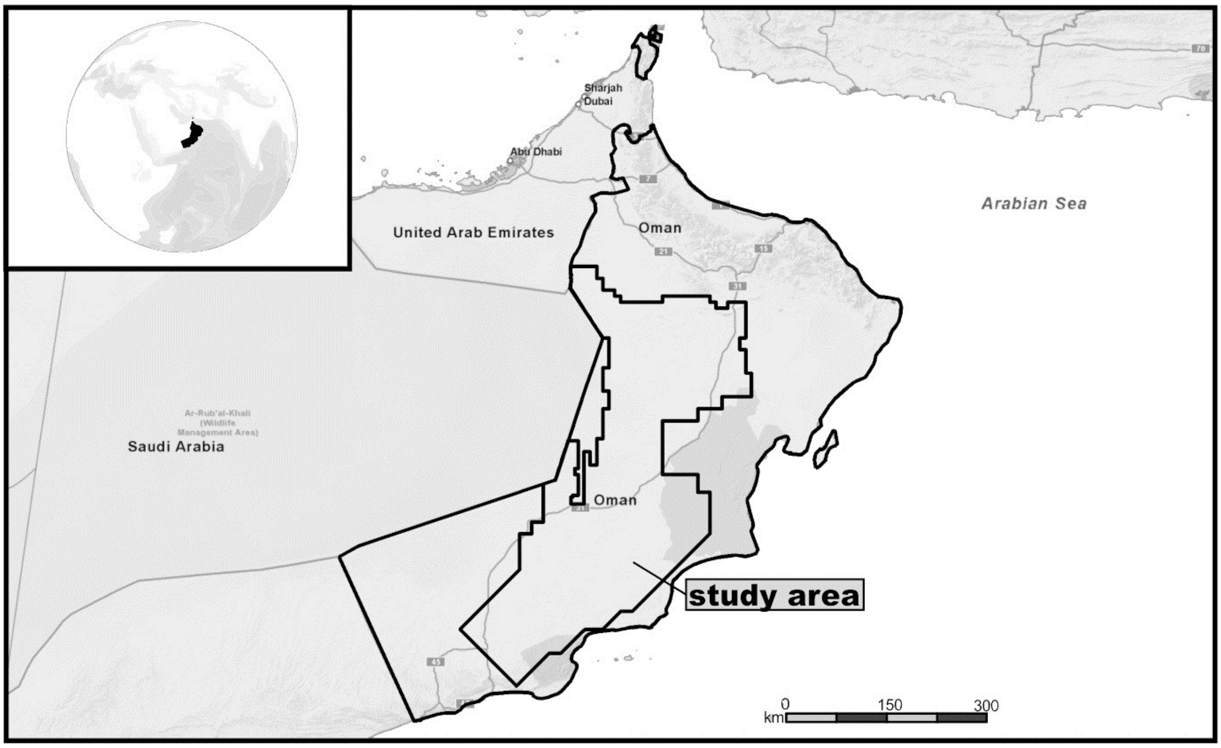


Figure 10: The study area in Oman.
(modified from ESRI, ArcGIS online maps)

General Geologic Setting

Oman occupies the south-eastern part of the Arabian plate. Once contiguous with the Iranian and African plates to the north and south, the Arabian plate formed a separate entity as a result of the opening of the Neotethys and the following onset of rifting that occurred to form the Red Sea. These events occurred consecutively around 34 Ma (Omar and Steckler, 1995; Alsharhan and Nairn, 1999).

The geology of the Sultanate of Oman (Figure 11) is well known for the northern part of the country where the Al Hajjar mountains have been well studied, particularly the obducted Sumail ophiolite (Coleman, 1981; Boote et al., 1990; Robertson et al., 1990; Hacker et al., 1996; Boudier et al., 1997).

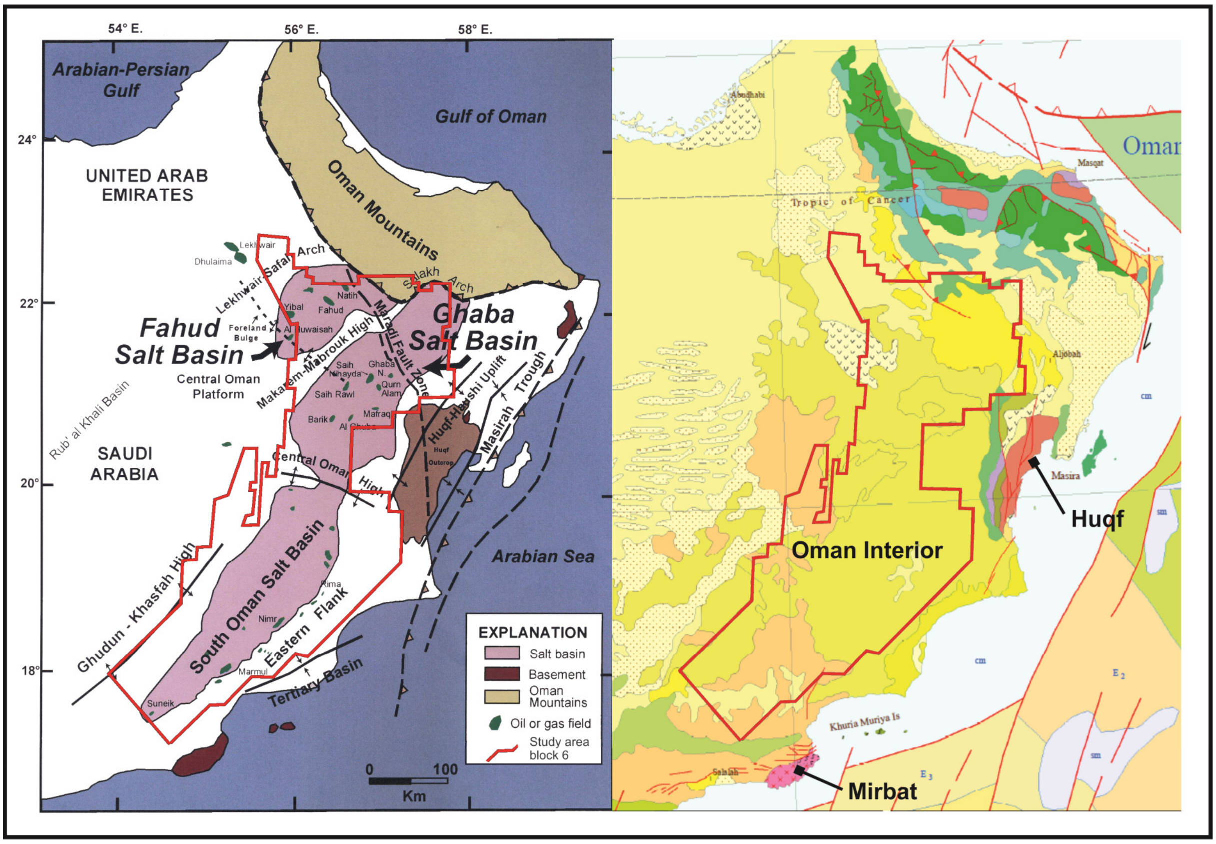


Figure 11: The salt basins of Southern Oman (left) and generalized geology (right). Left: salt basins and related oil and gas fields (modified from Pollastro, 1999); right: generalized geology of Oman and bordering countries (modified from CGMME, 2009 International Geological Map of the Middle East 1:5 000 000). Red outline indicates the study area in both maps.

The Omani interior south of the Al Hajjar Mountains has been well studied due to the area's potential for oil and gas (Heward, 1990; Mattes and Conway-Morris, 1990; Robertson et al., 1990; Pollastro, 1999; Rieu et al., 2006). Contrary to the Al Hajjar

Mountains, the interior is built up of a series of subsiding rift basins that are further extending all over the Middle East, Pakistan and India and dating back to Early Cambrian times (Mattes and Conway-Morris, 1990).

Specifically the study area (Figure 11) is set up around the South Oman Salt Basin, the central Ghaba Salt Basin and the northwestern Fahud Salt Basin, all containing a >10 km thick sediment sequence ranging intermittently from Early Cambrian to the Cenozoic. The Cambrian Ara Formation is a member of the Huqf Group, and is significant as it represent evaporitic deposits that underlie younger clastic and marine sediments in all three basins (Pollastro, 1999). The Ara formation is responsible for the development of oil and gas traps in the overlying sediments via the gravitational and tectonic emplacement of salt domes (Mattes and Conway-Morris, 1990). The surface geology of interior Oman is defined almost exclusively of Cenozoic sediments, whereas Paleozoic and basement rock outcrops are only known from the Hajjar Mountains, their foreland and the coast line in the Huqf-Haushi and the Mirbat area east of Salalah (Rieu et al., 2006). As the field work concept was based on the evaluation of the surface geology in correlation with seismic data interpretation of the three salt basins (Figure 11), mainly Cenozoic outcrops were analyzed that could be related to underground uplift. Of particular importance were the Eocene marine strata of the *Rus and Dammam Formations,* the Miocene marine strata of the *Dam, Ghubara, Ghaba Formations* and the continental *Shissr* and *Montassir Formations* as well as the Pliocene/Pleistocene *Marsawadad* and *Barzaman Formations*. All formations contain to a great extent various types of limestone.

2.3.2 DGM Study and Development of the Approach

Specific Study Objectives and Execution

The study was aiming at testing the potential of the existing DGM system, to cope with specific requirements of the project and general needs of geologic mapping. Generally the project setup longed for an approach that could deal with an iterative comparison of remote sensing data and geologic field observations, in the best way possible. Interpretations in the office had to be updated according to new field observations and seismic interpretation layers. As the interpretation had to be based on specially prepared remote sensing data (chapter 2.3.1), it was necessary to have that data at hand while in the field.

Two field work campaigns were planned as ground verification surveys with only limited field time, therefore selected car traverses were planned instead of extensive foot traverses. The limited field work time, the large working area and the small team size made a precise selection of representative observation points obligatory.

The reliability of all sorts of field work equipment under desert environment conditions was seen as an obvious requirement.

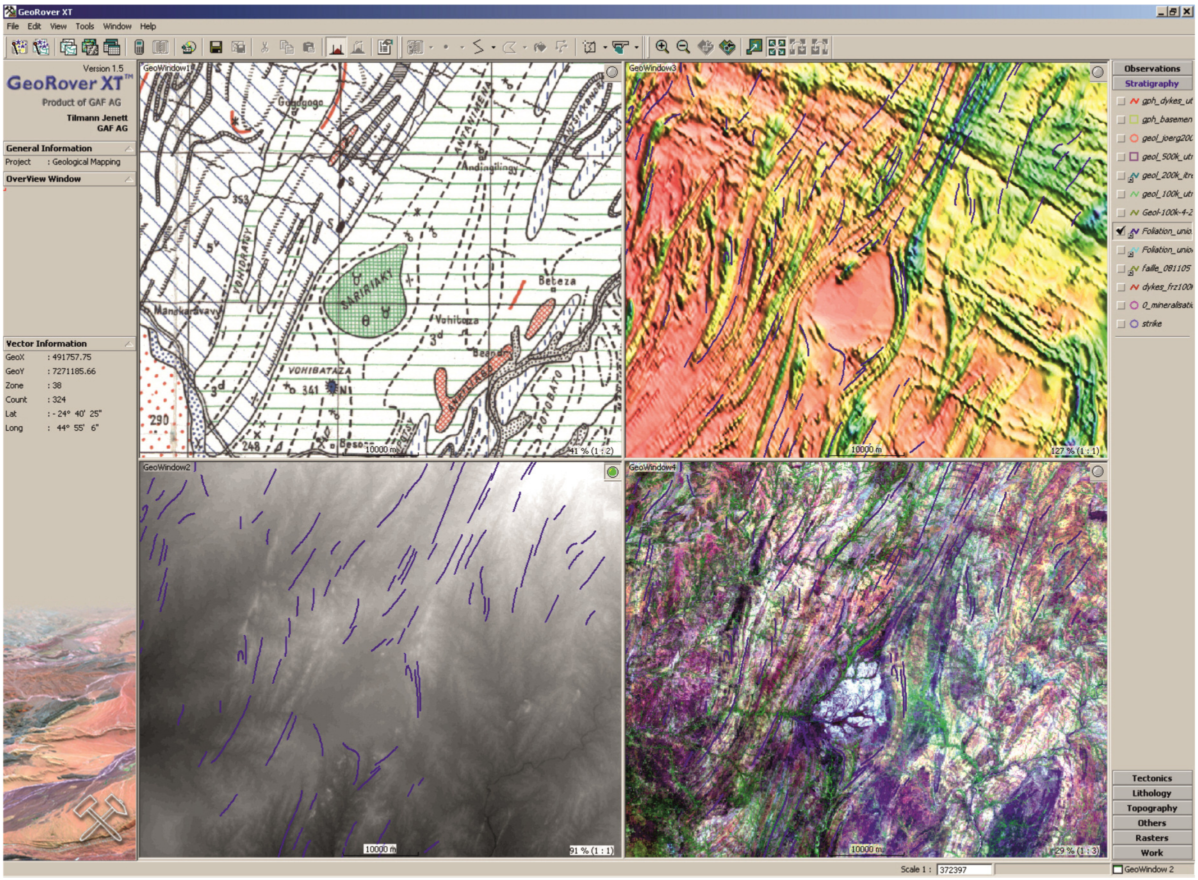
The final delivery product of a digital uplift probability map based on the intersection of defined indicators anticipated the use of a digital GIS.

Technical DGM System Status

The initial DGM setup was based on the GeoRover XT software, built with the intention to facilitate the pre-interpretation of multiple digital datasets, the integration of field work results and the following post-processing work. The design allowed for the use of multiple information layers at the same time and the ability to draw vector points, lines and polygons. Within Georover XT the multiple information layers were viewed on up to four concurrently active working windows that were geographically linked and could be used simultaneously for interpretation (Figure 13). Much effort was put into an easy point-, line- and polygon drawing mode. These basic functions generally remained in the newer software versions, although with adaptations.

As the geologist is used to start an interpretation process from point observation in the field to drawing lithological outlines and finally creating units as polygons on a map, the software kept this routine but in a digital environment. A digitizing mode was simplified to a non-topological (chapter 1.2.1) format for constructing linear features. Instead of working directly in a polygon construction mode, requiring topologic accuracy, the construction layer was designed to simply create a network of lines, based on vertices and automatically set nodes at intersection points.

Once a set of lines formed a closed feature without any dangles, it could be “filled” and copied into a polygon shapefile, with the topology being set automatically (Figure 13). This aspect made it possible to progressively map features, without topological restraints and in concordance with a traditional geological mapping workflow. A basic digital field book was implemented into the software that made it possible to provide entered points with geologic attributes. Additionally, to work conveniently with digital



Project : Geological Mapping

GeoX : 491757.75
GeoY : 7271185.66
Zone : 38
Count : 324
Lat : - 24° 40' 25"
Long : 44° 55' 6"

☐ gph_dykes_ut
☐ gph_basemen
☐ geol_joerg20(
☐ geol_500k_uti
☐ geol_200k_itr
☐ geol_100k_uti
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Scale 1 : 372397

Figure 12: The graphical user interface of GeoRover.

Four window mode showing various interpretation layers (from top left clock-wise: geologic map 1:100 000, processed aeromagnetic imagery, Landsat ETM 742 (RGB), SRTM elevation data) of the same geographic extent in southern Madagascar, satellite images displayed by courtesy of Projet de Gouvernance des Ressources Minérales" (PGRM), Republic of Madagascar and GAF AG; the basic editor toolbar is positioned on top of the map layers and access to vector and raster layers is implemented in the toolbar on the right.

images, the software allowed the user to customize image histograms manually or applying automatic standard deviation stretches, optimizing the interpretability of digital imagery.

When working in the field with a laptop, an external GPS unit could be attached via communication port (COM port) using the NMEA protocol. Hence, the users were able to see their actual position projected onto the selected information layers. Thus a direct comparison between field observation and ancillary data could be realized. GPS data could be used to track the movements and store them in shapefile format. An extension existed for external devices that could in principle be used for more remote field observations, although not conveniently connected to the digital field book of the main program.

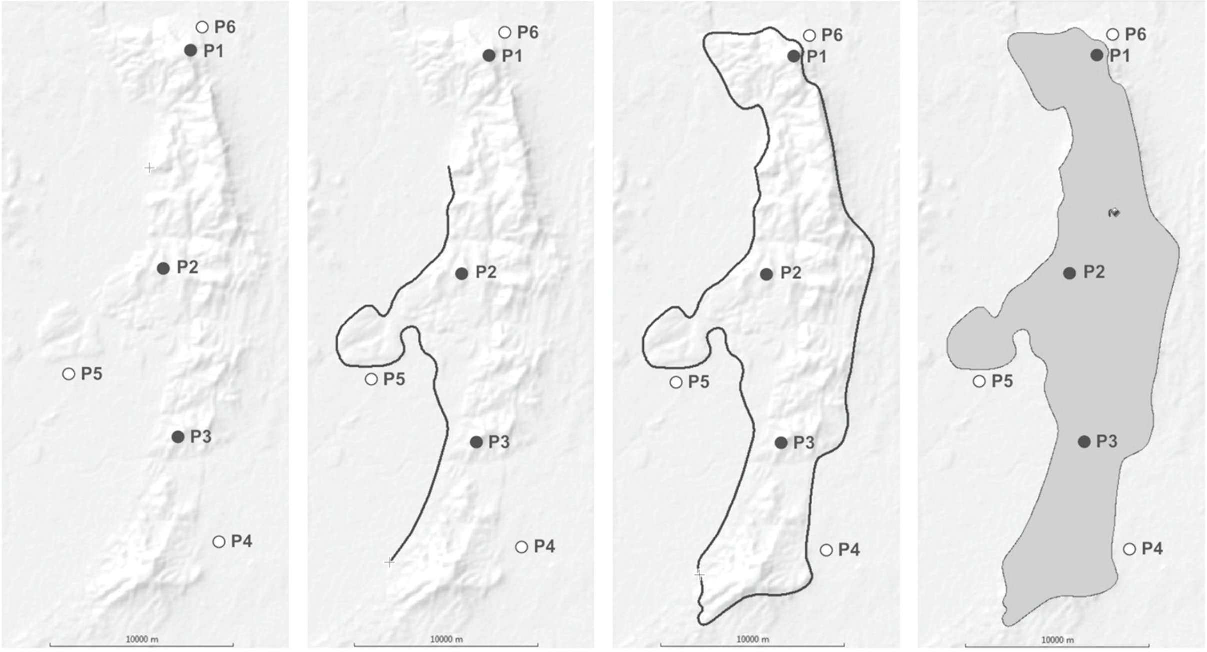


Figure 13: Digitization work flow of the GeoRover XT software.

From point observations to lines, closed line features and finally "one-click" transfer into a polygon.

DGM Workflow Management

To face the challenging requirements of the project it was tried to streamline the process as much as possible (Figure 14). The GeoRover XT software was used as DGM setup to compile all available data in one system and to have it at hand for preliminary interpretation and mapping of potential uplift indicators. However, the complex remote sensing intersection of RADAR and optical sensors had to be done with ERDAS Imagine. Data only available in analog format was digitized and integrated into the DGM system. To make the most of the short field visit, potential areas of high interest were mapped in the DGM system according to the interpreted features. These areas were automatically referenced with coordinates to facilitate the orientation in the field. The whole DGM system was finally copied onto a rugged field laptop with GPS connection. As the mapping mostly comprised of long car drives to access the pre-selected areas of interest, the laptop was used as a geologic navigation tool, showing the exact position on the selected background imagery. Additionally, during the car drives the geologist could at any time visually compare field observations to digital data in the DGM system and enter geo-referenced information into the digital field book system. The same procedure was used, although in much more detail, when reaching a pre-selected outcrop. When the geologist had to leave the car behind and walk a certain distance, a mobile handheld

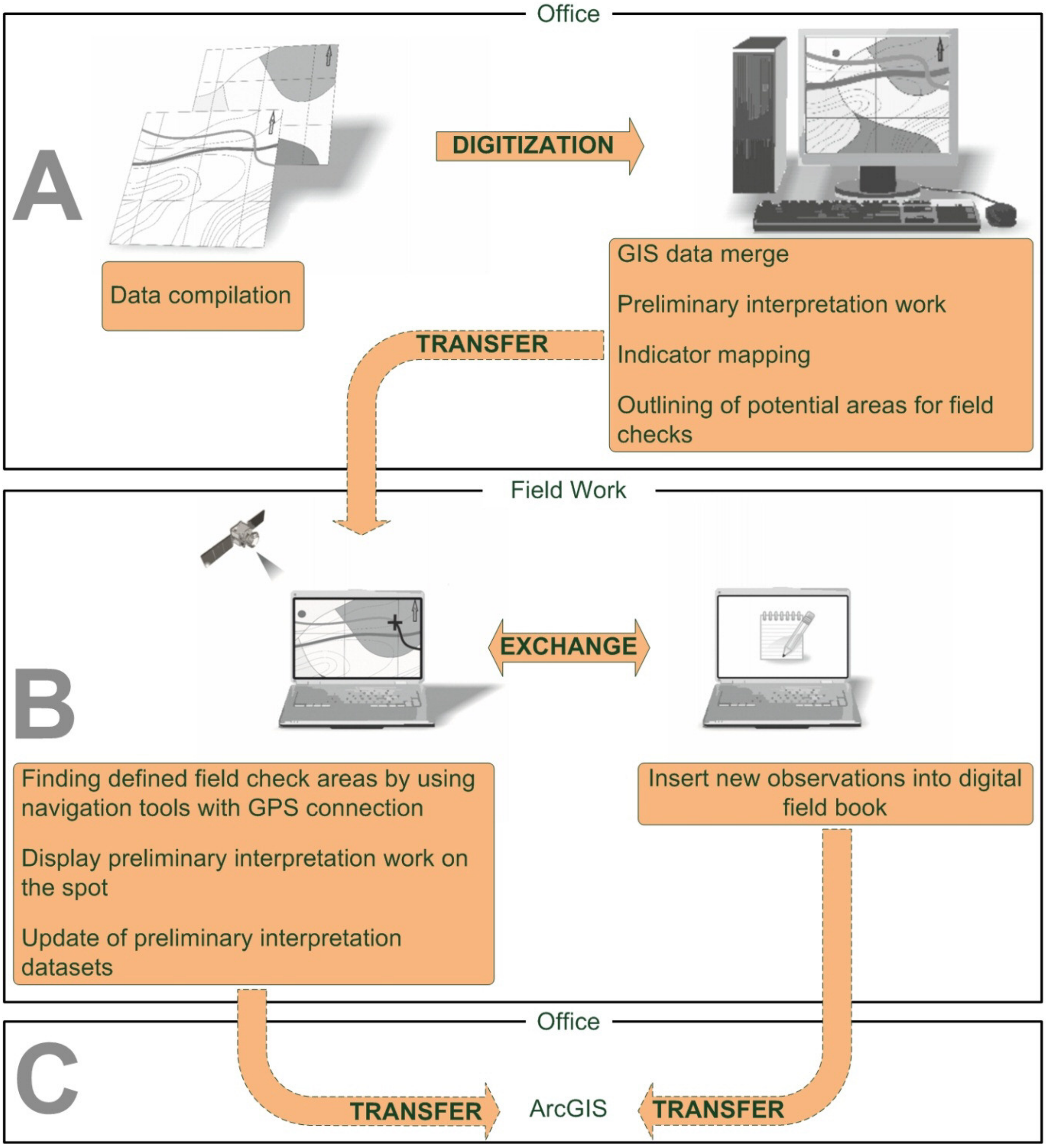


Figure 14: General digital mapping approach of study I in Oman.

A) preparation of the field campaign; B) Field work navigation and digital field book; C) Transfer of digital data into ArcGIS for final map production (chapter 2.3.1).

PDA equipped with a very limited raster viewer could be used to add observation points into the digital field book. As the access to the points of interest was excellent this option was merely used though. All gathered information was used to update the preliminary digital interpretation layers while being in the field, using the GIS capabilities of the DGM system.

When returning from the field the updated interpretation and indicator layers were integrated into ArcGIS to start the intersection of the indicators and produce an uplift probability map. As this procedure describes the general workflow (Figure 14) the specific setup of the uplift probability project made another field work campaign necessary that was carried out in a similar way (Figure 15).

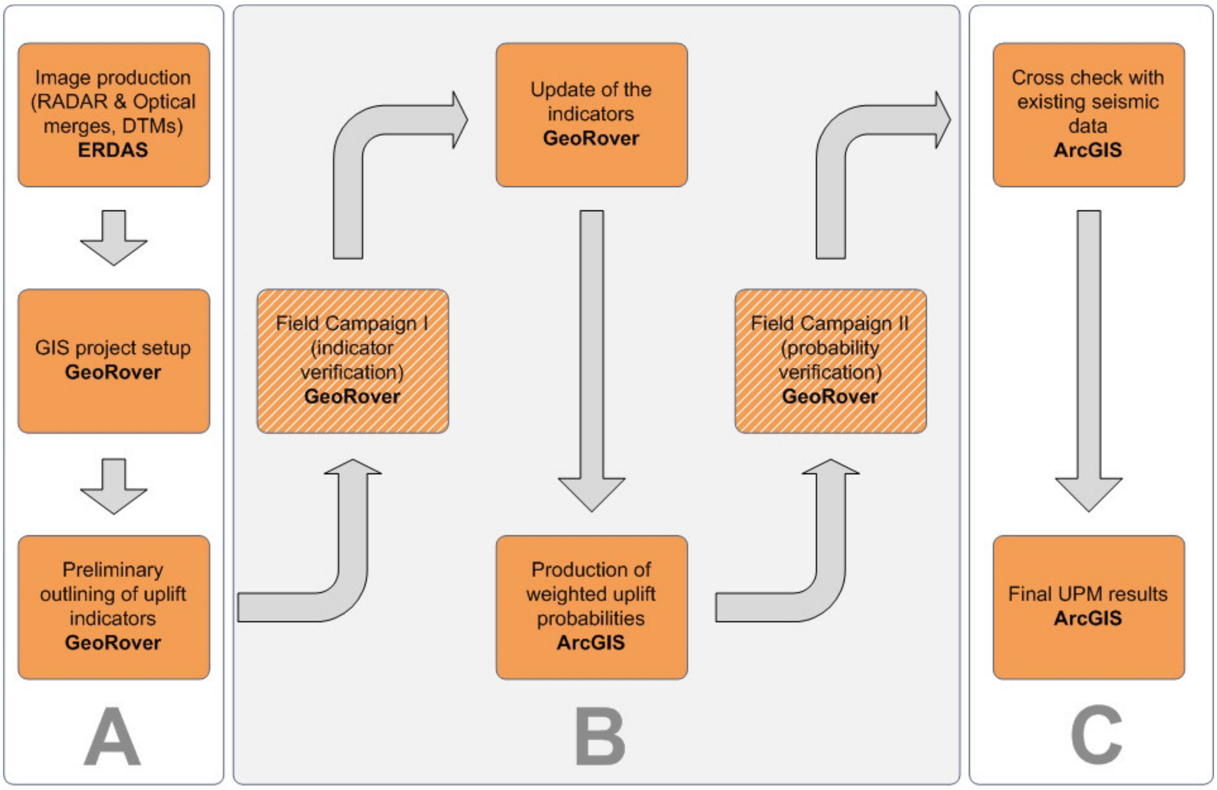
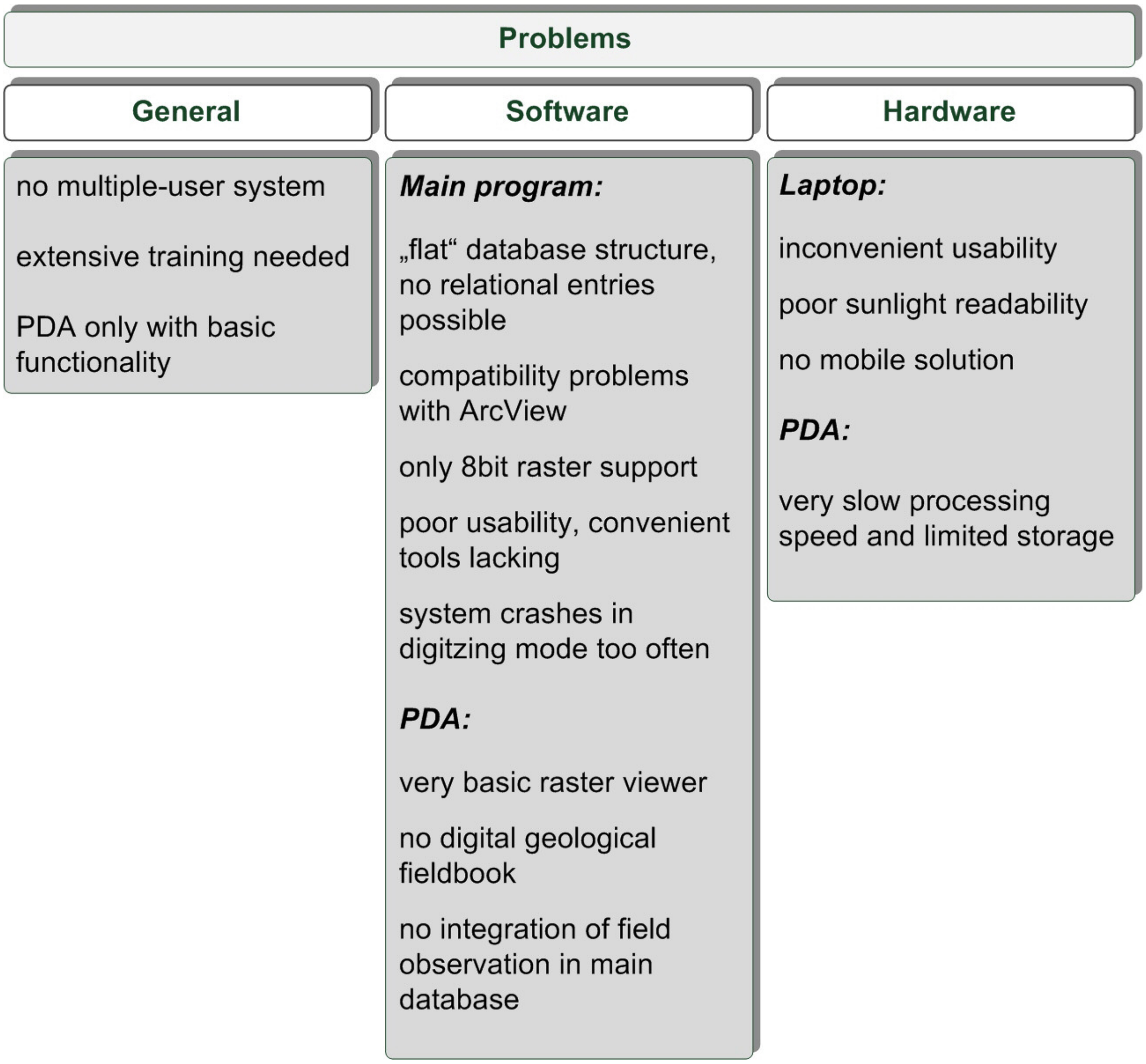


Figure 15: Specific DGM implementation during the uplift probability project.

A) **Starting phase with preparatory GIS work and outlining of uplift indicators; B) Field work phase with ground verification of indicators, definition of preliminary uplift probabilities and second verification in the field; C) Intersection of results with existing seismic data and production of a final UPM map; Used software printed in bold letters.**

Problems and Improvement Potential

In general the author concludes that the DGM system worked quite well for the specific type of geologic mapping. However, some crucial problems are highlighted in the text and in Figure 16.



Problems

General

- no multiple-user system
- extensive training needed
- PDA only with basic functionality

Software

Main program:

- „flat“ database structure, no relational entries possible
- compatibility problems with ArcView
- only 8bit raster support
- poor usability, convenient tools lacking
- system crashes in digitzing mode too often

PDA:

- very basic raster viewer
- no digital geological fieldbook
- no integration of field observation in main database

Hardware

Laptop:

- inconvenient usability
- poor sunlight readability
- no mobile solution

PDA:

- very slow processing speed and limited storage

Figure 16: Main problems of the DGM approach in study phase I.

At this stage of development the software was used solely by one individual geologist as a car-borne digital data collection tool and basic GIS. As this geologist was involved in the development of the system and familiar with GIS, remote sensing and database techniques, the setup could hardly be tested according to its usability for untrained geologists. Relatively complex workaround structures were accepted that would have provoked major problems when handled by inexperienced users. A multi-user capability of the system that could merge different database entries efficiently and reliably was not implemented at that time and therefore the system was not suitable for larger geologic mapping projects normally carried out by more than one geologist.

Although the necessity of a mobile hand-held solution and a data integration routine was understood, and principally designed, an external PDA was not conveniently usable. The functionality of the PDA and the transfer capability between main program (Laptop) and the mobile version (PDA) was very limited and potential problems with this setup remained at that stage. Within GeoRover XT the database architecture was such that observation data entries were integrated into a flat file database structure. This architecture did not allow relational data entries that are often obligatory in geology; for example when several strike and dip values from various structures are collected at a particular observation point (many-to-one relation). Compatibility problems with ESRI software arose when the GeoRover XT vector shapefiles were transferred from GeoRover XT to ArcView (3.2) and vice-versa. Shapefiles compiled in ArcView 3.2 were not editable in GeoRover XT without workaround procedures, a problem related to different ID tagging methods. This was highly problematic as some GIS work between the field campaigns had to be done in ArcView (later ArcGIS).

Further problems affected the use of different raster imagery. Images had to be in 8bit format as the software did not support higher bit imagery. Apart from the time loss when converting raster images to 8bit data, working with digital elevation models was particularly problematic as height values cannot be represented in 8bit format. The whole problem was aggravated by the fact that the transfer from 16bit or higher to 8bit format is relatively complex and has to be done using image processing software like ERDAS Imagine or PCI.

Within GeoRover XT the conversion from the non-topologic construction layer into a topologically correct vector shapefile very often crashed the software when large segments were transferred at once. The same happened when polygons with a large number of vertices were checked for topological errors like gaps and overlays.

Minor problems occurred due to the lack of an on-the-fly transformation for data referenced with other geographic projections than UTM. An undo function was also not implemented often leading to tedious working processes.

With respect to the working speed, the system (Figure 17) was relatively slow compared to modern standards and, although the field laptop was shock resistant and dust proof, it was quite uncomfortable to use due to strong heat dissipation, a clumsy keyboard and the very poor readability of the display in direct sunlight. These facts lessened the advantage of having access to digital data in the field. Further, the processing power, disk storage and operating systems for PDA's were very limited at that time, making the work with a PDA inefficient. Battery lifetime of both laptop and PDA was insufficient for longer independent work but unproblematic in the particular work setup.

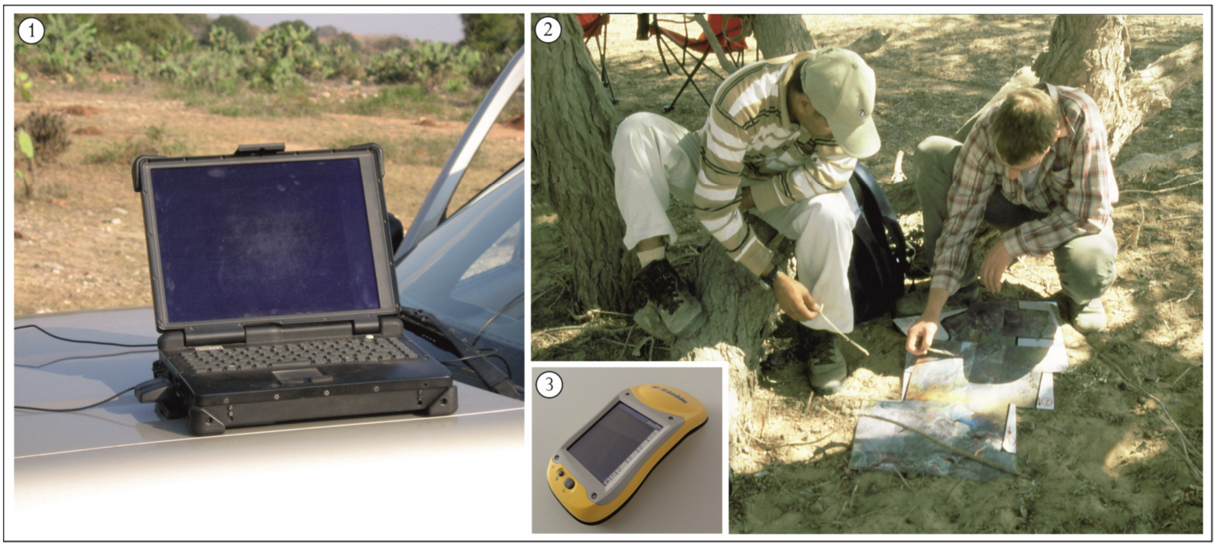


Figure 17: Technical setup of field work in Oman.

① Rugged laptop "Rocky I"; ② discussion in the field with printed satellite maps; ③ Trimble GeoExplorer CE handheld.

Summary

The first study deals with the general potential of a new DGM approach. The basic requirements of field work were tested without weighing the GIS proficiency of users too high. It remained an expert system at that stage. The study showed a high potential of the approach for modern geologic mapping projects involving remote sensing interpretation. However, it became obvious that strong improvement was needed in managing relational geologic datasets and multiple-users.

2.4 Study Phase II - Adaptation

Where the first study was dealing with the general potential of digital techniques used in geologic mapping projects, the second study primarily tested the potential of the improved system to deal with multiple user groups and challenging work conditions in the field.

By reviewing the problems of study phase one as part of this thesis, the system was upgraded from a basic single-user GIS, into a multiple user GIS with mobile digital field book based on a relational database. The database structure allowed complex relationships between the datasets and the organization of individual geologist entries via unique identifiers. Field observations were entered into the digital field book via PDA, supported by a raster and map viewer.

The study analyzed the following main objectives as part of an extensive geologic mapping project in Madagascar:

- *The potential of the approach to deal with* ***multiple user groups*** *and independent data entries*
- *DGM approach under* ***challenging field conditions***
- ***Usability*** *of the system for geologists without profound GIS knowledge*

2.4.1 Study Framework and General Procedure

The study was conducted as part of the Madagascar geologic mapping project. The project was carried out under the patronage of the “Projet de Gouvernance des Ressources Minérales” (PGRM) within the “Projet de Réforme du Secteur Minier (PRSM-2)” and supervised by the Ministère de l’Energie et des Mines (MEM), of the Republic of Madagascar. The objective of PRSM-2 was to assist the Government of Madagascar in implementing a strategy to accelerate sustainable development through strengthening the governance of mineral resources and artisanal mining.

GAF AG and the Federal Institute for Geosciences and Natural Resources Germany (BGR, Hannover, Germany) formed a consortium for a mapping area of approximately 130 000 km^2 in southern Madagascar. Other mapping areas covering most of the rest of Madagascar were contracted to The British Geologic Survey (BGS) and the United States Geologic Survey (USGS) in the north, the Council for Geoscience South Africa (CGS) and the Bureau des Recherches Géologiques et Minières (BRGM, France) in central parts of Madagascar. The main objectives of the project were to re-map, upgrade and improve the existing geologic information and create a comprehensive and uniform coverage of geologic mapsheets at the scale 1/500 000 and a 1/100 000 coverage of selected areas in close collaboration with the other mapping groups.

Along with the map production it was intended to gather new geochronological and geochemical data and to undertake geomorphological, hydrogeologic, structural geologic and mineral potential research, to be presented in several thematic map sheets. The contract was bound to several milestones that separated the project phases into a compilation phase, an intermediate phase and a final phase, with the production of map outputs as deliverables for each phase. The project itself was carried out between 2005 and 2009, whereas some logistical problems related to the late 2009 coupe in Antananarivo and the resulting political upheaval delayed the finalisation of the project until 2011.

The style of field work was influenced by the two different mapping scales (1/500 000 and 1/100 000) and the variable geographic terrains encountered, resulting in completely different mapping strategies in the 2005, 2006 and 2007 field seasons that had to be considered in the DGM approach. Three main mapping areas consist of the Vohibory and Tôlanaro structural domains, mapped in 2005 and 2006 field seasons and the Ihosy area, mapped in 2007. This subdivision of field work is followed in the structure of this thesis.

Because of the very remote mapping areas and poor infrastructure the field campaigns were carried out in two six months periods in 2005 and 2006 and a two month period in 2007. In each season three to five geologists were typically in the field at the same time, allowing a rapid data collection and map production.

Following this general project setup, the study and DGM development is subdivided into three field study parts Vohiboy, Tôlanaro and Ihosy, separated by upgrade phases in which the system and the approach could be improved accordingly.

Regional Geographic Overview

The study area stretches up between the Malagasy cities of Tôlanaro, Toliara, Antsirabe and Morondava. The mapping work was divided into four map sheets of the scale 1/500 000 and two sub-areas that had to be mapped at 1/100 000 scale: (A) The Vohibory area in the south-west, comprising nine map sheets at the scale of

1/100 000 and (B) the Tôlanaro area in the south-east comprising of twelve map sheets (Figure 18).

The landscape of Madagascar is characterized by a strong heterogeneity from east to west. The central part is built up of strongly eroded highlands forming several peneplain levels that are cut by an abrupt north-south trending escarpment in the east, while much more gently sloping to the west into Mesozoic sedimentary basins. In the south, the east coast escarpment occurs in the mountainous area between Midongy and Andohahela, the highlands exist in a wide area south of Betroka and they descend to the Vohibory low-lands west of Bekily. The southern part of the area, around Tsivory is defined by a Cretaceous volcanic complex. Southern Madagascar is subjected to a subtropical climate with one rainy season between November and March, followed by a dry season from April to October.

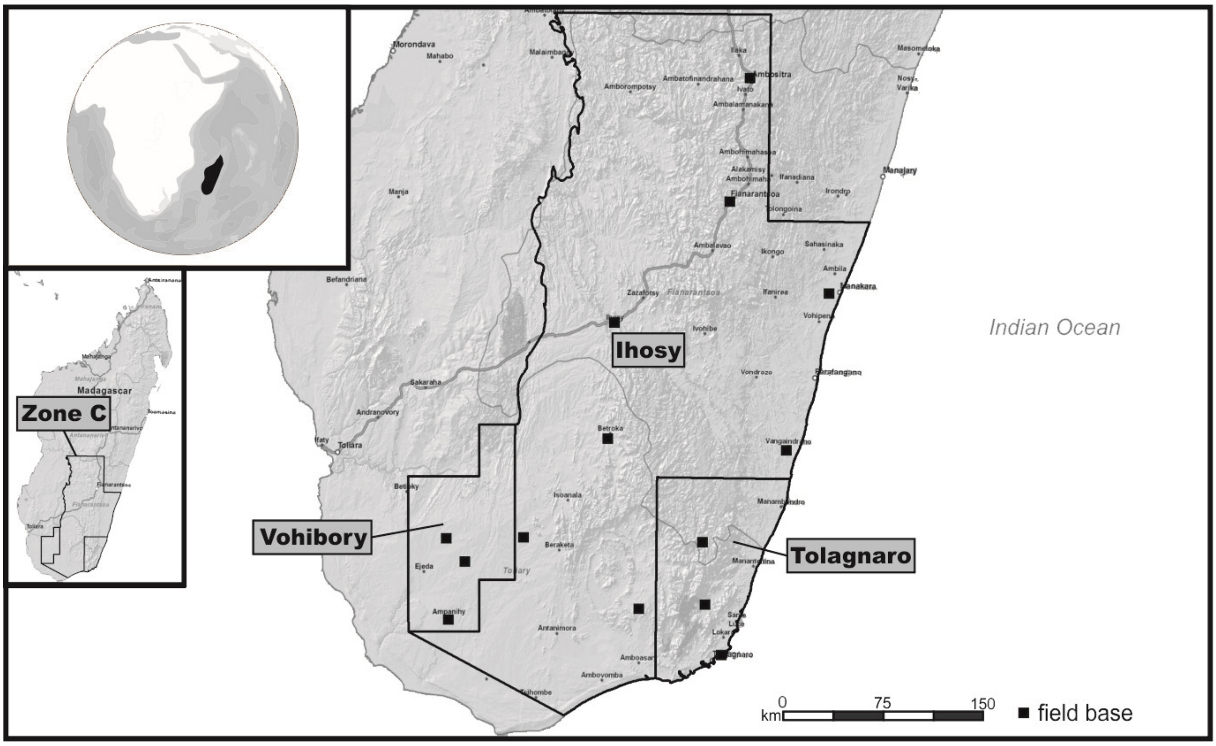


Figure 18: Zone C Southern Madagascar.

With Ihosy, Vohibory and Tôlagnaro (formerly Fort Dauphin) mapping areas (modified from ESRI, ArcGIS online maps).

Temperatures can be quite low in the higher mountain areas and conversely quite high in the south-western low-lands. During the rainy season the monsoon winds hit the mountains on the east coast leading to heavy rainfall and thunderstorms in this area. Precipitation decreases strongly further to the west. There is a clear correlation in the vegetation pattern, ranging from thick rainforest in the east to semi-arid desert in the far south-west.

In general the infrastructure of Madagascar is very limited. A couple of national routes exist, although in the south only one is continuously paved. The western part of the study area is transected by small graded tracks that are fairly passable in dry season. In the mountainous eastern part much less tracks are found and often impassable, making large parts of the study area only accessible on foot.

General Geologic Setting

Madagascar can be generally divided into two major geologic and topographical domains (Figure 19). The western third of the island is represented by a continuously deposited Phanerozoic sedimentary cover that is shallowly dipping to the west. The eastern two thirds of Madagascar are dominated by metamorphosed and highly deformed basement rocks that date from Neoproterozoic to Archean (Bésairie, 1969/1970). Along the coastline and prominently at the southern tip of Madagascar the basement rocks are intruded or overlain by Cretaceous volcanic and intrusive rocks (Mahoney et al., 2008) and related dyke swarms of similar age (Ernst and Buchan, 1997).

The Precambrian evolution of Madagascar has been progressively described over a period of more than 40 years (Bésairie, 1969/1970; Moine, 1974; Hottin, 1976; Nicollet, 1990; Paquette et al., 1994; Windley et al., 1994; Kröner et al., 1999; Martelat et al., 1999; De Wit et al., 2001; Collins and Windley, 2002; Collins, 2006; Tucker et al., 2007; Boger et al., 2009; Schreurs et al., 2009). These publications have resulted in the division of the island into several tectono-metamorphic domains that owe their present configuration to the formation of Gondwana (Stern, 1994; Collins, 2006).

The Bemarivo, Antananarivo and Antongil-Masora domains define the northern part of Madagascar. The Vohibory domain in the south west of Madagascar’s basement has been recognized concordantly as being unique (e.g. Bésairie, 1969/1970; Collins and Windley, 2002; Boger et al., 2009; Schreurs et al., 2009). However the intervening central part of the island has been the matter of diverging scientific opinion. This region is firstly presumed to be split by the Ranotsara Shear Zone, a structure that is argued to split the Malagasy geology into northern and southern halves and which is variably linked to other regional tectonic features of India and Africa (e.g. Windley et al., 1994; Kriegsman, 1995; Martelat, 1998; De Wit et al., 2001; Collins and Windley, 2002).

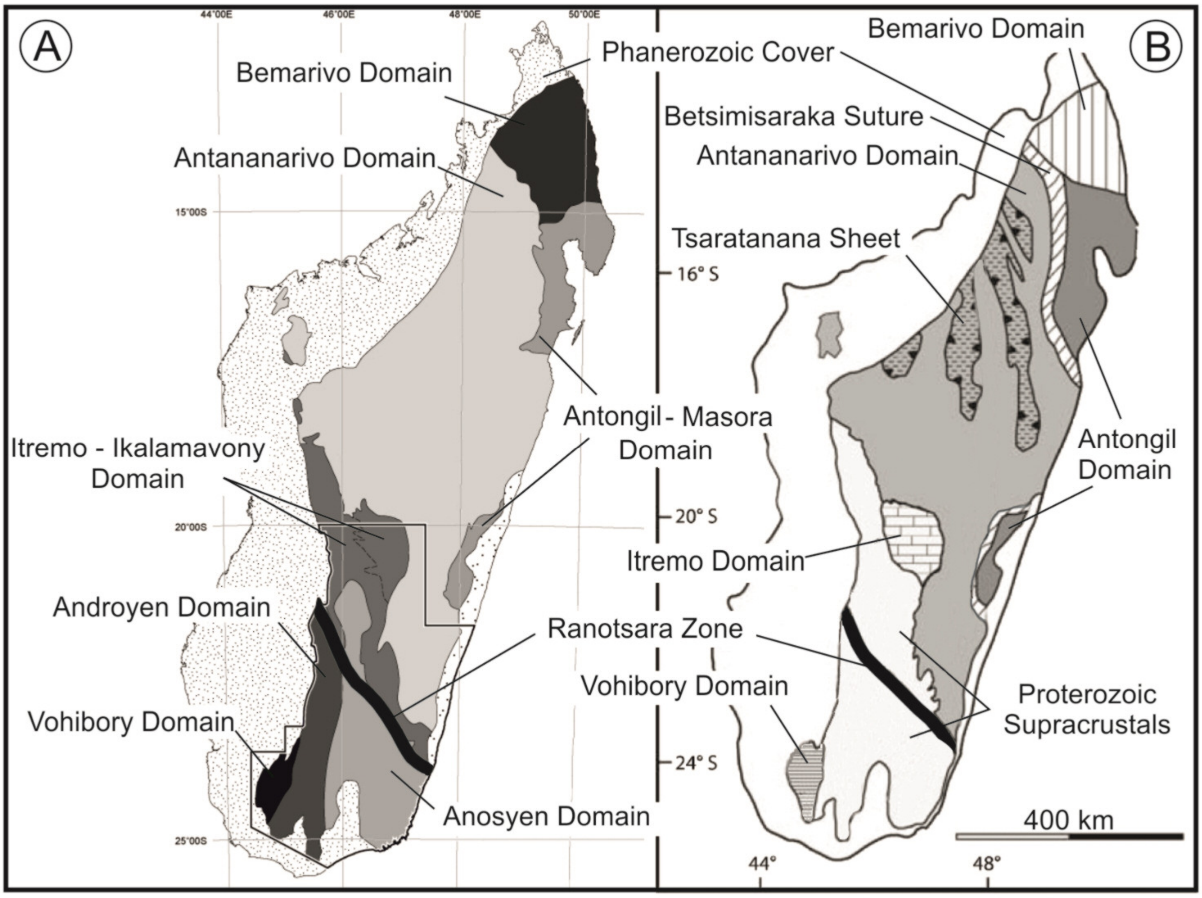


Figure 19: Overview of the main tectono-metamorphic domains of Madagascar.
Left: modified from Boger et al. (2009); right: modified from Schreurs et al. (2009). Main difference can be seen in the controversial outline and discussion of the Tsaratanana sheet, the Betsimisaraka suture and the Itremo domain (Cox et al., 1998; Collins et al., 2000; Fernandez and Schreurs, 2003; Fernandez et al., 2003; Fitzsimons and Hulscher, 2005; Collins, 2006; Tucker et al., 2007; Boger et al., 2009; Schreurs et al., 2009; Tucker et al., 2011).

To the north of this structure the Malagasy basement is thought to include the Archean Antongil and Antananarivo blocks, the Tsaratanana Sheet and the Neoproterozoic Bemarivo belt (Collins, 2006). South of this structure the rocks outside the Vohibory domain were divided originally into the Graphite and Androyen Series (Bésairie, 1967) although especially the studies of Collins (2006) tended to merge these series into a combined Androyen unit.

The Ranotsara zone's role in the geologic setting of Madagascar is interpreted differently (Figure 20) concerning tectono-metamorphic domains in the southern Malgache basement (Katz and Premoli, 1979; Müller et al., 1997; Tucker et al., 1999; Boger et al., 2009; Schreurs et al., 2009). However, a number of more recent studies question this interpretation and instead argue that the "Ranotsara shear zone" does not mark a significant litho-tectonic boundary, but rather represents a zone of significant sinistral displacement and that the tectonic domains of southern and central Madagascar can be extended across this structure (Boger et al., 2009; Schreurs et al., 2009; Tucker et al., 2011). It is therefore suggested to refer to it as the "Ranotsara high strain zone" (Boger et al., 2009) or more general the "Ranotsara zone" (Giese, 2009; Schreurs et al., 2009).

The subdivision of the central and southern Malagasy basement remains controversial. Based on different interpretations Bésairie (1973) describes eight subdivisions, Hottin (1976) divides the area in thirteen, whereas Windley et al. (1994) separate five sequences and Collins (2006) three tectonic domains, namely the Molo, Androyen and Vohibory, of which the latter is accepted in all interpretations.

The GAF AG-BGR study divided central Madagascar into four domains. From the southwest to northeast these are; (1) the Vohibory domain, (2) the Androyen domain, (3) the Anosyen domain and (4) the Ikalamavony domain. The Ikalamavony domain is bounded to the northeast by the Antananarivo domain and forms a complex infolded boundary with the Anosyen domain. This domain extends to the far south-east and south of Madagascar and shares a common north-south trending border with the Androyen domain in the west. The eastern and western borders of the Androyen domain are marked with prominent high strain zones that are referred to as the Beraketa (east) and Ampanihy (west) shear zones respectively (Martelat, 1998; De Wit et al., 2001).

Accordingly the Precambrian basement of Madagascar can be divided into the following seven domains (Figure 19), here briefly summarized from Boger et al.(2009) and Giese (2009):

- **Antongil-Masora domain**

  Middle Archean metamorphic sequences containing late Archean intrusions.

- **Antananarivo domain**

  Late Archaean orthogneisses containing middle Neoproterozoic to early Cambrian intrusions. Locally overlain by Palaeoproterozoic (Itremo) to early Neoproterozoic (Ambatolamby and Manampotsy Groups) sedimentary rocks.

- **Bemarivo domain**

  Amphibolite to granulite facies metasediments in the south, granitoids and metagranitoids in the central part and metavolcanics and metasediments in the north. A Neoproterozoic arc/marginal basin assemblage is most likely the protolith of the metasediment sequences in north and south (Thomas et al., 2010).

- **Ikalamavony domain**

  Late Mesoproterozoic sediments intruded by the early Neoproterozoic Dabolava and Imorona-Itsindro suite and east of the Beraketa high-strain zone by the late Neoproterozoic (Paquette et al., 1994) Ambalavao suite.

- **Androyen domain**

  Sequence of felsic volcanics, metasedimentary rocks and calc-silicates. Ages of protolith range from 2-1,2 Ga (Windley et al., 1994), more recent studies of Collins (2011) postulate protolith ages between 2,2-1,8 Ga with peak metamorphism at 531±7 Ma. According to Boger et al. (2009) the Androyen domain is intruded by the Ankiliabo suite between 930-910 Ma, metamorphosed at 610 Ma and again between 560-530 Ma, when it is intruded by the Ambalavao suite.

- **Anosyen domain**

  Consists of widespread commonly aluminous paragneisses, calc-silicates and felsic volcanics. Deformation ages remain controversial. Boger et al. (2009) argue an age of 740 Ma, based on the extrusion age of a felsic volcanic. Deformation ages are argued to be appreciably older by Tucker et al. (2011) and Collins et al. (2011). The supracrustals are widely intruded by granitoids of the Amablavao suite between 580-510 Ma (Boger et al., 2009).

- **Vohibory domain**

  Mainly felsic and mafic orthogneisses intercalated with paragneisses and locally prominent marble layers. The sequence is thought to represent back-arc and island-arc basalts (Jöns and Schenk, 2008) intercalated with shelf sediments and partly oceanic crust (Windley et al., 1994). The main metamorphism stage in the Vohibory domain is dated between 630-600 Ma (De Wit et al., 2001; Emmel et al., 2008; Jöns and Schenk, 2008), preceding the metamorphism peak of the neighboring domains (Boger et al., 2009).

Figure 20: Study area zone c in an reconstruction of Madagascar's position in Gondwana at 200Ma (modified from Reeves et al., 2002).

The more recent geologic history of Madagascar is closely related to the breakup of Gondwana in the Mesozoic (Figure 20). This period is divided by Giese (2009) into three stages of a) the decoupling of Madagascar from Eastern Africa, (b) the separation of Madagascar and India, and (c) the evolution of Madagascar during the Cenozoic. The decoupling of Madagascar from Eastern Africa began in the Late Jurassic when a rift system cut through the center of Gondwana. However continental extension was underway somewhat earlier, resulting in the deposition of the Karoo sediments, the equivalents of which overlie western Madagascar and define the rocks within the Morondava and Mujunga basins. Extension ultimately resulted in an interior seaway and separated Madgasacar - still combined with India – from eastern Africa (Simpson et al., 1979; Storey, 1995; Reeves and de Wit, 2000). Madagascar and India moved south-east compared to Africa until the Late Cretaceous, when India changed direction and moved rapidly to the north. At this time Madagascar separated from the Seychelles and India and was left as an isolated micro-continent close to its present position relative to Africa.

Vohibory Mapping Area

The regional geology of the Vohibory domain can be divided into three groups of supracrustals and one igneous suite (Boger et al., 2009). All rocks are metamorphosed to high grade and strongly deformed (Figure 21).

The protoliths of the Vohibory are of Ediacaran age and consist of mafic extrusive rocks (Mahafaly Group), felsic extrusive rocks (Gogogogo Group), and terrigenous and chemical sediments (Linta Group). Intrusive rocks (Marasavoa Suite) are also widespread and of intermediate to felsic composition. These rocks intruded contemporaneously with the extrusion of the felsic volcanic rocks. The whole domain is cross-cut by numerous Cretaceous basaltic dykes, most probably related to the Volcan d'Androy in the east, while the central part of the domain is thinly covered by Cenozoic sediments and duricrusts. The Phanerozoic sediments of the Morondava Basin onlap the Vohibory to the west, while in the east the domain is bordered by the Ampanihy high-strain zone, a10-20 km wide steeply dipping lineament of tectonic significance that separates the Vohibory domain from the Androyen domain.

The main metamorphic event in the Vohibory domain reached its peak between 630-600 Ma (De Wit et al., 2001; Emmel et al., 2008; Jöns and Schenk, 2008). Accompanying deformation resulted in at least four overprinting fold generations (Boger et al., 2009). Another earlier orogenic phase is recorded in the older Vohitani Group dating back to 660 Ma (Boger et al., 2009). These rocks are only exposed in a tectonic window located a little north of the village of Andranomilitsy. This region is unique within the wider Vohibory domain.

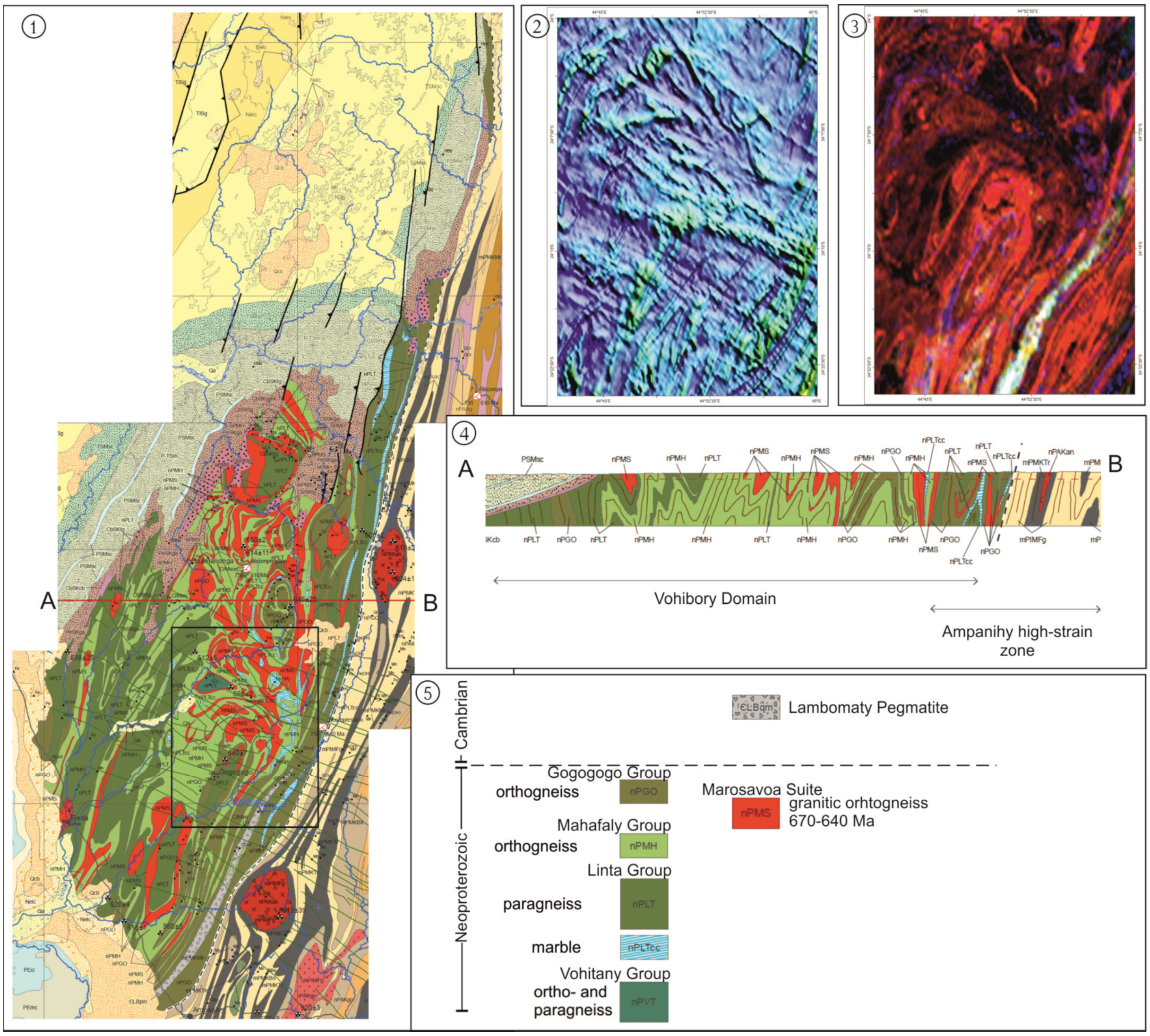


Figure 21: Geology of the Vohibory domain (all modified from GAFAG-BGR, 2009). ① Overview of the geology taken from the 1:500 000 scale geology map (sheets 10,11,12) produced by GAF AG-BGR consortium (GAFAG-BGR, 2009); ② Enhanced aeromagnetic data (extent see black rectangle in ①) with good visibility of the east-west trending dyke swarms; ③ Ternary image of radiometric data (R: Potassium, G: Thorium, B: Uranium), the Lambomaty Pegmatite is clearly visible in the south east corner; ④ cross section (along A, B); ⑤ Legend of the main lithology occuring in the Vohibory domain; map images displayed by courtesy of "Projet de Gouvernance des Ressources Minérales" (PGRM), Republic of Madagascar and GAF AG.

Tôlanaro Mapping Area

The Tôlanaro mapping area lies almost completely within the Anosyen domain (Figure 22). This domain is bounded in the west by the Beraketa high-strain zone and in the north by the irregular northwest trending contact between the Anosyen domain and the Ikalamanony-Itremo domain.

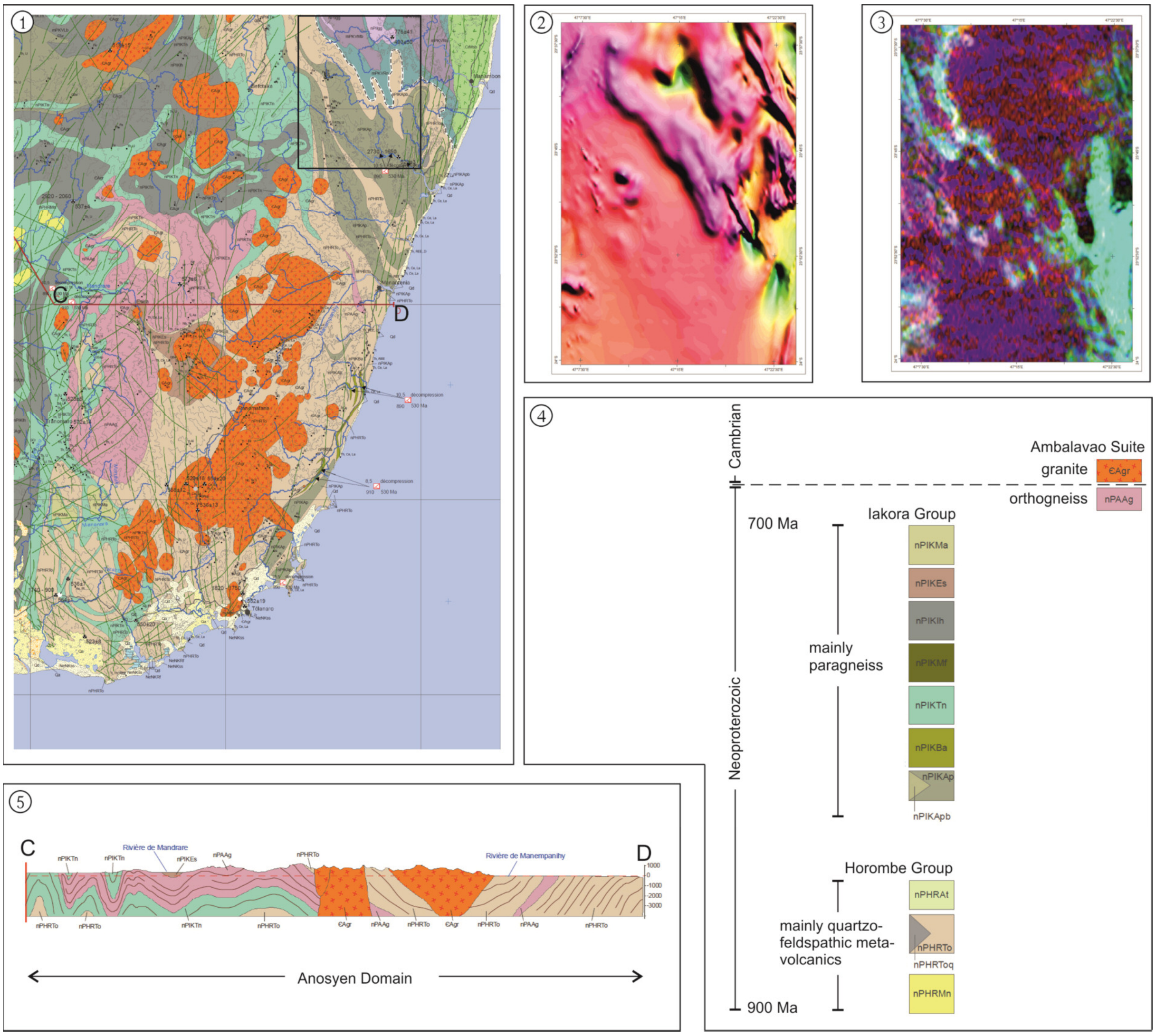


Figure 22: Geology of the Tôlanaro mapping area.
(All modified from GAFAG-BGR, 2009). ① Overview of the geology taken from the 1:500 000 scale geology map (sheets 11,12) produced by GAF AG-BGR consortium (GAFAG-BGR, 2009); ② Enhanced aeromagnetic data (extent see black rectangle in ①) with good visibility of the boundary between Anosyen and Itremo-Ikalamovony domains; ③ Ternary image of radiometric data (R: Potassium, G: Thorium, B: Uranium) picking the outline of the Tôlanaro Formation (Horombe Group) very clearly; ④ Legend of the main lithology occuring in the Tôlanaro mapping area; ⑤ cross section (along C,D); map images displayed by courtesy of "Projet de Gouvernance des Ressources Minérales" (PGRM), Republic of Madagascar and GAF AG.

The Anosyen domain is divided into two lithologic groups, the Iakora and Horombe Group. Both are of Neoproterozoic age and are interpreted to have been deposited at around 740 Ma (GAFAG-BGR, 2009). The Iakora Group comprises rocks mainly of sedimentary origin whereas the Horombe Group is defined by several quartzofeldspathic formations interpreted to be of metavolcanic origin. Both groups are intruded by the Ambalavao suite. This suite of granitoids consists of intermediate to felsic intrusions of late Neoproterozoic to Cambrian age. Rocks of this suite intrude widely, but are especially prevalent in the south west of the area. The majority of the Ambalavao suite define late- to post-tectonic intrusions (Boger et al., 2009) that are semi-circular in shape and can vary in aerial extent from some 10’s of km^2 to bodies of batholotic extent. Deformation slightly preceding these intrusions is characterized by generally open to tight folds with north-south trending axes in the south and somewhat tighter folds with a similar trend in the north (GAFAG-BGR, 2009).

The northern Anosyen domain is cross-cut by the Ranotsara zone (see above). Additionally the Anosyen domain is cross-cut by north and east to northeast trending dykes that are related to Cretaceous volcanism associated with the Volcan d’Androy. Remnants of this volcano are exposed in the west of the Anosyen domain.

2.4.2 DGM Study and Development of the Approach

Specific Study Objectives and Execution

The Madagascar geologic mapping campaign was used by the author to study the potential of the improved DGM system when dealing with the challenging tasks of an extensive mapping campaign with large expert teams involved. When in study phase one only a basic test of the system was applied by one trained user, the conditions in Madagascar confronted the DGM approach with much more requirements.

Although a multiple-user capability was technically implemented as a result of the first study it had to be thoroughly tested and the project conditions (chapter2.4.1) made it necessary to develop and further improve specific working routines for different conditions as part of the DGM approach:

- *The **Vohibory** mapping area with good access, little vegetation and abundant outcrops.*
- *The **Tôlanaro** area with very poor infrastructure, thick rainforest cover and only few outcrops.*
- *The **Ihosy** area, covering more than 100 000 km^2 with changing conditions and very limited field work time.*

As an enormous amount of digital and analog data products had to be delivered at the end of the project, the integration of the field data into a final production workflow was another study objective. To streamline the use of the new techniques, the author was involved in the whole process as a DGM expert responsible for setting up working routines, training of the geologists and supervision of the whole DGM process.

Technical DGM System Status

Whereas the first version of GeoRover XT worked well for a trained single user doing mostly car-based geology, this setup proved unsatisfactory in Madagascar. The complex regional geology of Madagascar and a large team of field geologists made three changes to the DGM approach mandatory: (A) The construction of a complex, relational database structure; (B) the intelligent management of multiple user data integration into one system; (C) data collection with easy-to-use mobile devices for the field work in rough conditions. These preconditions were achieved by upgrading the mobile GIS component while maintaining the functionalities of the main desktop GIS.

An independent transfer tool was programmed using C# .NET compact framework that managed the input and output of gathered observation data from and to a relational database, between PDA and laptop. The possibility to export raster imagery onto an external hand-held PDA was maintained, but both exported database and imagery were combined on the PDA in one program, allowing the entry of data to occur in a simple digital field book linked to a GPS raster viewer. All gathered field work data could be managed via unique ID for every user and integrated on a regular basis into the main database. The main hardware components of the field work in Madagascar are shown in Figure 23.

Figure 23: Main hardware components of the technical setup in Madagascar: ① Rugged "Tetranote XS" laptop; ② Trimble Recon PDA, ③ Trimble Recon with open lid connected to laptop via USB; ④ open lid of the Trimble Recon reveals the mountable CF card GPS receiver.

To visualize field work results, the main database could be used to export various SQL queries and integrate them as dbf-files into the desktop GIS.

Additionally, the author's review of the Vohibory field work phase lead to several other features that were integrated in the digital geologic mapping system prior to the Tôlanaro mapping campaign:

- *An easy selection of existing **observation points** to be exported to the PDA*
- *Existing **observation data accessible in the field** – comparison with data entries of other geologists in the field*
- ***Usability upgrade** of transfer tool*
- *Improvement of semi-automatic **field photo integration***

- *Quicker and more reliable* ***raster export function***
- ***Merging*** *of different main databases*

Whereas in the Oman project a single laptop (Roda Rocky I) in combination with a single Trimble GeoExplorer CE Handheld (Figure 17) was used, the Madagascar project had completely different needs. Over the duration of the project, the Roda laptop was replaced with faster and more convenient rugged laptops (TetranoteXS). The field teams were each equipped with a Trimble Recon PDA with GPS connection via Holux CF-card adapter, as well as adapters for power supply via car battery (Annex IV). In addition each team was provided with a Garmin GPS for backup and cross-checking of the measurements. During the Vohibory and Tôlanaro mapping campaigns, a digital field camp was equipped with a complete PC workstation, A3 colour-printer, A4 scanner, two laptops, and power recharging facilities supported by a small Honda generator.

DGM Workflow Mangement – Vohibory

To cope with the specific conditions of the field work in the Vohibory area the geologic field work was organized from a moving field base that worked also as a hub for incoming supplies and for the backhaul of rock samples from the field. It worked as a central point from which the mapping work was undertaken. The field teams headed out in assigned directions mostly returning daily, but sometimes fly-camping for several days depending on the most efficient way to deal with the mapping. When the area in the vicinity of the field camp was sufficiently mapped, the whole field camp was shifted to another central spot. The field camp was established in or close to the villages of Ampanihy in the south, Soamanonga in the central north, Gogogogo in the central south and Bekily in the east (Figure 18). To facilitate the DGM work, buildings were rented and used as field office whenever possible, with a camp built around. Whenever buildings were not available, the camp was arranged with tents. The power supply for the digital field office (Figure 24) was provided by two Honda generators, delivering enough power output to guarantee the simultaneous work of all the electronic equipment as well as provide light and other necessities.

Figure 24: Various digital field office setups in Madagascar.
① Field camp in Befotaka, basic digital mapping equipment, data transfer via satellite phone (mounted on the roof; ② Digital field office in Bekily, fully equipped with PC, printer, scanner, laptops; ③ On-screen discussion of digital mapping results; ④ Digital field office in Gogogogo with PC workstation; ⑤ Discussions by using print-outs of the digital mapping results.

Apart from the production of new geologic maps, the setup of a modern digital geologic database was part of the projects deliverables. To streamline this process it was tried to implement modern digital methods right from the beginning, manageable by a user group, not profoundly familiar with GIS and DGM methods. The improved DGM approach therefore considered the need to support the field geologists with a GIS and remote sensing geologist in the field, familiar with the DGM setting that had been established during the previous study. The intention was an ongoing "on-the-job" training of the geologists in regards to the new procedures, the supervision of the backup process, the production of tailored remote sensing image products, and the overall maintenance of the digital field office and the field database. It was planned to transfer more and more of the DGM responsibility onto the field geologists in order to integrate their work directly into the digital system. A seamless integration of the gathered field observations and individual interpretations into a GIS work flow was a main objective.

In general the geologists were trained by the author in his function as DGM expert, to export raster imagery from the main GIS program, to collect point and observation data directly with the PDA in the field, and then to integrate these data into the central field database. They were supervised in turns by the DGM expert in these processes. General problems could be attended directly in the field or the field office, not significantly slowing down the overall progress of the work.

A general DGM work routine had been established by the author during the Vohibory mapping campaign that is best described on the basis of a standard field work day, starting with the preparation in the field camp and ending with post-processing work. The several steps are referring to Figure 25, starting with the selection of the working area and the export of auxiliary data onto the PDA's raster viewer (①). The raster imagery was exported directly from the selected working window in the main program by using the developed transfer tool (②). Although direct vector transfer onto the PDA was not possible, vector information could be transferred as geo-referenced screenshot onto the PDA. These screenshots could include an outline of already interpreted lithologic boundaries to be checked in the field (⑨).

In addition, the field book database for the individual geologist had to be exported onto the PDA in order to set new observation points in the field (②). The transfer tool organized this procedure by linking the geologist ID – a three character code – with the mobile digital field book database that was exported onto the PDA. Once the individual mobile database was transferred onto the PDA, the geologist was ready to start field work, being equipped with raster imagery, auxiliary data and online GPS positioning (③).

In the field the geologist was taught to use the PDA as a navigation tool and follow his position on the selected background image, commonly a topographic or geologic map. As the Vohibory was well accessible by car (Annex VII) the geologist could navigate to the geologic or geophysical features of interest with little effort. In most cases good rock exposures could be reached within 500 meters of the car. This meant the battery life and weight were both negligible issues. Even on longer foot trips, which rarely extended beyond half a day, neither battery power nor weight was found to be a limiting factor.

When reaching a point of interest, the PDA was used in its primary function as a digital field book. A geocoded point could be created at the outcrop with a simple click. That point was automatically linked to a large amount of standardized attributes that were selectable via drop-down menus and defined in the preparation phase of the project (④). Field photos could be included in the database semi-automatically. Photo names had to be entered manually into the PDA database and the transfer tool renamed the photos according to the geologist and outcrop ID, storing the images automatically in a separate folder.

Apart from the data entry, the PDA's raster viewer could be used to interpret information and develop ideas while standing on the outcrop (⑤).

Returning from the field, the PDA was re-connected to the main database. Using the transfer utility the new data could be imported and merged into the main database (⑥). The database could then be used to export selected data and visualize them in the desktop GIS. Default SQL queries were created in the MS Access database that allowed quick data selection, including planar structural data, linear structural data, field lithology names and point IDs. Those could be visualized in the main program and used as the basis for interpretation (⑦). The post-processing work and analysis of the field work was undertaken on the desktop GIS. The geologist was able – after being assisted for a couple of times by the DGM expert – to do this digital interpretation autonomously. With the bigger screen in the field camp and the possibility of using several linked interpretation windows, theories that might have come up during the field day could be evaluated and further developed. Ideas could be directly put onto the digital map by creating vector layers or previously created vectors could be edited as needed (⑧). Further, the centralized field camp allowed for discussions amongst the geologists and especially the on-screen analysis of mapping problems between adjacent working areas. A basic digital field map was evolving as a “growing GIS” that everybody was contributing to. Finally new data could be transferred onto the PDA again to be ready for the next field day (⑨).

Due to limited map layout capabilities of GeoRover the DGM expert was simultaneously maintaining an ArcGIS project with the construction layers and field data. This maintained a provisional field map that met the standards of the contract and could be presented at short notice. That map was also printed occasionally to support the discussion amongst geologists and to see the areas in need of extra attention or second visits in the field

The field work did not always follow the work flow described above. Quite regularly one or two geologists were fly-camping for several days. In that case the geologists were provided with a laptop running a copy of the main desktop project and database to facilitate the backup of new data and enable the export of new raster extents onto the PDA. When returning to main camp the two databases could be merged with a developed application.

Although all integration and digital interpretation work was done by the corresponding field geologists, their work was supervised by the geologic team leader responsible for the “big picture” of the regional geology. The DGM expert assigned the team leader with the synthesis of the various vector layers and the regulation of field work schedules for the other field geologists according to the progress. The DGM expert trained the team leader specifically regarding the GIS procedures and assist him when was required to stay in the field office every now and then, to update the digital map according to the field work progress.

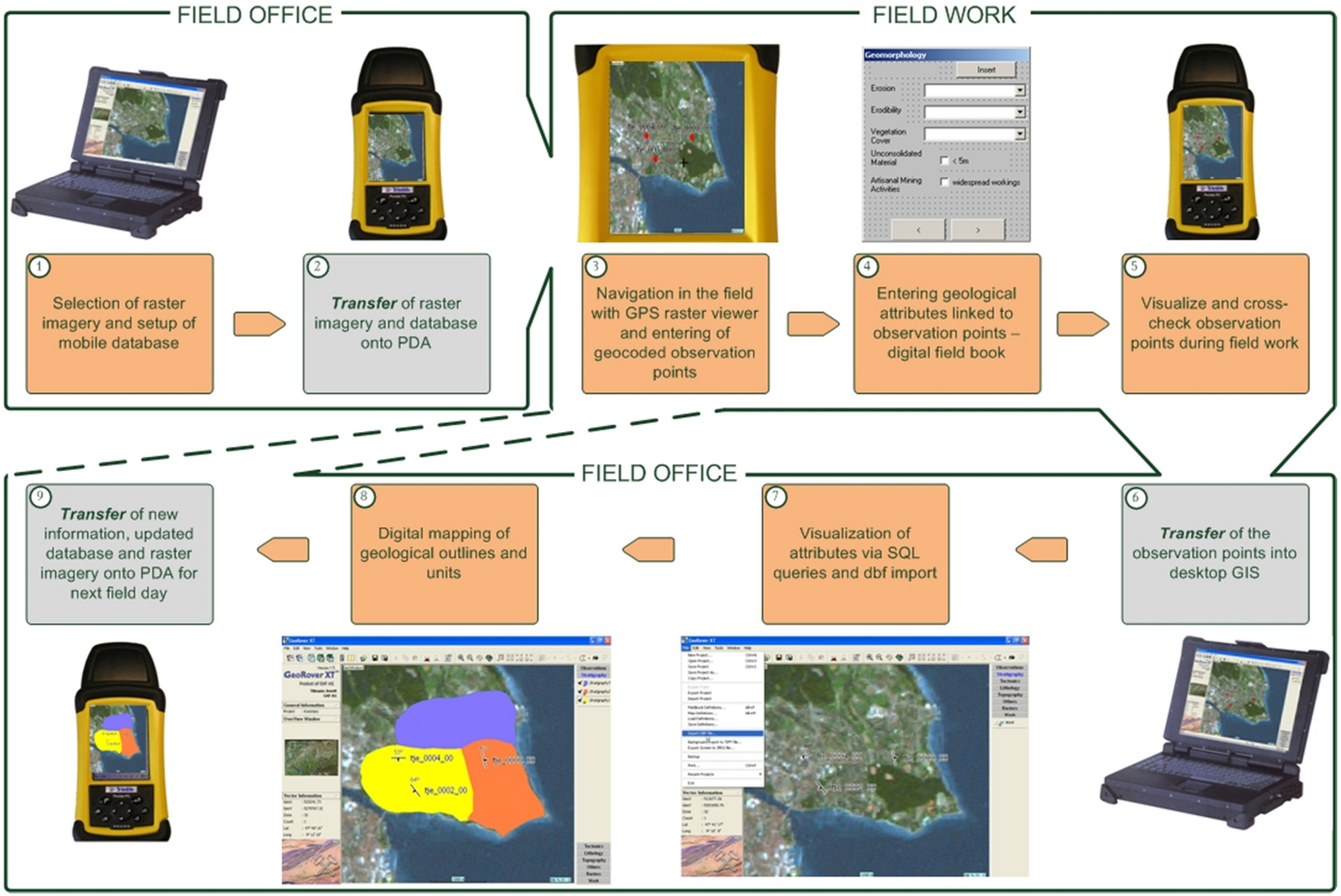


Figure 25: Schematic overview of the daily DGM working procedure during the Madagascar mapping campaigns.

DGM Workflow Mangement – Tôlanaro

Whereas the Vohibory area consists mostly of low-lying and sparsely vegetated semi-desert, the Tôlanaro area is mountainous and largely covered by thick rainforest. Additionally very limited and poor road infrastructure made geologic mapping in this area extremely challenging. The setup of a moving central field camp as in the Vohibory was generally maintained. Two main camps were established, one in Befotaka that worked as the base of operations for the first three months of the field season – the second in the village of Ranomafana, located in the center of the Ranomafana National Park for the rest of the field campaign.

Due to the very poor infrastructure in the northern part (Annex VIII) of the working area geologic field mapping mostly had to be carried out on foot. The same applied for the stream sediment surveys that were conducted in the area. Foot traverses of several days or more were planned in the camp and undertaken by teams, supported by local porters. The field teams were in the field for variable lengths of time, which could extend to eight or more days, before returning to the field camp. Additional car traverses were undertaken along the east coast and the western border of the Tôlanaro mapping area, where better road access existed.

The work flow that was established in the Vohibory area was only partly applicable in the Tôlanaro region. As the geologists stayed away from the field camp for longer periods, the daily working routine changed into a weekly one. Because of the time interval between data backup, on-screen interpretation and mapping in the field camp, teams were equipped with a laptop when working remotely. The training during the first campaign in Vohibory made the unattended work of the individual team in most cases unproblematic. On return to the field camp their preliminary results were integrated together with the DGM expert into the main GIS system.

For longer foot traverses laptops were not practicable. The PDA with an additional battery provided enough power for an eight to ten day traverse without problems, as long as the PDA was not permanently used as a navigation tool. PDA use was therefore limited to the collection of GPS coordinates and data entry at the outcrop, as well as for the identification and checking of the proximity to particular geologic features.

The main purpose of the digital field office in the main camp remained the same as in the Vohibory. The team leader was able to work on the final field map, having access to the data and interpretations from the various field teams. As the DGM expert was less needed in the run of the project, he was contributing to field work and DGM testing as additional field geologists.

DGM Workflow Management – Ihosy

In contrast to the relatively detailed (1/100 000) mapping of the Vohibory and Tôlanaro domains, the intervening area was mapped at the scale of 1/500 000. To cover the huge area, individual teams were required to carry out mapping work that involved limited field checks and widely distributed observation points. Due to these differences, the establishment of a central field camp was considered inefficient. Three teams were sent into defined areas, where they operated autonomously, meeting every two to three weeks for exchanging results. Most of the observations were made along main roads or tracks to cover the large area in the short time period. Accommodation was either arranged in small motels or fly camps. Some foot traverses were still undertaken where the road coverage was poor, particularly in the east and northwest.

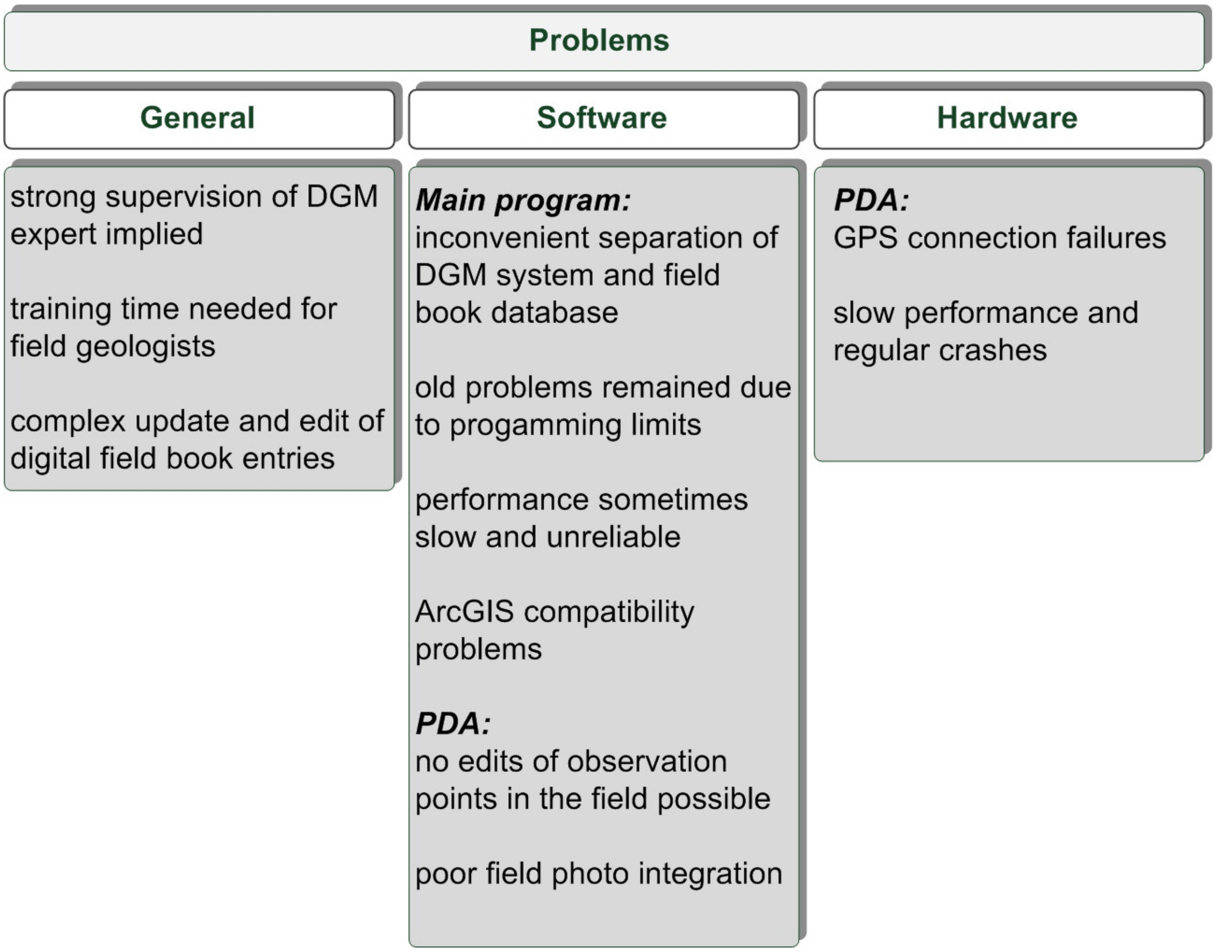
Although the experience of the geologists had far progressed to the point where they worked mostly autonomous in respect to the digital data collection and mapping, the position of the DGM expert was still considered as necessary by the author, mainly in regards to more complex GIS, remote sensing work and unforeseen problems with the DGM system. Apart from that, the three teams were capable of managing the transfer of data between PDA and main program, as well as mapping with the desktop GIS to document the regional geology of their assigned area. When meetings were arranged in the field, the database layers were merged and synchronized.

A considerable amount of digital mapping and interpretational work had to be done at that stage. Preliminary field maps were produced during and directly after the mapping phase, so that finalized vector files were available directly after the mapping campaign. These were used for the production of the final map products, starting immediately after the end of the field campaign.

Problems and Improvement Potential

The most severe problems that were analyzed by the author were relating to the communication between digital field book database (PDA) and GeoRover main program (Figure 26). As the field book database was not fully integrated into the desktop GIS, numerous error-prone work around procedures remained. With some training the field geologists were able to do digital mapping in the field office and data collection in the field independently but updating and editing the digital field book entries required advanced database and GIS skills that cannot be expected of all mapping geologists. As these processes had to be supervised by the DGM expert, the overall working speed during field campaigns was decreased.

As the system was still not completely compatible with ArcGIS a smooth integration into the general project workflow could not be realized at that time. Additionally most problems of the main program observed in the first study remained, as the software could not be significantly reprogrammed by software engineers at that stage. Thus it was highly recommended by the author to completely rebuild it according to modern programming standards.



Problems

General	Software	Hardware
strong supervision of DGM expert implied training time needed for field geologists complex update and edit of digital field book entries	***Main program:*** inconvenient separation of DGM system and field book database old problems remained due to progamming limits performance sometimes slow and unreliable ArcGIS compatibility problems ***PDA:*** no edits of observation points in the field possible poor field photo integration	***PDA:*** GPS connection failures slow performance and regular crashes

Figure 26: Main problems of the DGM approach in study phase II.

Summary

Study phase II is the most extensive one in many aspects. It deals with the management of large user groups and the geologic mapping of a huge work area. The specific requirements of the three sub-studies improve the significance of the study as the approach is tested under very challenging conditions. The position of the author as a DGM expert is established, being a mediator between the various experts groups involved in the new approach and an analyst of the requirements.

The resulting work concept and software system shows a strong maturation process compared to study I but still remained limited and error-prone concerning the usability for unversed users.

2.5 Study Phase III – Maturation of the Approach

The valuable information on digital geologic mapping that was gathered during the Madagascar project was thoroughly analyzed by the author and used as the basis for further improvement. Although an efficient DGM workflow was principally set, study phase II resulted in a great number of improvements concerning the software and the concept as such that were addressed prior to study phase III. The overall reliability and usability of the software was improved to a great extent and the implementation of new tools and work routines made the work more efficient. The multi-user handling was enhanced and the database management became much less error-prone.

This third study is dealing with the maturation of the DGM approach and a direct comparison with conventional mapping methods as observed during the Uganda geologic mapping project.

2.5.1 Study Framework and General Procedure

The study was conducted as part of the project “Geologic Mapping, Geochemical Surveys and Mineral Resources Assessment in Selected Areas of Uganda” tendered by the Ministry of Energy and Mineral Development of the Republic of Uganda, co-financed by the International Development Association. The project was carried out by GAF AG in a consortium with the Finish (GTK) and South African (CGS) Geologic Surveys, International Institute for Geoinformation Science and Earth Observation (ITC) Netherlands and FELS Consultants Ltd. Uganda (FELS). The project is currently ongoing and anticipated to finish at the beginning of 2012, although GAF AGs contribution was completed already at the start of 2010.

The study area covers the part of Uganda south of 01°N latitude, with an area of approximately 100 000 km^2. The project objectives were to update the existing maps on the basis of new field observations supported by additional geochemical and geochronological analyses. The results were to be presented on final thematic maps at scales of 1/250 000, 1/100 000 and 1/50 000. The data compilation phase, which included the generation of a uniform dataset of information layers and a full coverage of preliminary maps in 1/100 000 scale, was produced by GAF AG prior to the field work. Two field campaigns were carried out from March to April and from June to August 2009. As part of the study, upgrades and adaptations of the system were realized in between the field campaigns.

Regional Geographic Overview

The working area (Figure 27) straddles the equator and consists of a topographically varied and generally well-vegetated region typically underlain by a thick lateritic soil profile. Despite its equatorial position, Uganda experiences moderate year round temperatures of approximately 25˚C as a result of its generally high elevation (> 900 m) above sea level. Two rainy seasons, which coincide with the equinoxes, separate the drier periods from May to September and from December to February.

South western Uganda is mostly characterized by gently sloping hills and small non-perennial streams that dissect a broad peneplain at around 1300 meters. A thick laterite defines the peneplain surface, with bedrock exposed locally below this surface. In the southernmost part of Uganda, close to Rwanda and Congo, the morphology changes and the basement is widely exposed in mountain ranges south of Mbarara. In the central southern part of the country, in the Mubende and Jinja regions, outcrops of phyllite, quartzite, amphibolite and younger granites define areas of higher relief. In the south east of the study area quartzite ridges of the Lake Victoria Complex and the outstanding Mesozoic carbonatites related to the East African Rift System are well exposed and define topographic highs. The study area is limited to the south by the Lake Victoria shoreline, although including a number of small islands close to it.

Uganda’s economy and infrastructure is relatively well developed, consequently all of the standard necessities for a mapping campaign are available in larger towns and the road network is sufficient to allow mapping via car traverses in 100 000 scale mapping projects. The main roads are paved and mostly in good condition. The graded secondary roads are generally well maintained most time of the year. A large number of well distributed hotels, lodges and guesthouses can be found, as fly-camping could be quite problematic due to a high population density in the south. The mobile telephone network in the south is well developed, making satellite phones dispensable.

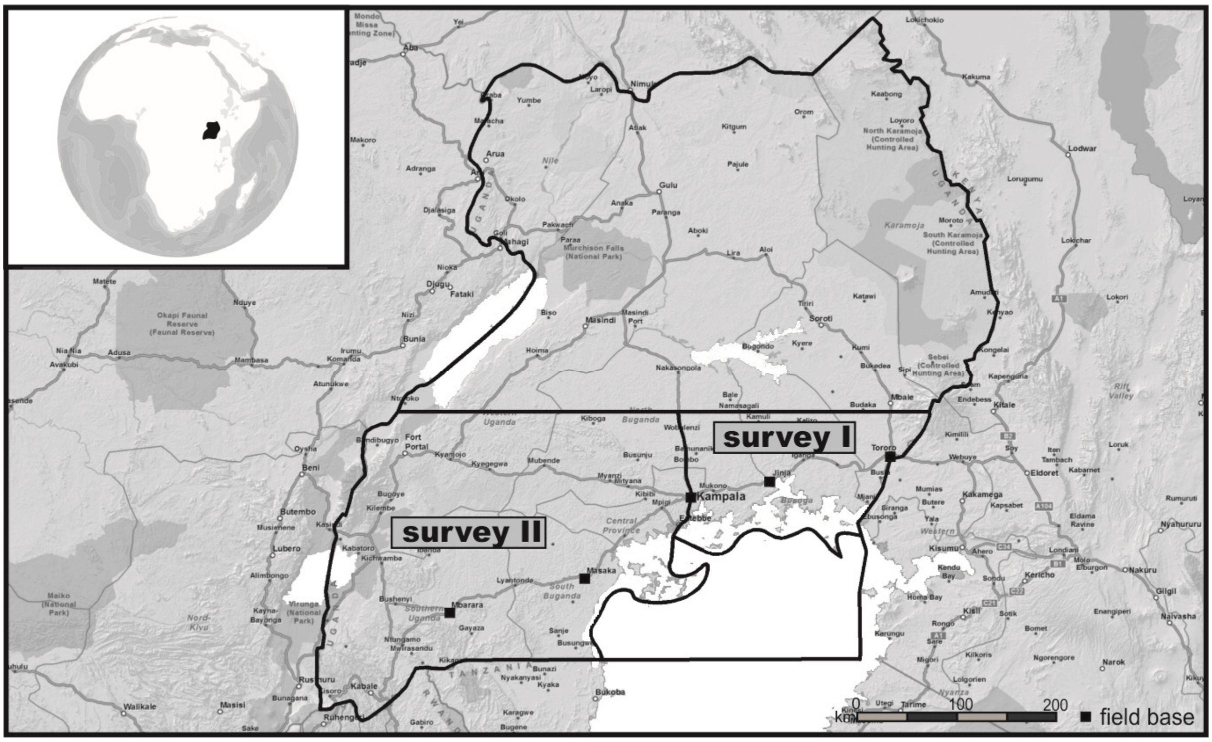


Figure 27: Uganda survey area I and II.

Survey area I was visited March to April 2009, survey area II from June to August 2009 (Modified from ESRI, ArcGIS online maps).

General Geologic Setting

More than two thirds of Uganda is underlain by Archean rocks (numbers in brackets refer to Figure 28). The vast majority of these rocks (①) is referred to as the Uganda and West Nile Basement Complex by Westerhof (2008) and crop out mostly in the central part of the country. The northern tip of the Tanzania Craton is also exposed and these rocks crop out in the south east of Uganda at the border to Kenya. Both are considered components of the central-African Congo Craton. According to Hepworth and McDonald (1966) the Uganda and West Nile Basement Complex of northern and central Uganda is further subdivided into two principle components. The first is defined by the granulite facies gneisses of the Watian Group (2.9 Ga ②), the second by the amphibolites facies gneisses of the Aruan Group (3.9 – 3.5 Ga). These rocks are overlain or intercollated with the gneisses of the Mirian Group (1 Ga) and metasediments of the Aswa Group (650 - 500 Ma). The Aswa group is deformed by the prominent Aswa shear zone (⑧) that bisects northern and central Uganda. It has a north-north-west trend, showing a range of ages between 500 and 430 Ma (Cahen et al., 1984; Westerhof, 2008). Rocks of the Tanzania Craton (part of the

Lake Victoria Complex) crop out south of the village of Tororo and are defined by the Neoarchean Nyanzian (③) greenstone belt (Pinna et al., 1996) or supergroup (GTK-Consortium, 2009). The Nyanzian Supergroup is intruded by younger post-tectonic granitoids (④) dated to 2.8 – 3 Ga (Borg and Shackleton, 1997).

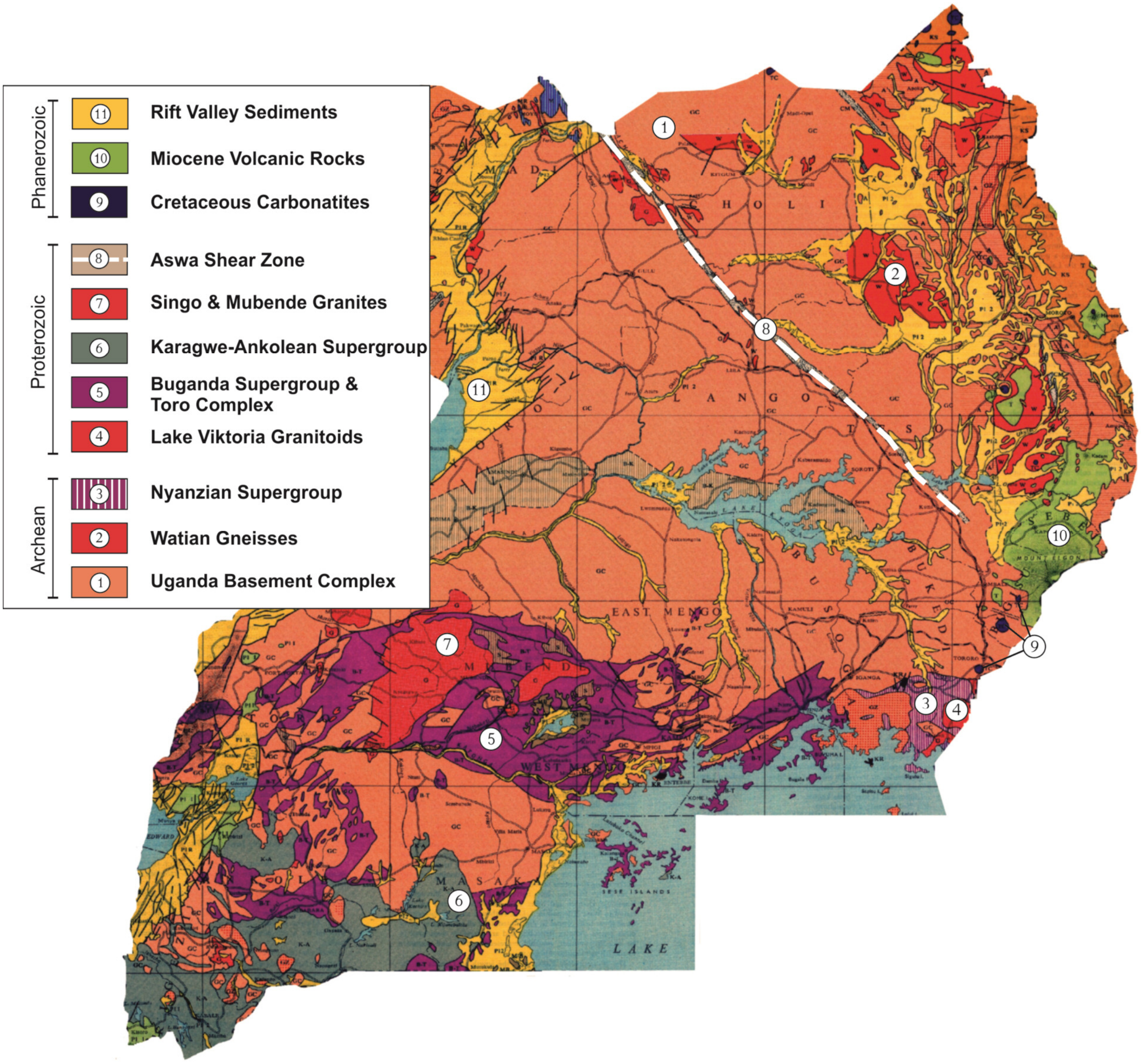


Figure 28: Overview of the simplified geology of Uganda.
(Modified from Macdonald, 1966). Numbers are referred to in the text.

Overlying these rocks are the rocks of the Paleoproterozoic Buganda Toro “System” (e.g. Macdonald, 1966; Schlüter and Trauth, 2006). The Buganda-Toro System extends as a ca. 50 km wide corridor from the Rwenzori Mountains approximately 350 km to the east (⑤). A discordant contact between these rocks and the older Lake Victoria Complex is exposed near the village of Jinja. Based on the mapping results of the present study the Buganda Toro "System" has been divided into the Buganda supergroup and Toro complex (GTK-Consortium, 2009). The Buganda Supergroup comprises of quartz-mica metasediments, while the Toro Complex consists of quartzo-feldsphatic gneisses of felsic volcanic origin that are considered older than the Buganda metasediments (Boger, 2009). The emplacement of the Singo granite in the Buganda Group and Toro complex is dated to the Paleoproterozoic, although the age is imprecise. Pinna et al (2001) attribute an age of 1847 ± 6 Ma, while Nagudi et al. (2001) suggest it is markedly younger (1615 ± 19 Ma).

These ages are believed to be similar to those of the larger Mubende (⑦) granitoid further to the west (Johnson and Williams, 1961; Macdonald, 1966). In the extreme southwest of Uganda along the border with Rwanda and the Democratic Republic of Congo, the metasediments of the Karagwe-Ankolean Supergroup (⑥) are exposed. These rocks were deposited during a post-Eburnean period of extension dated to between 1330 and 1250 Ma (Theunissen, 1988). Rhyodacitic tuffs at the base of the Karagwe-Ankolean Supergroup equivalent in Burundi give an age of 1353 ± 46 Ma (Klerkx et al., 1987). The Karagwe Ankolean Supergroup was shortened during a period of crustal shortening dated to between 1.1-0.95 Ga (Westerhof, 2008). This event resulted in the development folds of varying trend – NNW in the east and E-NE in the southwest. Deformation preceded the emplacement of the Kibaran "tin granites" at around 900 – 1000 Ma (Pohl and Günther, 1991). Where found within the Karagwe-Ankolean Supergroup, contact metamorphic aureoles surround these granitoids.

In the south west of Uganda an extensive swarm of mafic dykes intrude the Toro Complex and the Buganda Group. They are clearly observed in aeromagnetic data, and can be found locally exposed in the field. The dykes have not as yet been dated but seem not to intrude the Karagwe Ankolean Supergroup. If correct, this observation implies that these dykes pre-date the deposition of the Karagwe Ankolean Group which would limit these to ≤ 1350 Ma (Boger, 2009). These dykes also show a curved intrusion pattern that appears to be part of a bigger circular feature (Reeves, 2009) of probably more than 100 km diameter (Figure 29).

Rocks of Paleozoic age are not common in Uganda. The Cretaceous initiation of the East African Rift System resulted in the emplacement of several carbonatites (⑨) whose eroded remains define prominent landmarks today (e.g. Tororo). During the Miocene, volcanic rocks (⑩) extruded in the eastern rift valley of Uganda forming Mount Elgon, Mount Moroto and Mount Kadam. Ongoing sedimentation into both rift valleys in the east and west of Uganda is represented by the Pleistocene to recent rift valley sediments (⑪) (Macdonald, 1966).

In the southeast of Uganda close to Lake Victoria a well-developed peneplain overlies the basement. The surface of the peneplain is defined by a hard lateritic cap, the incision of which may relate to a period of Cenozoic uplift in this area (Boger, 2009).

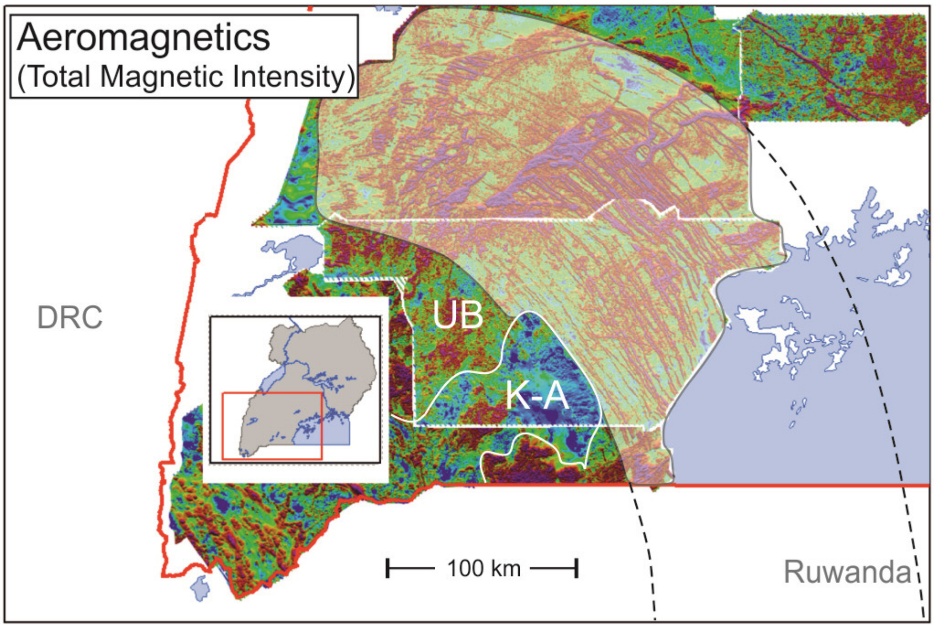


Figure 29: Mosaic image of aeromagnetic data from south west Uganda.
(Modified from GAFAG, 2009); UB: Uganda Basement, K-A: Karagwe-Ankolean Soupergroup; semi-circular dyke swarm (highlighted corridor) does not cut the K-A/UB border and is supposed to be traceable to Rwanda (dashed black lines). Aeromagnetic imagery displayed by courtesy of the Department of Geologic Survey and Mines, Republic of Uganda.

2.5.2 DGM Study and Development of the Approach

Specific Study Objectives and Execution

The field work in Uganda was split into two parts. During the first part of the study the eastern part of the project area between Tororo and Kampala was mapped. This campaign was carried out between February and April 2009. The western project area, Mbarara, lies between Kampala and the border to the Republic of Congo and was mapped and studied during a longer campaign from June to September 2009. The Tororo campaign was carried out by a team of approximately ten geologists, who worked independently or in teams of two geologists, depending on the given circumstances. It was agreed on separating the working area into a northern and southern part, the former being the responsibility of a GTK led team, the latter of a team of CGS and GAF AG geologists supervised by GAF AG. This separation was sustained in the Mbarara project area. The DGM setup had to deal with more fluctuation in personnel and the field work methods varied strongly between the two teams of GTK and GAF AG. The GAF AG team was using the improved DGM system resulting from the previous study (Figure 30), whereas the GTK team was mapping with a conventional setup. Hence the project gave the excellent opportunity to study the different working methods directly and made it very valuable for the evaluation of the DGM approach (chapter 4).

Technical DGM System Status

The long-term experience gathered during the Madagascar project was used to update the system and improve the DGM approach. On basis of the author’s analysis and discussions with software engineers the GeoRover software was completely reprogrammed and made compatible to ArcGIS, using C# and the ArcObjects library of ESRI, one of the market leaders in GIS technology with a market share of over 40%, estimated by the ARC Advisory Group (2010). This adaptation allowed the software to handle all standard raster, vector and geodatabase files that were compatible with ArcGIS. Additionally the mobile GIS application used on the PDA, or other Windows Mobile based devices, was programmed by the software engineers in C# .NET compact framework. It was combined with a raster viewer and a digital field book based on a relational MS Access database. All transfer functions for multiple

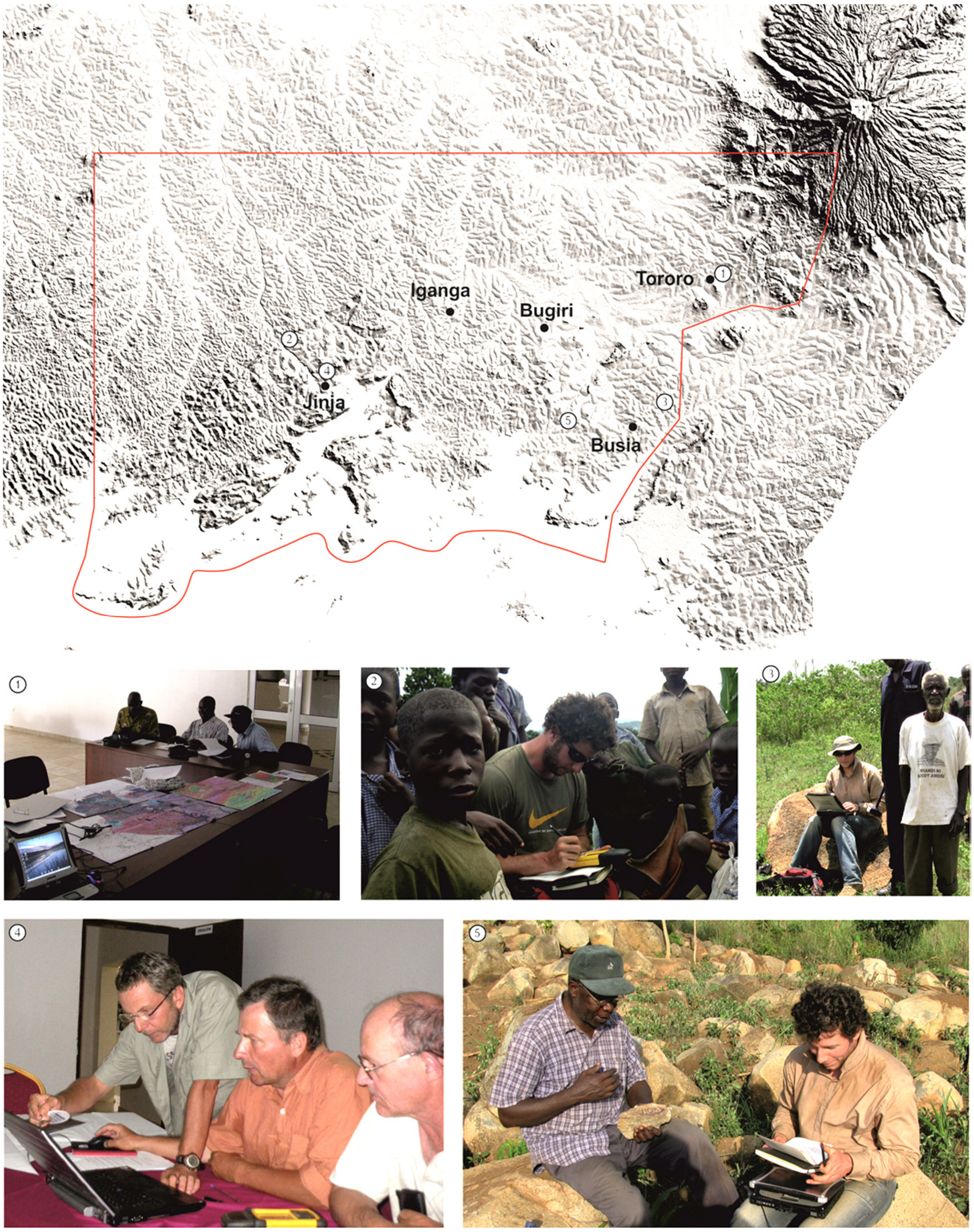


Figure 30: Field work and digital mapping during the Tororo mapping campaign.
① Discussions in the meeting room facility of a hotel in Tororo using analog and digital methods; ② working/explaining with the mobile PDA GIS version on an amphibolite outcrop north of Jinja; ③ using a tablet PC/laptop convertible with full desktop GIS version in the field; ④ discussion of field work results with transferred points from the PDA in Jinja; ⑤ using digital field book and analog observation form sheets on the outrop.

user groups were implemented in the main program and tedious work-around structures of the Madagascar study were avoided. The digital field book database now formed the backbone of the system accessed by both, the mobile GIS device and the desktop GIS.

Other additional functionalities were added by software engineers, according to the requirements that were analyzed by the author:

- *An **integrated editor** enabling features like undo-button.*
- *A simple and quick routine when creating **polygons and attributes from construction line** layers.*
- ***Direct access** to all field work information via digital field book.*
- *Extensive **symbology and label tools.***
- ***on-the-fly projection** and a more convenient table of contents menu.*
- *The display of features on the PDA was made customizable for a better visualization.*
- ***GPS tracks** could be collected **on the PDA** and easily transferred into the main program.*
- *Enhanced data export to PDA.*
- ***User access right management** for database edits.*

A lot of applications were integrated helping to streamline the production of geologic reports and final maps after field work. Apart from a customizable link to Google Maps to quickly compare positions with the digital atlas of Google, three very important tools were realized:

A) A high performance **3 D viewer** that had been developed as part of a diploma thesis (Gocke 2008). It handles a quick display of borehole data and seismic profiles, basic functionalities of vector editing and a quick calculation and editing of digital terrain models based on thematic raster layers.

B) A geologic **cross-section application** that manages the extraction of the relief along a customized line segment, while also marking lithological boundaries. Subsurface structures can then be drawn manually, by using the simple tools of the main program. Finished cross-sections can be exported as jpeg file and placed onto/within the final maps or reports. In addition, the cross-sections can be transferred into the 3 D viewer to analyze surface and sub-surface relations.

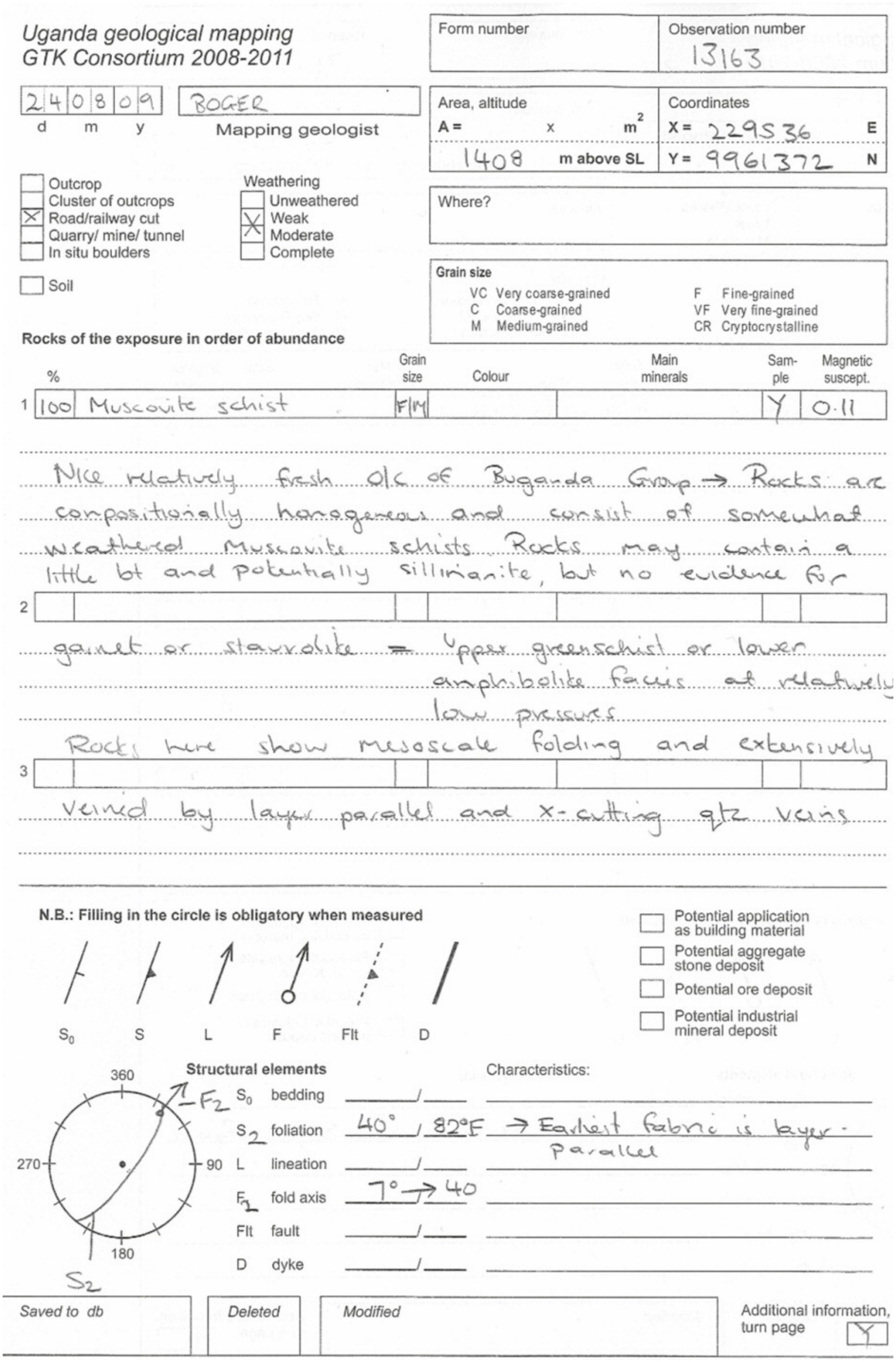
C) A **stereonet and rose diagram application** that can handle selectable structural content and datasets. The results can be exported and integrated into map or report (Figure 42, page 102).

With respect to the hardware, the expensive field (i.e. rugged) PDAs were gradually replaced by cheaper “office” PDAs. Although geologic field work generally represents a very tough environment that sets limits on the operational life equipment, the project work showed that in most cases cheaper “office” hardware sufficed, a tendency also described by others (e.g. Wilson et al., 2006). In the same way the rugged tablet PC convertible was more and more used for car drives but digital mapping work was done on a standard laptop in the field office due to its larger screen size and faster hardware components.

DGM Workflow Management

DGM techniques were not applied by all teams working in the field. GTK as the leading party followed a conventional work plan based on GPS handheld devices and analog field observation sheets. These were used for the detailed description of observation points and noting coordinates, structural measurements and further descriptive data as necessary (Figure 31). The analog field sheets were collected regularly in the field, processed and digitized by GTKs GIS experts and used for the plotting of intermediate and final maps in digital and analogue format. In contrast to this proposed mapping work flow, the GAF AG field geologists used the improved DGM work approach that resulted from study phase two in Madagascar. The analogue field sheets of GTK were used as a template for the digital field book on PDA and laptops (Figure 32), and the gathered observation data could be delivered to the GIS experts already in digital format. Additionally preliminary interpretation maps were delivered before leaving the field as part of the work results.

The new software setup reduced the daily preparation procedure and complexity, decreasing the need for a DGM expert. Error-prone work routines were generally minimized and the system became platform-independent, allowing the use of PDAs, tablet PCs and laptops without compatibility problems. All information of the database could now be accessed in the main program without the MS Access workaround of



Uganda geological mapping
GTK Consortium 2008-2011

Form number
Observation number 13163

24 08 09 (d m y)
BOGER (Mapping geologist)

Area, altitude
A = x m²
1408 m above SL

Coordinates
X = 229536 E
Y = 9961372 N

☐ Outcrop
☐ Cluster of outcrops
☒ Road/railway cut
☐ Quarry/ mine/ tunnel
☐ In situ boulders

Weathering
☐ Unweathered
☒ Weak
☐ Moderate
☐ Complete

☐ Soil

Where?

Grain size
VC Very coarse-grained
C Coarse-grained
M Medium-grained
F Fine-grained
VF Very fine-grained
CR Cryptocrystalline

Rocks of the exposure in order of abundance

	%		Grain size	Colour	Main minerals	Sample	Magnetic suscept.
1	100	Muscovite schist	F/M			Y	0.11
2							
3							

Nice relatively fresh o/c of Buganda Group → Rocks are compositionally homogeneous and consist of somewhat weathered Muscovite schists. Rocks may contain a little bt and potentially sillimanite, but no evidence for garnet or staurolite = Upper greenschist or lower amphibolite facies at relatively low pressures

Rocks here show mesoscale folding and extensively veined by layer parallel and x-cutting qtz veins

N.B.: Filling in the circle is obligatory when measured

☐ Potential application as building material
☐ Potential aggregate stone deposit
☐ Potential ore deposit
☐ Potential industrial mineral deposit

Structural elements Characteristics:

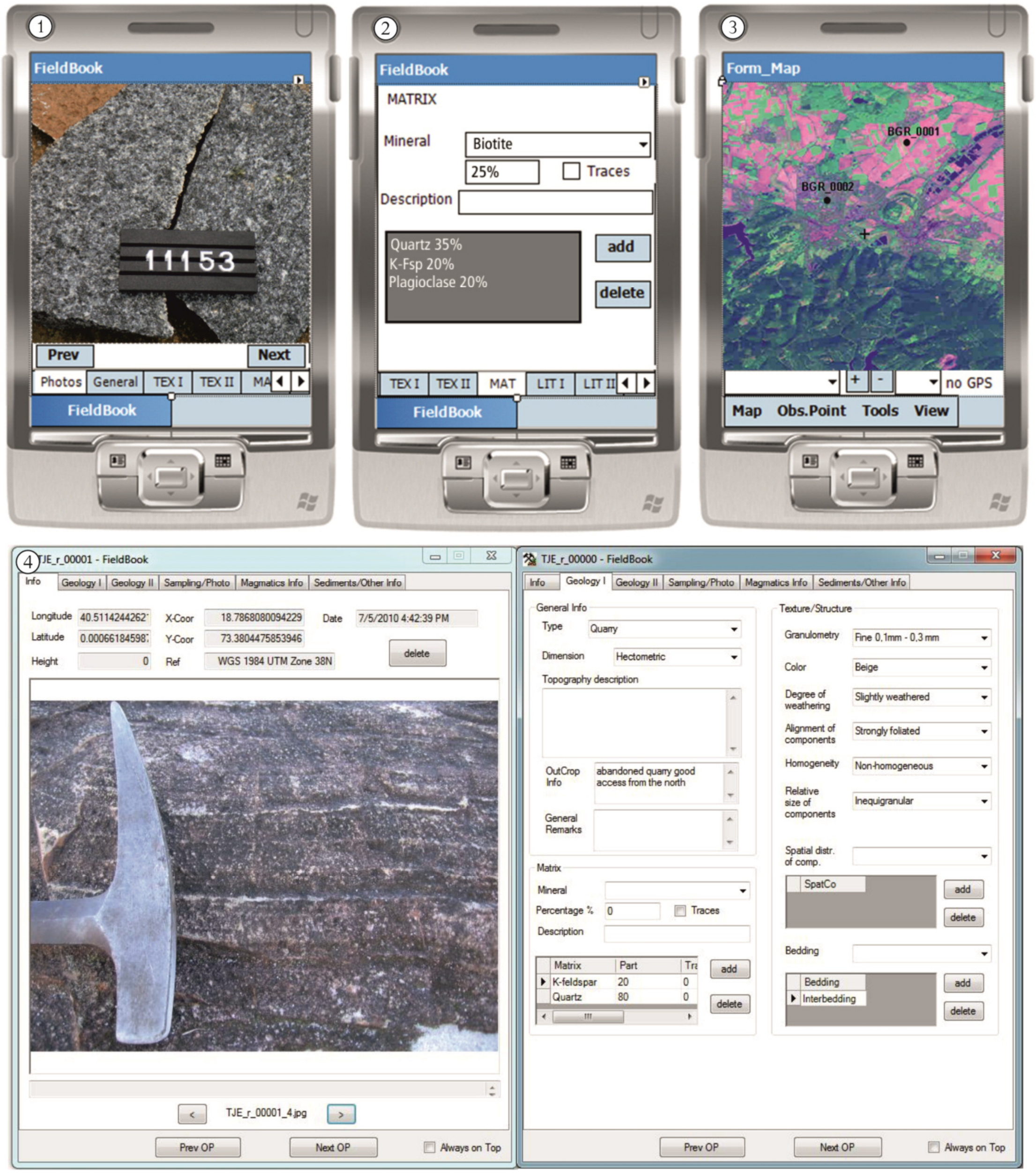
S_0 bedding ____/____
S_2 foliation 40° / 82°F → Earliest fabric is layer-parallel
L lineation ____/____
F_1 fold axis 7° → 40
Flt fault ____/____
D dyke ____/____

Saved to db
Deleted
Modified
Additional information, turn page Y

Figure 31: Analog observation form sheet used in the Uganda mapping campaign. (The form sheet is used by permission of GTK, Finland).

study phase two. Therefore the repetitive digital mapping and interpretation of field observations in the field camp was made much faster, more convenient and therefore better adopted by the geologists, putting the idea of a "growing GIS" into practice.

As the GAF AG team co-operated with Ugandan geologists not using DGM techniques in the field, the digital field book entry mask was used to easily integrate their data into the field observation database and keeping it up to date.



MATRIX
Mineral Biotite
25% ☐ Traces
Description
Quartz 35%
K-Fsp 20%
Plagioclase 20%

TJE_r_00001 - FieldBook
Longitude 40.5114244262
Latitude 0.00066184598
Height 0
X-Coor 18.7868080094229
Y-Coor 73.3804475853946
Ref WGS 1984 UTM Zone 38N
Date 7/5/2010 4:42:39 PM
TJE_r_00001_4.jpg
☐ Always on Top

TJE_r_00000 - FieldBook
General Info
Type Quarry
Dimension Hectometric
Topography description
OutCrop Info abandoned quarry good access from the north
General Remarks
Matrix
Mineral
Percentage % 0 ☐ Traces
Description

Matrix	Part	Tra
K-feldspar	20	0
Quartz	80	0

Texture/Structure
Granulometry Fine 0,1mm - 0,3 mm
Color Beige
Degree of weathering Slightly weathered
Alignment of components Strongly foliated
Homogeneity Non-homogeneous
Relative size of components Inequigranular
Spatial distr. of comp.
SpatCo
Bedding
Bedding
Interbedding
☐ Always on Top

Figure 32: Digital observation form (digital geologic field book).
① PDA field book: photo viewer; ② PDA field book: lithology entry mask; ③ PDA field book: raster map viewer with position and additional observation points; ④ Digital field book of main desktop GIS: data entries via drop-down menus and tabs.

Managing the overall progress of the field work, the team leader coordinated the field teams by analyzing their recorded GPS tracks and areas of poor observation point coverage were attended accordingly. The presentation of the current work status and preliminary interpretations during team discussions was done directly within the program, often with the use of a video beamer.

Problems and Improvement Potential

Most problems concerning the DGM methods as identified by the author were related to the fact that the teams were working with different setups during the Uganda mapping campaign. As no binding DGM approach was set, a dual system of conventional mapping and DGM techniques developed in the same team, creating extra work and lessened the potential of the working approach. Although the DGM software system was working very well and reliable, a very short “on-the-job” training left some geologists with too many uncertainties. This can be clearly seen as a training problem, not a DGM problem as such. Anyway this fact understandably favoured the attitude of the geologists to use well-known conventional techniques when minor problems occurred during field work.

The work with the Trimble Recon PDAs faced a lot of hardware problems at that stage, mainly relating to the age of the devices. Newer PDAs did not show severe problems. As tablet PCs became more common at that time, the screen size of the PDAs was often considered as too small by geologists. Tests with a tablet PC in the field proved the high potential of it, concerning screen size and functionality of the full desktop GIS version running, but they also showed that battery power, data entry, bulkiness and weight were still limiting the use. Especially the use of a touch screen with an active pen when digitizing features proved to be quite tricky and improvable.

Summary

Whereas the first two study phases concentrated on the development of the approach as part of this thesis, the DGM approach that developed as a result of study phase three can be seen as a solid work concept; though still with a high improvement potential, especially concerning the use of new hardware systems to come. The approach considered all theoretically defined necessities and requirements of an efficient implementation (chapter 2.1) with working procedures that matured over all study phases. The status of the approach is summarized in chapter 3 and used for the following evaluation of the specific DGM approach and DGM methods in general, in chapter 4.

3 SYNOPSIS OF THE NEW DIGITAL GEOLOGIC MAPPING APPROACH

The approach is based on two components: The organization and management of all experts involved in geologic mapping campaigns in relation to the overall DGM work flow and the conceptual development of a technical DGM system.

The experience gathered during the various mapping surveys and the specific studies (chapter 2) resulted in an approach that allows the implementation of all traditional field work know-how into a modern DGM work flow. The approach takes the established geologic working procedures and the new digital standards of modern surveys into account. Although the studies are focusing on geologic field work, the developed approach considers all different experts involved and their mutual interactions throughout the preparation, field work and final production phases (Figure 33).

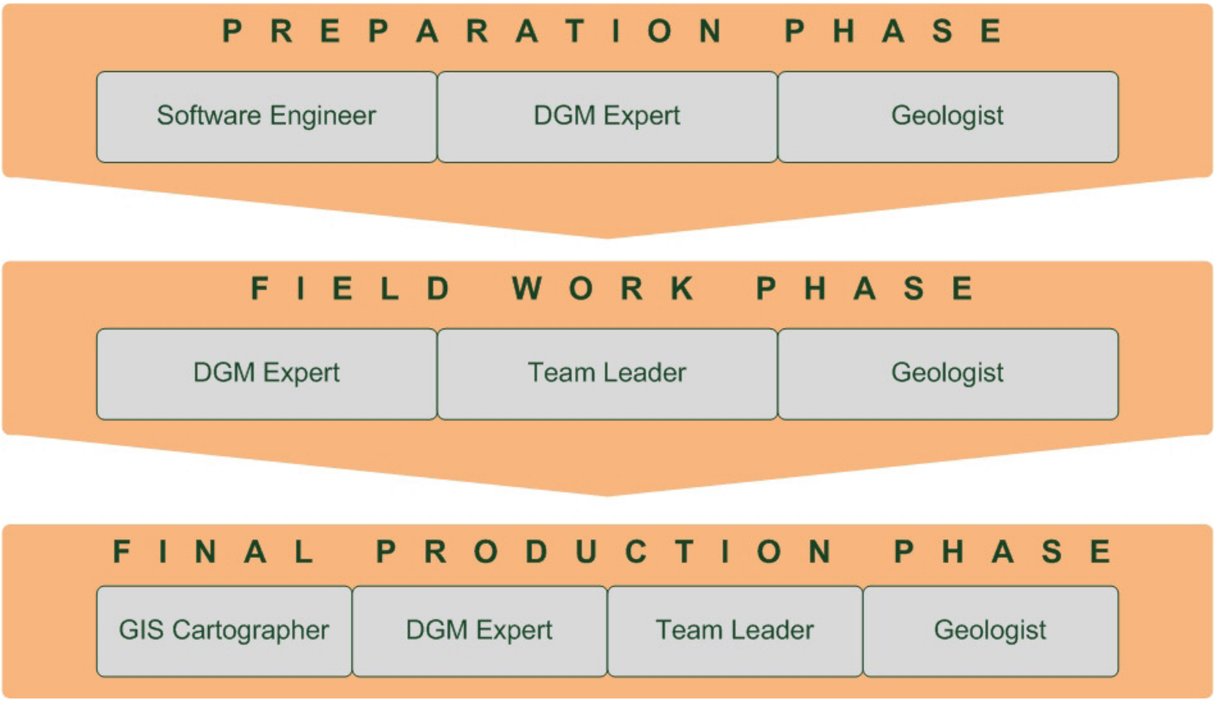


Figure 33: Schematized geologic mapping project phases and key experts involved.

When improving the DGM approach and conceptually designing specific GIS software tools as part of this thesis, the aim was to streamline the whole geologic mapping process. Therefore, the requirements of the geologist in the field and of the GIS expert in the office were seen as the two cornerstones that have to be considered in a smooth work flow. In order to create a flexible system and to maximize the efficiency the author shows that the position of a DGM expert as intermediary is advisable, understanding on one hand the working requirements of the field geologist and the GIS cartographer, and on the other hand the limitations of software engineering as the presented approach is based on the continuous development of a DGM software system. The DGM expert – a position the author was put in charge with during the thesis work - is therefore responsible for the analysis of field work requirements, the definition of specific soft- and hardware needs and the implementation of new features in close collaboration with software engineers (Figure 34).

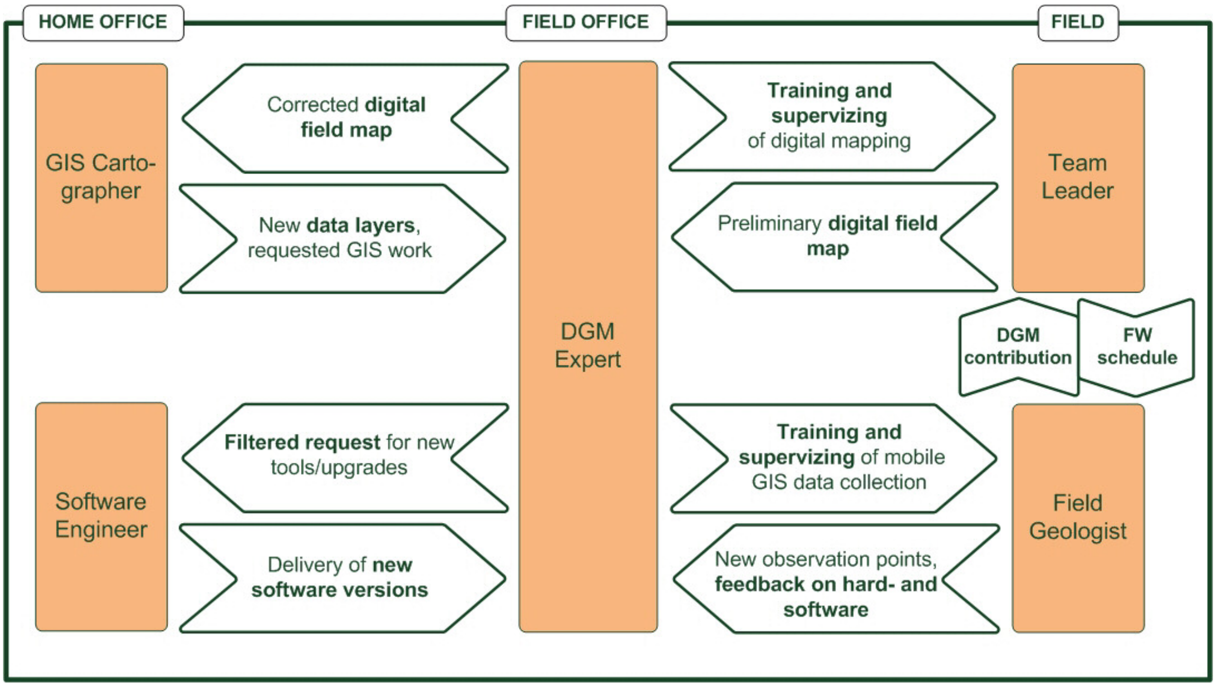


Figure 34: Schematic overview of the central role of the DGM expert as intermediate between key experts; (FW: field work).

The developing technical DGM system is based on a desktop version, including GIS mapping functionalities with special geologic tools and applications, and a mobile version for the use of handheld devices in the field. The data management in the office and the field is organized by a relational digital field book database that allows the handling of multiple users entries. Special tools that were developed since the invention of the GeoRover system include multiple working windows, a cross-section application, supervised classification tools, rose plot diagrams and stereonet projections. According to the contribution of the author, these improvements are presented by their design and functionality in geologic field surveys – not by their technical conversion.

3.1 Management of the Digital Geologic Mapping Workflow

This chapter summarizes the administrative part of the approach, dealing with the efficient organization of preparation, field work and final production phases, being a result of this thesis. The author in the position of a DGM expert describes his developed concept of managing all involved expert groups while aiming at the smooth implementation of the DGM methods. Figure 35, Figure 36 and Figure 38 find their equivalents in the assessment of the DGM approach in chapter 4.1.

3.1.1 Preparation Phase

Every phase of a geologic mapping project is characterized first by the definition of the survey's objectives. The complexity and extent of the work to be carried out also affects the technical and logistical setup of the DGM approach in various ways. It is comprehensible that a geologic compilation mapping with only limited field checks in 1/500 000 scale favors a different logistical, field work, and soft- and hardware setup in comparison to a detailed new mapping in a scale of 1:100 000. However, a generalized work schedule of the key experts in the preparation phase can be given in the following (numbers in brackets refer to the task numbers in Figure 35):

In a first step, geologists are characterizing and summarizing the regional geology in collaboration with the DGM expert (①). The DGM expert defines the special requirements of the software and provides the software engineer with the needed information to update the system accordingly (②). After the software has been tailored to the specific project needs (language, regional geology, hardware systems etc.), the scientific data compilation starts (③). It ends with the establishment of a GIS project containing all useful vector and raster information (④). The handover of the responsibility for the data to the geology experts and the start of a first interpretation phase (⑦) require a degree of basic GIS training (⑤) to allow the geologists to work independently in a digital environment. During this phase they are supported by the DGM expert in all aspects of GIS and remote sensing techniques (⑥) necessary for a thorough scientific study. Together geologists and DGM expert aim to produce a preliminary interpretation dataset that forms the basis for field work. The outlining of specific areas of interest (AOI) is the most important step in the preparation phase of the geologists, as these provide a provisional work schedule for the field campaign by highlighting specific targets. The AOIs are derived from various sorts of data combinations by making use of GIS functionalities (⑧).

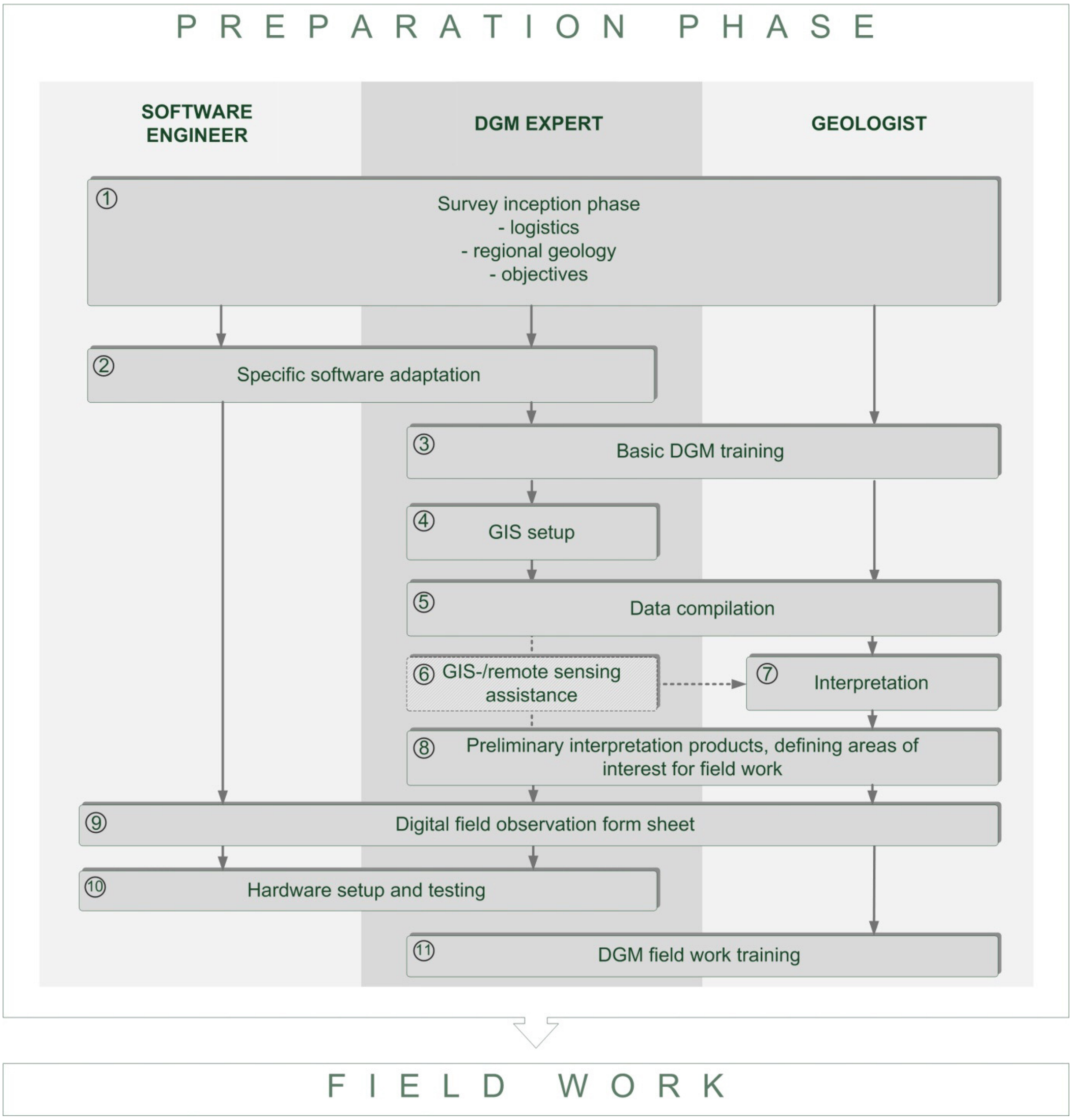


Figure 35: DGM working approach – preparation phase.

Involvement and interactions of the personnel during the preparation phase of a geological survey; dashed pattern resemble a part-time function; the task numbers are referred to in the text in brackets.

Once the geologists are familiar with the regional geology and some clear hypotheses for the field work have been established by the team, a digital field observation sheet (⑨) is set up in cooperation with the DGM expert. It is constructed as a relational database, containing all possible data entries that are likely to be needed during the field work. Further, it is designed in a way so that it can be adapted to upcoming needs of the geologists during field work. The database is afterwards integrated as a graphical user interface (GUI) into the software, allowing the digital data entry in the field via a mobile GIS unit.

Apart from the scientific and software preparation, the hardware and especially its interaction with the software need to be thoroughly tested. It is the role of the software engineer and DGM expert to check the system (⑩) under conditions as realistic as possible. This includes establishing a work flow that suits the needs of the geologist in the field *and* considers data security. Once done, the field geologists need to be trained in the use of the software and hardware (⑪). The whole phase is carried out in close cooperation with all team members under supervision of the DGM expert. Apart from the overall technical and scientific management of the preparation phase, updates of the software system are diligently recorded in order to avoid extra work in the follow-up.

3.1.2 Field Work Phase

The field work campaign starts with an inception phase in which all team members are based in the same area. Geologic working methods can be harmonized and the DGM procedures and techniques can be taught in one group.

The key positions during the field work campaign are held by the geologists and the DGM expert. As extensive mapping surveys tend to comprise of large teams, the position of a senior geologist working as a team leader is generally established. The team leader coordinates the schedules of the other field geologists in accordance to the working hypotheses and the need to produce a systematic coverage of observation points. Additionally, in the presented new approach, the team leader maintains close contact with the DGM expert and is responsible for the integration of digital data from the field geologists and the creation of the preliminary digital field maps (bracketed numbers in the following refer to task numbers in Figure 36). Once the first training phase (①) is completed and the field geologists are comfortable with

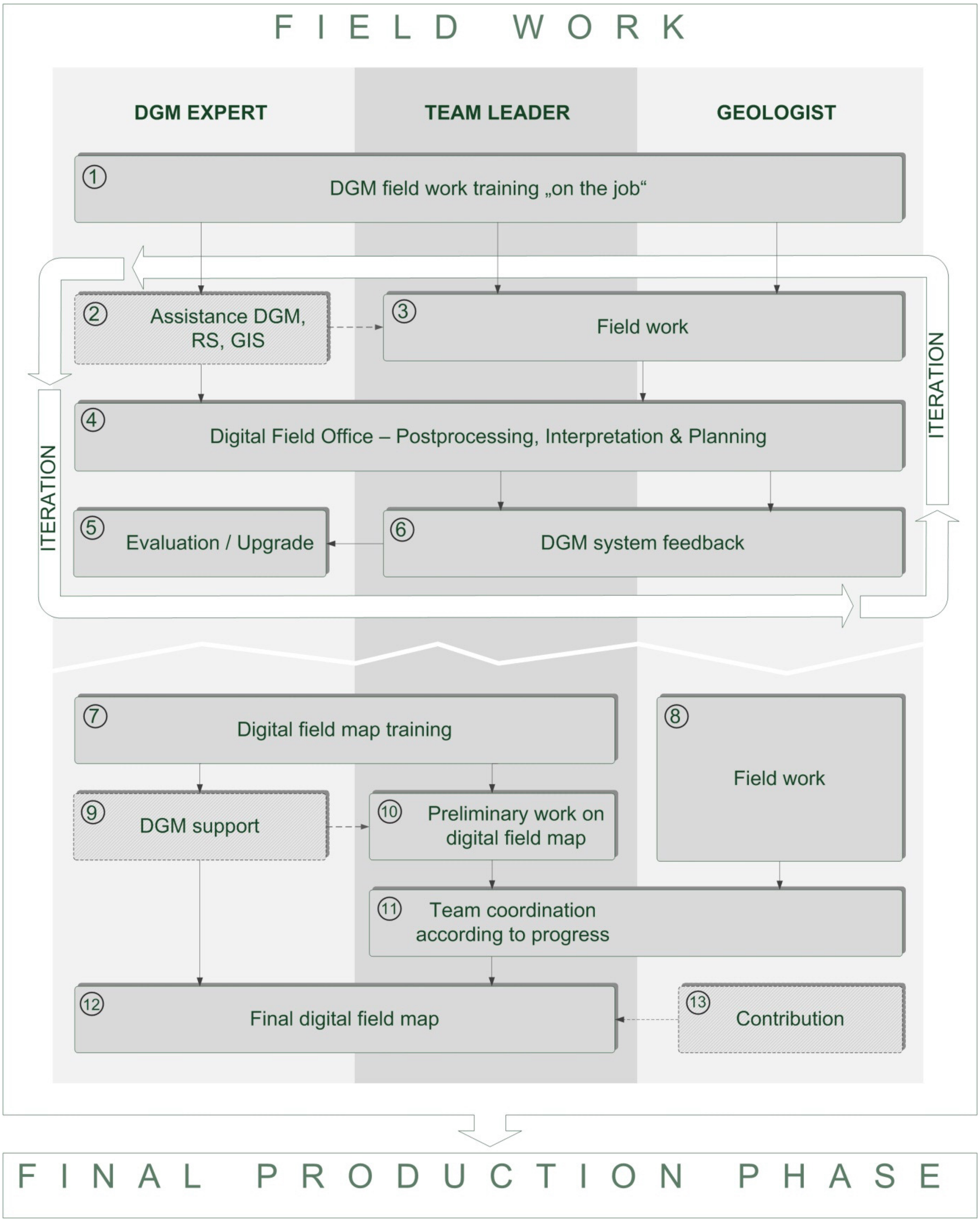


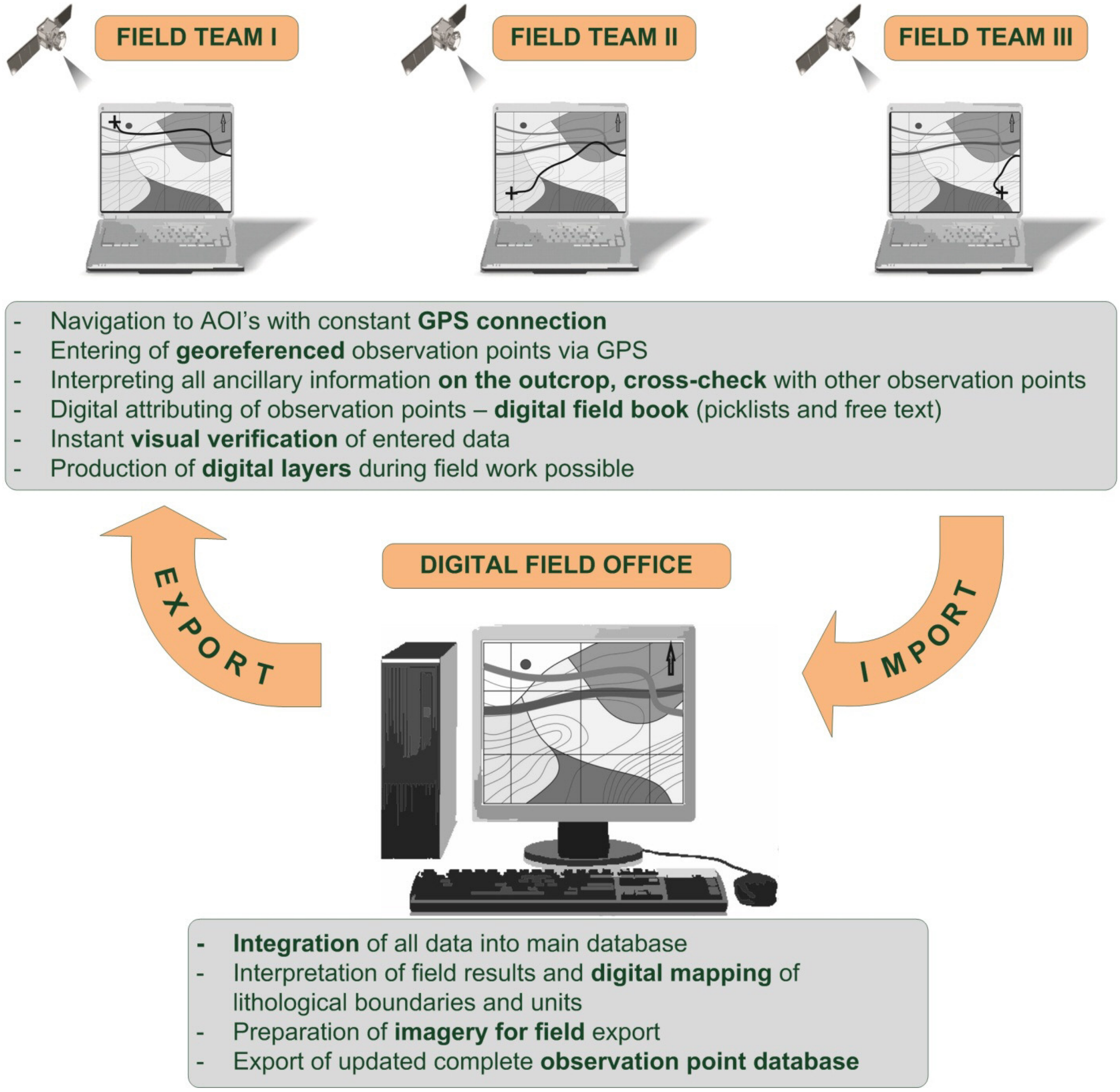
Figure 36: DGM working approach – field work phase.
Involvement and interactions of the personnel during field work of a geological survey; dashed pattern resemble a part-time function; the task numbers are referred to in the text in brackets.

the DGM work flow, the teams start their individual field work schedule. Their field work activity radius is bound to mobile field headquarters, consisting of a digital field office, storage and supply facilities. Although the geologists can be in the field collecting observation points for several days with mobile GIS units, they are ultimately obliged to return to the field office on a regular basis to integrate their data into the main database. Here they get the opportunity to interpret their field observations and upload an updated version of the project's main database onto their devices. Along with these DGM procedures the storage of rock samples and the refilling of supplies are handled as well. All teams are supported in a rotary system by the DGM expert who is based at the digital field office most of the time.

Apart from assisting in the data integration, the DGM expert provides the field teams with enhanced remote sensing data or other tailor-made datasets that might help visualizing or interpreting aspects of the local geology. The field teams are interviewed by the DGM expert regarding their feedback concerning software and hardware performance and other system-related issues. If software failures occur, or the data collection system needs improvement, this is communicated to the software engineer at the home office after evaluation by the DGM expert. Consecutively software modifications can be implemented and the modified software upgrades can be transferred back to the field office (Figure 34, page 88).

This whole process (②-⑥) runs through numerous iterations during the field campaign and comprises the main work flow in the field, resulting in a constantly growing observation and interpretation database (Figure 37).

Simultaneously – in collaboration with the DGM expert – the team leader (⑦) starts to produce a regional geologic model from the various interpretation layers outlined by the field teams. The digital database system supports this activity by granting access to all information entered by the various field teams. During the whole process of creating a preliminary digital field map (⑩), the team leader is supported by the DGM expert on demand (⑨). As the geologic model and the preliminary field map evolve, the team leader coordinates the work schedules of the field teams to fill in gaps in the observation coverage or to gather additional information needed to answer specific scientific questions (⑪). Finally, close to the end of the field work campaign, the team leader develops the final digital field map that best reflects the status quo of the field observations and interpretations (⑫-⑬). By using the established project GIS and the designed software tools, map boundary problems are handled and decisions are made concerning the classification of lithological units, their description and the selection of representative samples to be sent for analysis. The digital field map is technically cross-checked by the DGM expert and prepared for the smooth integration into the GIS system of the cartographers.



- Navigation to AOI's with constant **GPS connection**
- Entering of **georeferenced** observation points via GPS
- Interpreting all ancillary information **on the outcrop, cross-check** with other observation points
- Digital attributing of observation points – **digital field book** (picklists and free text)
- Instant **visual verification** of entered data
- Production of **digital layers** during field work possible

- **Integration** of all data into main database
- Interpretation of field results and **digital mapping** of lithological boundaries and units
- Preparation of **imagery for field** export
- Export of updated complete **observation point database**

Figure 37: Iterative field work cycle.

A constantly growing digital knowledge base by gathering and updating field observations and interpretation results.

3.1.3 Final Production Phase

This phase is characterized by the integration of the field campaign results into finalized maps and reports. Apart from the team that was involved in the field mapping, great importance is attached to the position of the GIS cartographer who is responsible for the professional technical production of the final map (bracketed numbers in the following refer to task numbers in Figure 38).

The final production phase begins with the handover of the final field database and map to the GIS cartographer, with additional information and explanations by the DGM expert regarding the working procedure and results of the field work campaign (①). At the same time, rock samples collected by the field teams are sent to laboratory for specific analyses (②). From this point onwards another iterative work cycle is established between the key personnel (③-⑨). The DGM expert's duties are shifted more to a regulatory role in between the team leader and the GIS cartographer. Input of the field geologists is also reduced, supporting the team leader.

The most important interaction in this repetitive cycle is the integration of the analytical data as it becomes available. As scientific work is naturally an ongoing process that keeps evolving with new information, the technical process of creating a final map version requires the opposite. In other words, problems are preprogrammed as it is an unavoidable practice in projects, to start final cartographic work while changes in the outlining and understanding of geologic features are still ongoing. To reduce these problems the update and integration process between team leader and cartographer (⑦, ⑧) is limited to the geologic layers only, giving the cartographer the possibility to finalize other content of the map that is not affected by changes in the geologic outlines. The map content is therefore constructed in parallel, a working concept that shows resemblance to the "Building-Block Principle" introduced by Meissner et al. (1990).

Once the iterations of geologic updates have come to a defined end, the finalization of map and digital database is completed by the GIS cartographer (⑩, ⑭) with the team leader focusing on reporting (⑫) with the help of the other field geologists (⑬). The DGM expert further supports the GIS cartographer and team leader as needed (⑪).

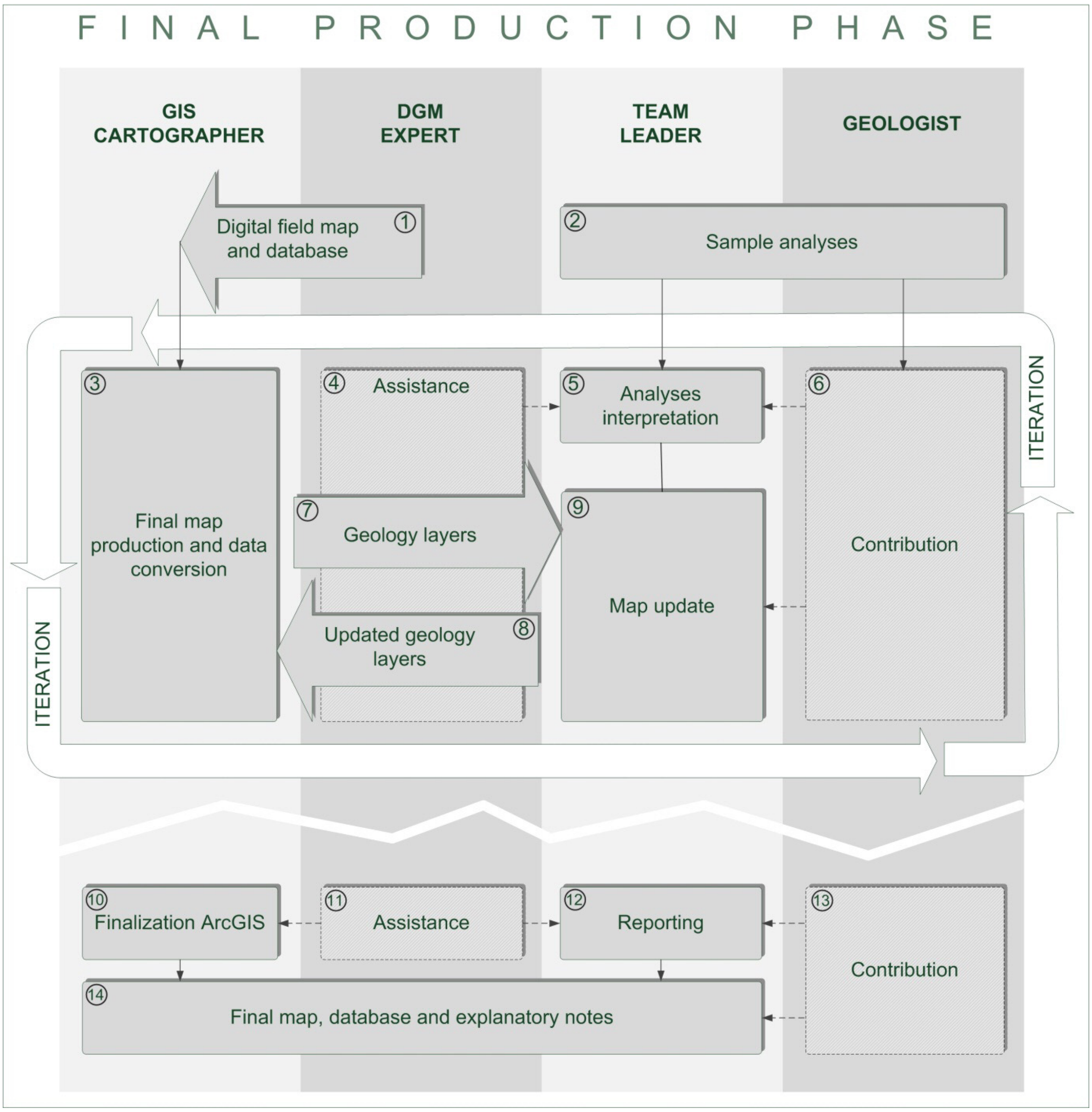


Figure 38: DGM working approach – final production phase.

Involvement and interactions of the personnel during the final production phase of a geological survey; dashed pattern resemble a part-time function; the task numbers are referred to in the text in brackets.

3.2 Conceptual Development of the Digital Geologic Mapping System

As part of this thesis the software concept was actively developed from a single user mobile GIS with limited data compatibility, into a DGM system for geologists without profound GIS knowledge. It is now able to manage multiple user groups and to combine field work observations and interpretations completely in one system. The software development and engineering went hand in hand with the experiences gathered during the project work. Functional analyses made in the field were directly used to communicate the needs to the software engineer to further improve the DGM work flow performance.

The software can be used with full functionality on all Windows based platforms or as a limited mobile version on hardware systems with performance limitations. Both versions make ancillary information quickly and easily accessible to the field geologist – on the outcrop and in the field camp. New field observations of the geologist are integrated into the system in no time and the field data are merged in a relational database managed by an integrated digital field book. This field book is used to edit, visualize and organize all field work information.

The software development aimed at keeping the software straightforward and in line with the specific needs of the geologist, while smoothing the overall work flow in geologic mapping projects. Thus complex GIS and cartographic layout functionalities were left aside for the benefit of an intuitive DGM approach. The software was initially programmed in C++ but was reprogrammed in 2008 using C# and ESRI's ArcObjects (.NET). Following the duality of the system, the software and its functionalities are separately presented as a main *desktop GIS* module and a *mobile GIS* application. The former is the main program with all functionalities whereas the latter is the basic version with limited capabilities, tailored for the mobile use in the field

3.2.1 Desktop GIS Module

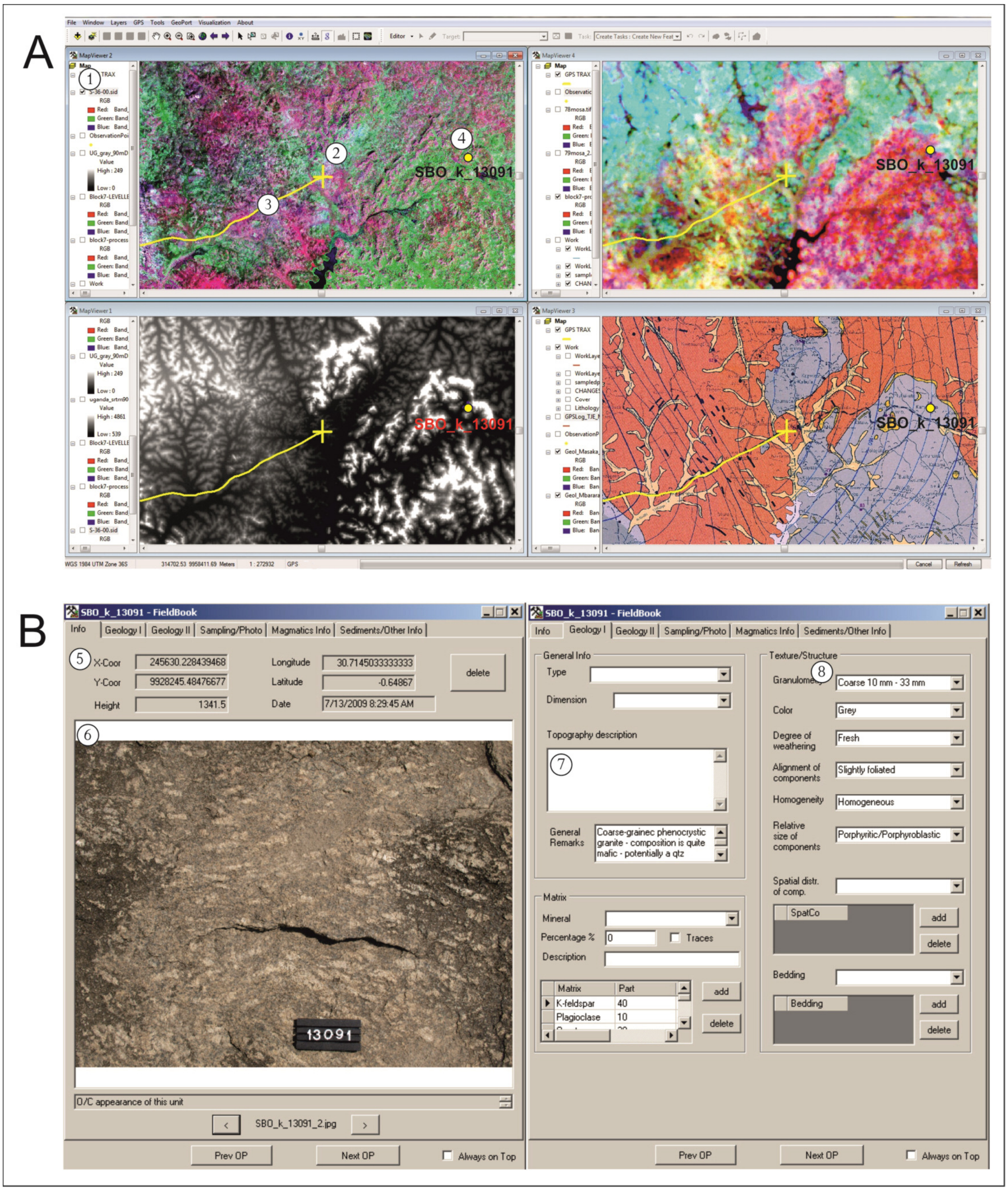
Referring to Bill (1991), the functionality of the software is described in the following chapters by using the four functional components of any GIS: Integration, management, analysis and production (IMAP).

The main program can be used on any MS Windows based hardware system and by being programmed with ESRIs ArcObjects it can handle almost any modern GIS data type without difficulties. Although each project is based on an assigned geographic reference, varying datasets can be projected “on the fly” or geo-referenced inside the program with a simple transfer tool. All projection files of ArcGIS can be used and custom projection files can be created. In general the transfer in between ArcGIS and the software is very simple.

The core system of the software is the digital field book (chapter 2.4), which is accessible from the main menu. It resembles the graphical user interface and management tool of a relational observation point database with customizable geologic attributes. Data entries can be made by manually clicking in the work window, by data import from a mobile device or by using the NMEA protocol of an attached GPS receiver. The attribution is done by choosing from predefined drop-down lists or by entering text information. Some of the attributes can be instantly visualized with the appropriate geologic symbols, e.g. strike and dip values of structural data. Additional information like photographs, sketches or free text notes can be integrated into the field book by simple clicks (Figure 39, B). With a simple transfer interface selected data of the digital field book and raster imagery can be exported to mobile devices. Conversely this interface manages the import and integration of data from the mobile device back into the main database.

Every set software project allows multiple, adaptable working windows that can be linked by geographic coordinates, for simultaneous observations and interpretations of various datasets (Figure 39, A). This functionality is combined with a multiple cursor tool that displays the cursor’s position of the activated working window on the equivalent position in the other windows (Annex I and Annex II). The visualized content of any window can be arranged individually but can also be interchanged between various windows by “drag and drop”. Once the GPS is connected and receiving data, a positioning cursor is shown in all windows and the NMEA stream can be used to record the GPS tracking and store the movement in a geodatabase.

In addition to the working windows, the multiple cursor position can be shown in Google Maps, to get access to high resolution data in many areas. This feature is further improved by the possibility to export visualized data as KML-file and integrate it into Google Earth or other virtual globe systems that became popular (Whitmeyer et al., 2010). Although Google Earth also offers a basic 3 D visualization, the



SBO_k_13091 - FieldBook

X-Coor 245630.228439468
Y-Coor 9928245.48476677
Height 1341.5
Longitude 30.7145033333333
Latitude -0.64867
Date 7/13/2009 8:29:45 AM

O/C appearance of this unit
SBO_k_13091_2.jpg

General Info
Type
Dimension
Topography description
General Remarks: Coarse-grainec phenocrystic granite - composition is quite mafic - potentially a qtz

Matrix
Mineral
Percentage % 0
☐ Traces
Description

Matrix	Part
K-feldspar	40
Plagioclase	10

Texture/Structure
Granulometry: Coarse 10 mm - 33 mm
Color: Grey
Degree of weathering: Fresh
Alignment of components: Slightly foliated
Homogeneity: Homogeneous
Relative size of components: Porphyritic/Porphyroblastic
Spatial distr. of comp.
SpatCo
Bedding

Figure 39: Basic functionalities of GeoRover main desktop GIS.

A) geographically linked four-window-mode; ① all windows can be filled separately with thematic content via individual table of contents; ② current GPS position; ③ GPS tracking converted to shapefile; ④ exemplary observation point SBO_k_13091 is selected, opened and edited in the digital field book; satellite imagery by courtesy of the Department of Geologic Survey and Mines, Uganda and GAF AG, Germany; B) main pages of the digital field book; ⑤ coordinates of the selected point; ⑥ inserted outcrop photos; ⑦ field for free text entries; ⑧ drop down menus (combo boxes).

GeoRover software contains a very sophisticated visualization tool that was programmed as part of a diploma thesis by Gocke (2008) and integrated to quickly create digital terrain models, displaying data in 3 D scenic views and showing sub-surface information, if available (Figure 42, ①, page 102).

When producing and editing vector information, a very basic principal of geologic mapping was maintained: All information starts from point observation, points lead to the production of lithological boundary lines and finally to geologic unit polygons. Therefore a topology-free construction line layer is used that automatically segments at intersections, allowing a quick and simple drawing. All segments can be edited individually and areas enclosed by line segments can be converted into polygons (Figure 40). During this procedure the topology is checked and verified. The attributes of the polygons can be directly chosen and entered from drop-down menus that become consecutively populated by new entries.

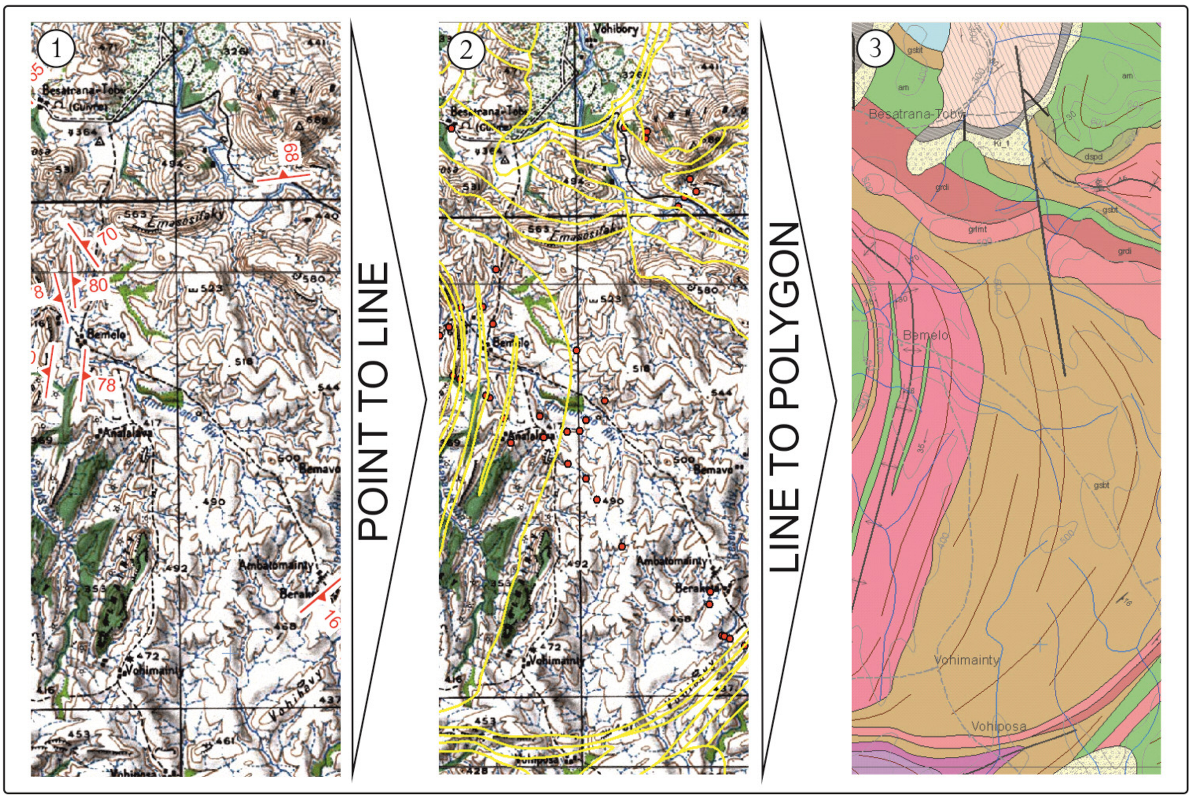
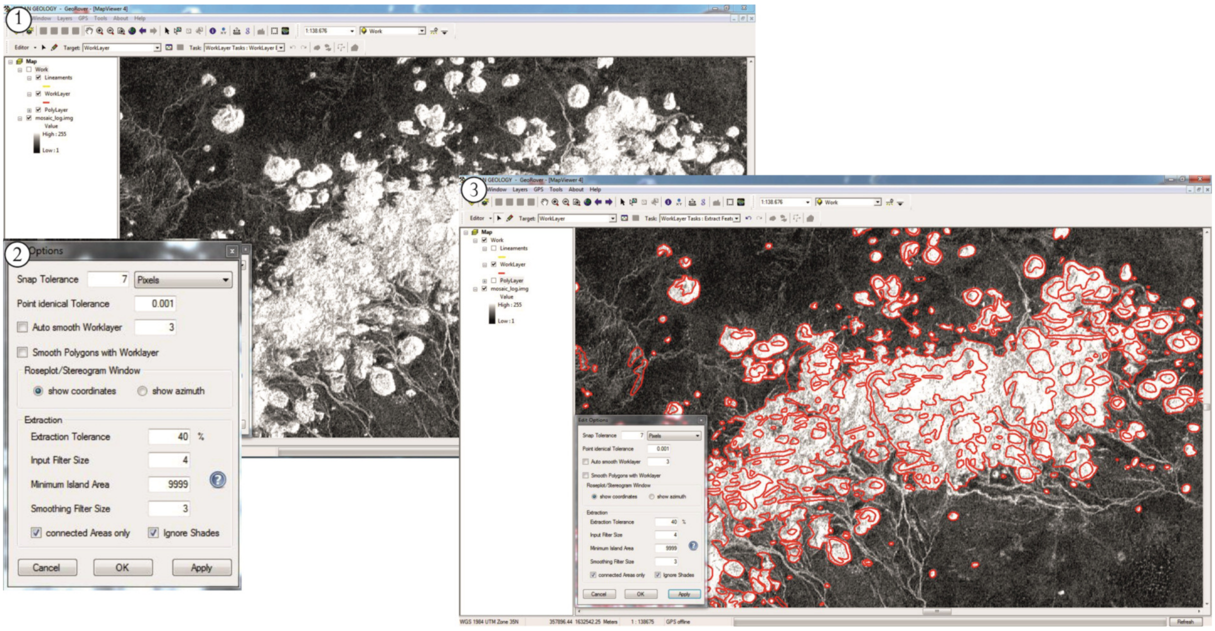


Figure 40: Traditional geologic mapping workflow as model for digital mapping. ① Field observation points (red) are used to ② draw lithological boundaries (yellow) with the construction layer; ③ closed outlines are transferred into polygons, resulting in a final digital map. The lines of the construction layer can be transferred into various output types (e.g. fault, lithological boundary, fold hinges).

Another very fast and convenient method to generate vector files is the use of an implemented supervised classification tool allowing the user to generate features by defining certain sample areas as a reference. The results can be influenced by the size of the selection kernel and various filtering options and it is possible to create large features with similar pattern in a very short time (Figure 41).

Especially designed for the geologic analysis, a cross-section application is implemented that allows using altitude information of DEM’s in combination with the lithological outcrop lines, to define a section. The sub-surface can be modeled in an extra working window by using the construction layer and the transferred symbols of the lithological units (Figure 42, ②, ③) in a very convenient way. The resulting cross-sections can be exported and be put into geologic context by using the implemented 3 D modeler (Figure 42, ④).



Snap Tolerance 7 Pixels
Point idenical Tolerance 0.001
☐ Auto smooth Worklayer 3
☐ Smooth Polygons with Worklayer
Roseplot/Stereogram Window
● show coordinates ○ show azimuth
Extraction
Extraction Tolerance 40 %
Input Filter Size 4
Minimum Island Area 9999
Smoothing Filter Size 3
☑ connected Areas only ☑ Ignore Shades

Figure 41: Feature extraction by using supervised classification tool.
The application uses the digital values of a definable area to select features with a similar pattern; ① raster features can be classified by: ② using the extraction tool; ③ features are transferred into vectors.

Another specific geology tool is the stereonet application that lets the geologist create simple stereonet projections and rose diagrams based on selectable point and line features (Figure 42, ⑤, ⑥), directly while mapping. According to editable parameters of data input values the results can be exported as image files for a further interpretation and analysis.

The output of all analyzed data can be quickly transferred into other GIS solutions. Every working window is stored as mxd-file that can directly be opened in ArcGIS. Additionally, all content can be exported as a geo-referenced image file and the kml-file export allows a quick visualization in Google Earth or Google Maps. Basic symbols can be used to create simple maps, although a full layout capability for producing complex maps is not intended.

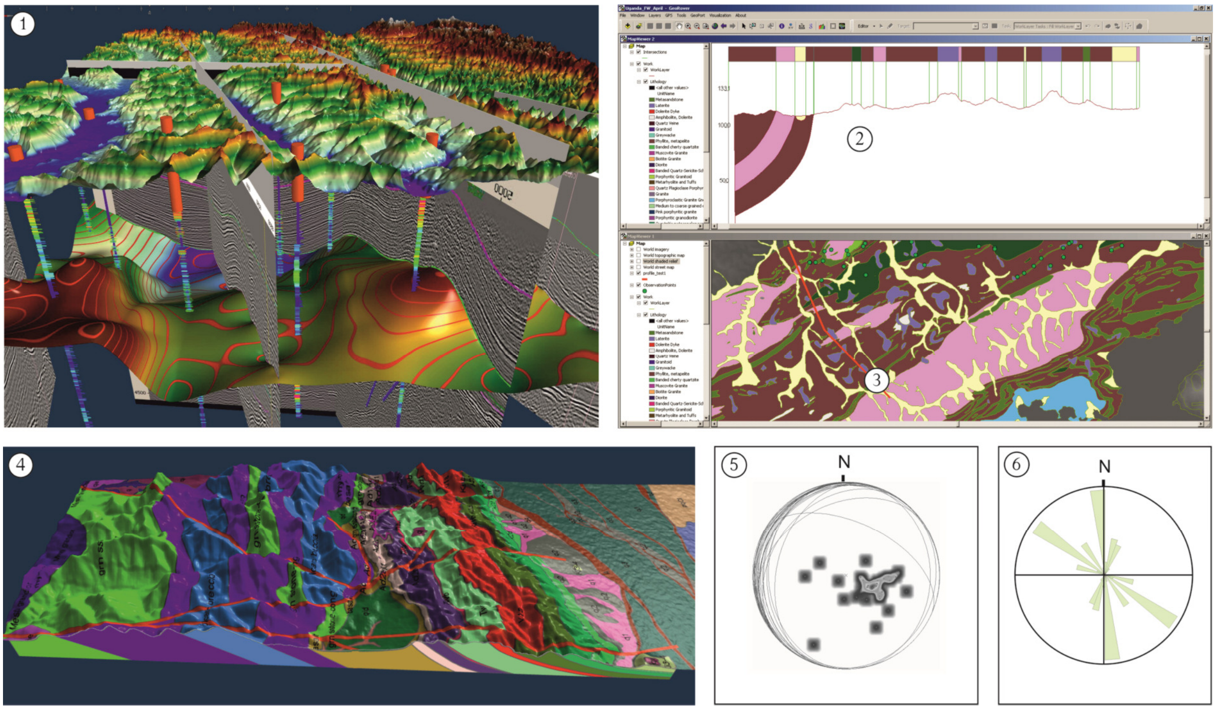


Figure 42: Selection of additional tools of the desktop GIS.

① 3 D viewer with borehole data, seismic profiles and interpolated subsurface layers; ② cross-section tool showing the lateral view of the cutting line and lithological outcrop corridors taken from the plan view ③; ④ a cross section visualized in the 3 D viewer; ⑤ simple stereonet projection of planes, related poles and density raster/isolines; ⑥ rose diagram showing the directional quantity of features.

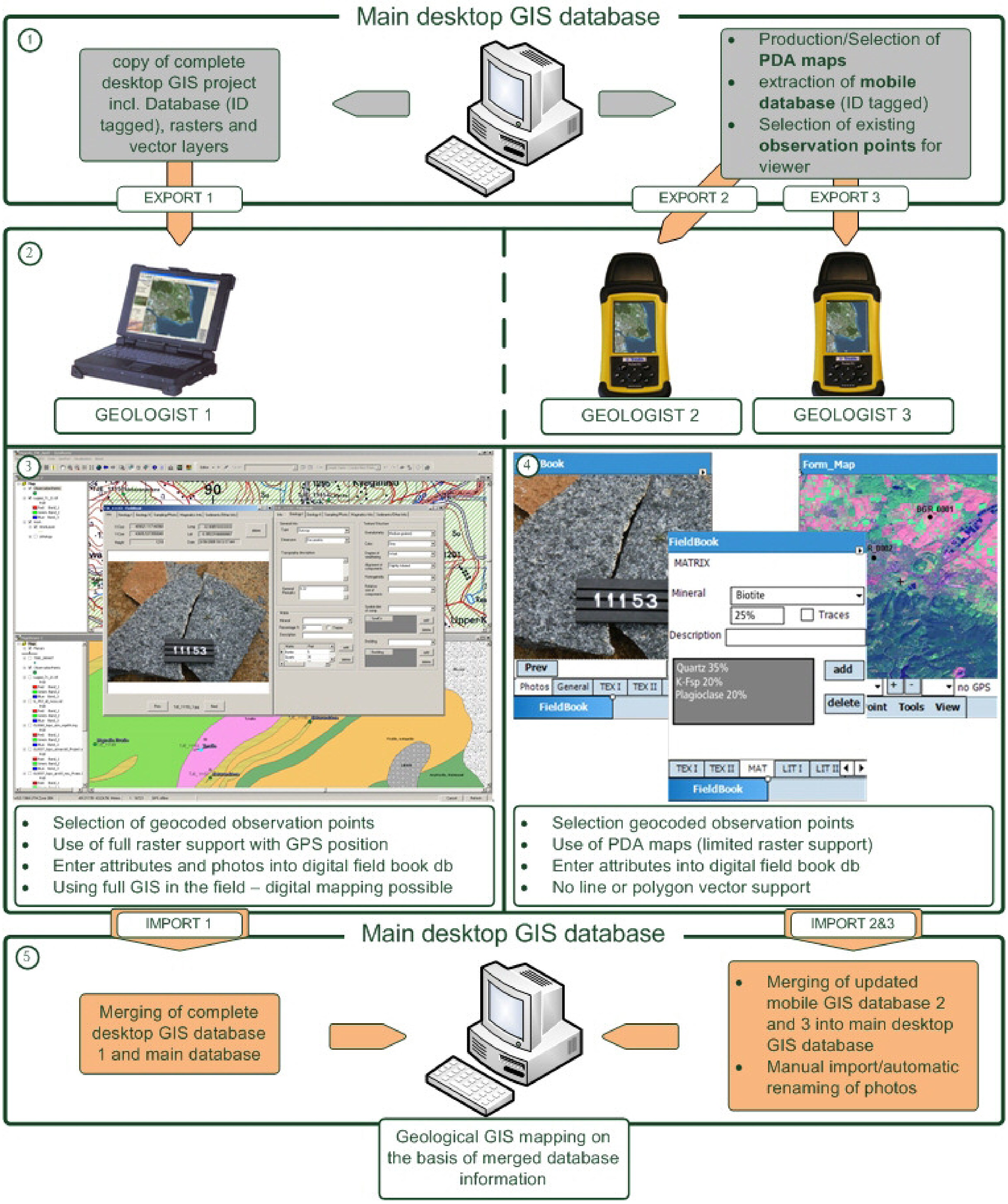
3.2.2 Mobile GIS Application

The mobile GIS application is usable on all Windows Mobile based platforms. It is written in C#.NET compact framework and completely independent from the ArcGIS Engine. It is a basic application that allows the most important information layers from the desktop GIS module to be taken into the field and to be at hand when collecting new observation points. New points are automatically integrated into a copy of the desktop GIS database, by using a mobile digital field book. The application uses a map viewer that visualizes the actual GPS position on selectable image backgrounds, previously exported from the desktop program. Further it displays new and older observation points contained in the mobile digital field book, with adjustable basic symbols and labels (e.g. lithology names or structural measurements). Observation points can be selected and their attributes shown in the map viewer.

Simple settings are used to change colors and sizes of the displayed features to optimize them for various illumination conditions and raster backgrounds.

New points can be set directly in the map viewer or by opening the digital field book from the main screen. In both cases the entry mask of the field book opens and the geologist enters the observations in drop-down menus or freetext fields that were customized during the preparation phase. Further it is possible to mark digital photographs for the integration into the digital field book and to prepare sample list for further analysis that are automatically numbered in relation to the outcrop.

The mobile version is not a standalone system but an extension of the main program and needs the desktop GIS version to be operable. By using the transfer tool all gathered information from the field can be integrated into the desktop GIS database and reviewed in the main digital geologic field book. By using a unique identifier system for all entries of every geologist, it is possible to merge all differently developing copies of the main desktop GIS at any stage, regardless if the copies are run on PDAs, laptops, PCs or similar. Therefore the field work can be run independently of the hardware and number of users. An exemplary field work procedure with the various working steps and the different hardware systems involved is presented in Figure 43.



copy of complete desktop GIS project incl. Database (ID tagged), rasters and vector layers

- Production/Selection of **PDA maps**
- extraction of **mobile database** (ID tagged)
- Selection of existing **observation points** for viewer

- Selection of geocoded observation points
- Use of full raster support with GPS position
- Enter attributes and photos into digital field book db
- Using full GIS in the field – digital mapping possible

- Selection geocoded observation points
- Use of PDA maps (limited raster support)
- Enter attributes into digital field book db
- No line or polygon vector support

Merging of complete desktop GIS database 1 and main database

- Merging of updated mobile GIS database 2 and 3 into main desktop GIS database
- Manual import/automatic renaming of photos

Geological GIS mapping on the basis of merged database information

Figure 43: Exemplary multiple user system setup.

①: main database is copied to different DGM field work devices in the field office; ② left: export of the full desktop project onto tablet PC/laptop used by "geologist 1"; ② right: various selection of data to be put on PDAs used by "geologist 2" and "geologist 3"; ③ digital field book integrated into desktop GIS; ④ three examples of photo viewer, field book entry page and raster viewer implemented in mobile application; ⑤ all data is merged into the main database accessible for all geologists.

3.2.3 Hardware Systems

GPS connectivity is becoming a standard feature in many devices today. Equivalent to the developments in the cell phone industry modern PDAs and tablet PCs normally contain built-in devices of sufficient accuracy for most geologic mapping purposes. In addition external units can be connected via cable, card slot, Bluetooth and other interfaces. The direct integration of the GPS signal depends on the software that is used to process the NMEA protocol.

During the described surveys three main types of hardware systems were tested regarding their field work usability: different PDAs, a tablet PC convertible and Laptops, in ruggedized and regular versions. Trimble Recon PDAs were used in Madagascar and Uganda, simple ASUS 696 office PDAs with integrated GPS module came to use in Uganda and various other projects carried out by GAF AG in Ghana and Morocco. The used tablet PC was produced by Panasonic and is more adequately described as a rugged netbook/tablet PC convertible. It is was used and tested in both its functions. During the various surveys numerous standard laptops were used. The rugged XS versions of Tetranote served as laptops in rough field conditions of Madagascar and were later also implemented in projects in Ghana with similar conditions. The outdated rugged version of Roda's "Rocky I" field laptop that was used in Oman (chapter 2.3.2) is no longer comparable to modern systems and is not included in the comparison. Detailed specifications of all hardware systems can be found in Annex IV. In addition further comparisons of similar hardware systems used in the field can be found in the publications of McCaffrey et al.(2005), Clegg et al. (2006), De Donatis and Bruciatelli (2006), Wilson et al. (2006), Athey et al. (2008) and Whitmeyer et al. (2009).

4 DISCUSSION AND RESULTS – A COMPARATIVE REVIEW OF THE NEW DIGITAL GEOLOGIC MAPPING APPROACH

This chapter presents the new DGM approach in direct comparison to conventional geologic mapping (CGM) methods. Specifically, the assessment takes the interdependency of the involved scientists and technicians during all stages of the mapping projects into account. In the same context the specific software and hardware of the DGM approach is analyzed and the time-effectiveness is weighed against a CGM approach. A set of recommendations and conclusive remarks is given at the end.

To arrange the assessment of the DGM methods in a comprehensible way, the previously described sub-divisions (chapter 3) for each geologic mapping survey will be used: The preparation phase, the field work phase and the final production phase (Figure 33). The software and hardware setup will be evaluated separately in relation to the various survey setups and experiences.

4.1 Assessment of the Digital Geologic Mapping Workflow

McCaffrey et al. (2005) describe the general improvements gained through digital mapping as: a) a higher spatial accuracy, b) a streamlining of the process from beginning to end of a mapping project, c) better visualization and d) better geologic insights through improved analysis tools. In all studies that have been carried out within the scope of this thesis, and in other geologic projects the author was involved in, these basic improvements were recognized. The comparability and homogeneity of all geologic data entries as well as the transparency and easy supervision of the field work progress would be examples of additional benefits, identified and presented in the following paragraphs.

The value of basic GIS as one major part of DGM is undoubtedly accepted in geosciences today. It is the modern library system to organize all available digital data and builds the backbone of all modern mapping projects, without the restriction to geosciences. Therefore, the presented DGM concept must be evaluated according to its efficiency in dealing with the whole project activity from beginning to finalization, including the field work component as the central aspect of the whole process. Consequently the streamlining of the survey as described by Mccaffrey et al. (2005) and Whitmeyer et al. (2010) will be the main criteria of the analysis.

As no standardized DGM work flow exists and published evaluation methods (Soller, 2000-2012; McCaffrey et al., 2005; Clegg et al., 2006) have rarely been applied to extensive mapping projects, the presented analyses of the developed DGM approach combined with long-term field work experience are considered to represent a valuable contribution for the scientific community, helping in future planning and promoting further development of DGM methods in general.

4.1.1 Preparation Phase

When applying the DGM approach, the largest increase in effort compared to conventional mapping methods occurs during the preparation phase. Although this involves extra investment of time and money, the analysis of the other working phases will show that the survey quality is enormously raised and costs are saved in the long run. The specific DGM work flow discussed in the thesis includes the full-time position of a DGM expert, a position not involved in other approaches and one which incurs extra costs (chapter 4.3). However, as the DGM expert's profile should be versatile with a strong background in geology, GIS/remote sensing and computer technology the costs are spread over several positions. For example, in most cases the GIS setup and data compilation work that is completed by the DGM expert in the new approach during the preparation phase has to be done by an extra GIS expert in conventional approaches today. Beyond that, a continuous involvement of the DGM expert within the presented framework of geologic mapping surveys, streamlines the whole process and helps to maintain a high quality of the digital output.

During the preparation phase the software development and engineering must be seen as the major investment of the presented DGM approach. As the real costs for developing a unique system like GeoRover are much higher than simple licensing costs, they are not specifically representative for a general DGM analysis. It is clear that the software development costs are an investment into the future and cannot be balanced in one single project. Instead the licensing costs of an “off the shelf” product should be put into the equation (chapter 4.3). Apart from the GeoRover software that is described in the thesis there are also several other alternatives like SIGMA mobile of the British Geologic Survey (BGS, 2010) or BeeGIS developed by LINEE and Hydrologis (LINEE and HydroloGIS, 2009) (chapter 4.2.2). These open source software solutions offer a wide range of DGM functionalities without additional licensing costs, but require some investment in time to get used to their operating procedures.

However, moderate software licensing costs are amortized by time and cost savings over the duration of the survey, even if the surveys are carried out with small teams and with a relatively small budget. Nevertheless the financial balancing must be done individually for every survey and user.

The close up evaluation of the various stages in the preparation phase is given in the following (numbers in brackets refer to the task numbers in Figure 44).

The inception phase of the DGM survey is similar to conventional surveys (①) and can be considered as cost neutral in this analysis, although a quick visualization tool for digital geodata is an advantage in any reconnaissance or fact finding mission that is undertaken during the inception phase.

The costs of software adaptations (②) are not referring to software programming costs but to the adaptation of specific features related to the survey's unique objectives. For example the language of the menus or simplification/reduction of the tools for a streamlined working processes. When working with the presented GeoRover system, costs of software adaptation are only minor and are indicated by a dashed red outline in Figure 44 (②).

The major efforts in the preparation phase include the consolidation of the great variety of datasets into a common structure and spatial reference during the data compilation phase (⑤). In traditional geologic surveys, when maps were used in the field for orientation and marking of observation points without GPS, subtle problems relating to map datum or geodetic inaccuracies were negligible. When working with digital geo-data today, the user is forced to precisely geo-reference these data sets as any imprecision becomes obvious by direct comparison. This necessary referencing process enhances the overall accuracy of the data, although it often requires laborious digital matching methods, not only when dealing with old data sets (chapter 2).

As the digital referencing procedure requires some understanding of geodetic projection and control parameters, it must be done by the DGM expert or another

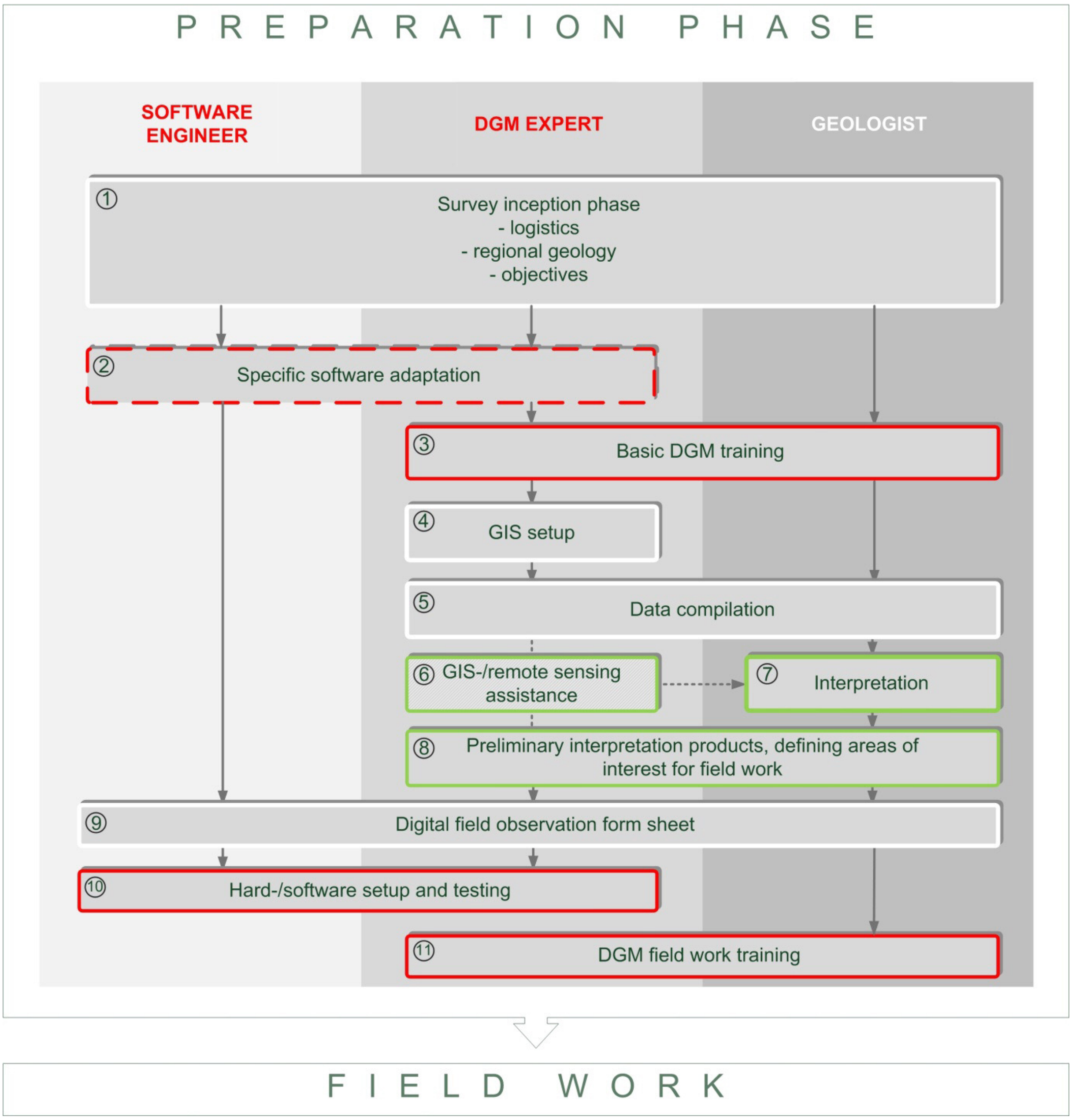


Figure 44: DGM work flow analysis of the preparation phase.
Highlighted according to their effects on quality, time and costs in comparison to traditional working methods (red: extra time/cost effort; green: quality improvement and/or time/cost savings; white: little to no difference; dashed outlines symbolize details that are commented in the text); dashed pattern resemble a part-time function; the task numbers are referred to in the text in brackets.

GIS- and cartography expert. This step is unavoidable, when working in any project that involves GPS technology and has the positive side effect of producing an accurate digital dataset which is not affected by distortion or physical deterioration, as is the case for many older analogue scientific materials.

Although the digital data compilation stage is more time-consuming compared to traditional compilation methods, the benefits of digital working procedures in the following phases depend on it. Hence it is an unavoidable preparatory step in every modern survey that deals with a digital final output, whether in conventional or digital geologic mapping approaches. The time spent on setting up a GIS project, containing all the digital data that are found useful for the following phases (④), falls into the same category.

One of the main advantages of the software used in the presented approach is the fact that geologists can interpret the existing data sets, without being dependent on GIS experts to do the technical work (⑦). Not only is the time of the GIS expert saved but the quality of the interpretation is improved as the geologist is able to test preliminary theories autonomously, having software tools and all existing data sets at hand. In this process the geologists are supported by remote sensing and GIS experts on demand, helping them with the interpretation of complex imagery, e.g. RADAR products or geophysical aeromagnetic and radiometric data (⑥). This supervision further helps to minimize the misinterpretation of image features, especially when complex principal component analyses or de-correlation stretches are used.

However, to use the proposed DGM software for preliminary interpretation in the preparation phase, some basic training of the geologists is needed (③). Although this expenditure of time and money is often an argument for not using DGM techniques (Whitmeyer et al., 2010), the experience from the Madagascar and Uganda studies proved that training with the presented DGM software could be done successfully in two to three days. Compared to the working hours of the GIS expert, when digitizing the preliminary interpretations of every single geologist, this seems well worth the effort.

The concrete digital results of the interpretation and the defined areas of interest (AOI) build a practical and easily shareable basis for discussions and the logistical preparation of the survey. With these AOIs at hand, the main geologic objectives of the field work can be defined and its effective preparations can start.

Finally, the main advantage of the digital interpretation layers is the possibility to take them into the field and constantly evaluate and update them according to new observations. It is much easier to evaluate a visual interpretation in the field then it is to start with a blank page as it was often observed in direct comparison with geologists using conventional techniques.

With the production of preliminary interpretation layers and AOIs (⑧) the geologic frame of the field work is set. In the next step a common standard for field data entries based on the regional geology is defined. This is done traditionally with paper form sheets that are digitized after field work. Here the usage of the digital field form (⑨) integrated into a digital field book shows some major advantages (Figure 45) to this methodology, mainly relating to comparability and shareability. The visualization of these data is also done easier in a digital format, becoming obvious in the field work and final preparation phases.

The testing of the hardware and software (⑩) following the setup phase is an obligatory though time-consuming aspect. Depending on the survey setup and the field work location, improper testing can lead to ongoing problems, for example hardware failure or software bugs. The latter was a highly sensitive issue during the development of the presented approach as the software was repeatedly redesigned. However, this should be less problematic when using existing DGM software. In traditional surveys the hardware setup and testing is less time-consuming as it mainly concerns GPS receivers and laptops.

As the working approach involves the use of technical equipment most field geologists are unfamiliar with, a training session dealing with the use of the hardware and software in the field is obligatory. Although the training again implies an extra effort compared to classical surveys, it is absolutely essential for a smooth accomplishment of the field work and the costs have to be seen in the major perspective of the costs of the entire survey.

The discussed advantages and disadvantages of the new DGM workflow compared to a CGM workflow during the preparation phase of a geologic mapping project are schematized in Figure 45 and Figure 46.

ANALOG FIELD OBSERVATION SHEET			**DIGITAL FIELD OBSERVATION FORM**
Handwritten entries, often free text – poor readability and **no standard**	-	+	- Mainly **standardized** entries - Free text entries limited to a necessary minimum
Fix format – no easy changes possible once in the field	-	+	Database **adaptable** to evolving requirements during field work
- Entries have to be digitized eventually – extra cost factor and error-prone - **No GIS access** in the field	-	+	- No further work needed when integrating into any GIS - **GIS capabilities** can be used already **during field work**, e.g. visualization, comparison
Entries of all geologists cannot easily be compared in the field – **problems** are often **overseen**	-	+	- All individual **entries are directly comparable** in the field by everybody - Data of all geologists are **directly integrated** into the interpretation process – **problems can be faced directly**, while still in the area
Data can get lost or become unreadable	-	+	Database can be **easily duplicated** and sent by email or stored on any medium for **backup**
Free text entries force the geologist to formulate and **rethink**	+	-	Dropdown list selections are prone to fast and **unreflected decisions**
Stand-alone pen and paper	+	-	Dependant on **electronic** equipment and **power**
Geologist is used to workflow	+	-	Geologist has to be trained in digital data entry

Figure 45: Advantages (+/orange) and disadvantages (-/grey) of analogue and digital field observation form (digital field book) in direct comparison.

CGM SURVEY			DGM SURVEY
No additional software costs	+	-	DGM Software licensing costs or open source solution
No additional training costs	+	-	Costs for basic and field work DGM training
Data compilation and GIS setup is done by GIS expert	-	+	Data compilation and GIS setup is done by DGM expert
No cooperation between geologist and GIS expert GIS expert without geological background; not involved in the field work			DGM expert is involved in the whole survey process Streamlined workflow GIS setup and data compilation is done with the same DGM software used in the field – geologists can be involved from the beginning
Preparation and interpretation by geologists is normally done without the efficient use of a complete GIS	-	+	Preparation and interpretation is conducted by the geologist while making use of the full GIS potential
Geologists mainly use maps, literature and print-outs for preparation as GIS software is often too complicated No use of multi-layer analysis, unless GIS expert is assigned			Geologists have visual access to the complete set of data in one system, allowing multi-layer analysis without the help of GIS experts DGM expert is able to assist on demand
No preliminary interpretation products during preparation	-	+	Preliminary interpretation products and defined field work schedule with areas of interest
No production of digital results, unless GIS expert is assigned No easily shareable results Areas of interest are not clearly pointed out, logistical preparation is harder			Shareable digital results without the help of GIS expert Results can be used for update and editing in the field – continuous process line The outlined areas of interest can be used for logistical preparation
No extra time for observation form sheets	+	-	Costs for customization of digital field observation forms
Only if they should not be adapted to regional specifics Have to be put into digital format at some stage			Default digital observation form sheet can be used without further work Changes have to be programmed by software developer
Hardware testing (GPS, laptop) relatively simple	+	-	Hardware and software testing (PDA, GPS, Laptop, Tablet PC, PC) more time-consuming

Figure 46: Summary of the advantages (+/orange) and disadvantages (-/grey) of DGM and CGM setup during preparation phase.

4.1.2 Field Work Phase

The improvement of the general field work procedure is based again around the DGM expert, whose duties vary between field geologist, GIS and remote sensing, expert. Although the position results in higher costs in the field, the technical GIS and remote sensing assistance provided to the field team, especially in the beginning of the field work, contributes significantly to the quality and efficiency of the field work results. The positions of a geologist team leader and several field geologists are equally required in any other working approach, but the team interactions built around the DGM expert position vary greatly, making the approach very effective (Figure 34, page 88). The close up evaluation of the various stages in the field work phase is given in the following (numbers in brackets refer to the task numbers in Figure 47):

The DGM field work training (①) can be done “on the job” (Annex VI) and is more relating to specific questions that need the attention of the DGM expert – as most of the training is done prior to the field work start. The field work cycle (②-⑥, combined in the next paragraphs) already described in chapter 3.1.2 (Figure 36, page 92) often depends on the installation of a main field camp that can be moved according to the work progress. On the one hand this helps to keep the driving ranges for each field team relatively low and provides a possibility to refill supplies and store rock samples. On the other hand this setup permits a digital field office with generated power supply, needed for any DGM approach. Further, its setup helps to organize the field work, serving as a hub for transportation of general supplies, samples, field work staff etc. If the infrastructure in the field allows it, the field headquarters can also be based in a guesthouse or hotel, further simplifying the digital field office setup. The repetitive working procedure of all geologic field teams built around a growing digital data base (Figure 37, page 94) presents numerous advantages connected to the specific software setup:

When the geologists start field work equipped with mobile DGM devices they can use the GPS tracking function to navigate. Especially the on-screen navigation with geologic information and topographical map layers proved to be extremely effective. By having the option for multiple working windows on a laptop or tablet PC, numerous other combinations are possible for the navigation. When using a PDA or

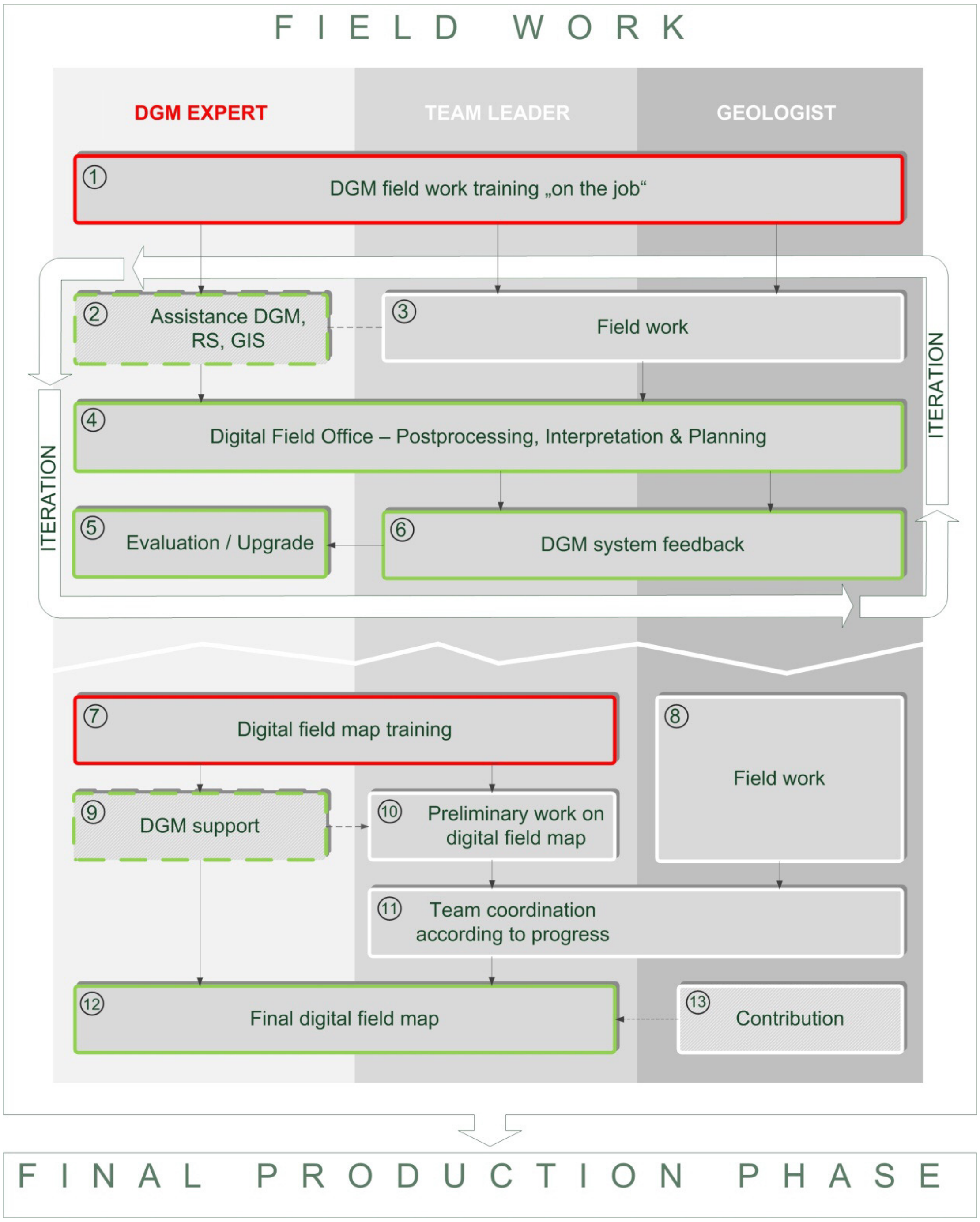


Figure 47: DGM work flow analysis of the field work phase.

Highlighted according to their effects on quality, time and costs in comparison to modern CGM methods (red: extra time/cost effort; green: quality improvement and/or time/cost savings; white: little to no difference); dashed outlines symbolize details that are commented in the text); dashed pattern resemble a part-time function; the task numbers are referred to in the text in brackets.

smartphone, such a procedure is still effective, though limited by screen size and data amount.

This geologic navigation system makes it easy to follow lithological boundaries or other geologic features and facilitates the collection of observation points that are of geologic significance. This fact alone makes the difference between just “covering ground” and finding crucial connections of field observations and third-order information (chapter 1.2.2, Annex I and Annex II). When standing at the outcrop, the geologist starts with collecting observation points that are directly geo-referenced via GPS, without having to carry around another GPS handheld or looking up coordinates on a map. New observation points are directly attributed by using the digital field book. The predefined drop-down menus in the field book help to maintain standards that are directly comparable by digital queries, facilitating the compilation of the field data. The content of the drop down menus can be edited and updated during field work to include new geologic observations, for example new lithology names or mineral contents. Although this option represents a great opportunity to adapt the digital field book to developing needs, new dropdown menu entries must be handled with care: It could often be observed in the field that users created unnecessary new entries in the drop down menu list, resulting in a vast number of entries with a similar meaning, e.g. “biotite gneiss”, “gneiss, biotite”, “bt gneiss”. As this obviously affects the quality and usability of a digital dataset, individual updates were carefully observed and filtered by the DGM expert.

Apart from drop down menu lists, the digital field book also offers the possibility to enter free text whenever necessary as it is neither possible nor reasonable to standardize all information. Additionally it allows the direct link of the observation point with digital photos and sketches helping in the later review and comparison of the data and permitting a useful backup procedure.

As the geologist is supported with all ancillary information stored on his device directly at the outcrop, the overall quality of the observation point is raised. Additionally, observation points and field book entries of other team members can be visualized making it much easier to discuss geologic ideas and to sort out map sheet boundary problems. As discussion and interpretation can be done literally on the outcrop, developing ideas can be checked and evolved directly on the spot, not back in the office, from where returning to the field is mostly impossible. The observations made can be symbolized directly and cross-checked with the current geologic understanding of the area. That is in particular helpful when measuring structural data. Nevertheless it has to be pointed out clearly that the digital field book as such cannot be a full substitute for a hand-written field book, where drawings and sketches are done much faster and easier.

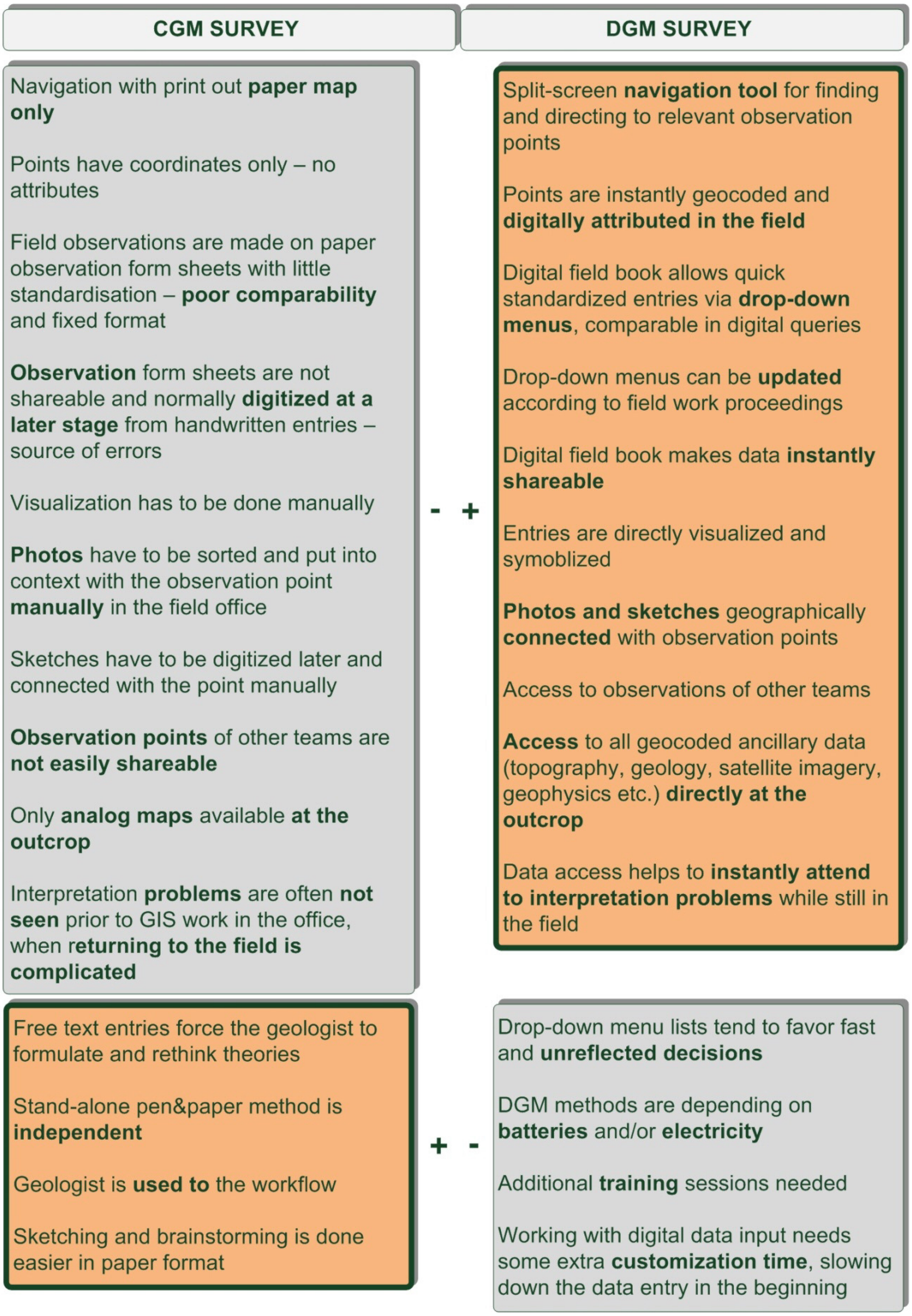
Although it is possible in the presented DGM approach to produce digital vector layers already in the field – when using mobile PC systems – the reality showed that most geologists are used to the iterative work flow of collecting data in the field and doing more intensive interpretation in the field office. This work flow is supported by the approach, as all collected point observation data is imported fast and easy, with unique IDs into the main GIS database for further visualization and interpretation in the field office with the support of the DGM expert. The use of the same database containing the continuously updated interpretations done by all team members strongly facilitates the discussion amongst the different teams. These are further supported by the digital field office setup with a large computer screen or video beamer, scanner, printer and other office conveniences. Discussions with the full data awareness of all teams represent a major improvement compared to all other working approaches: It is much easier to attend inconsistencies in the geologic interpretation of an area while still being in the field. Newly evolving interpretation ideas can be entered directly into the system and the field work schedule of every team is instantly adaptable to specific geologic problems that are not recognizable prior to the field work campaign, making a constant geologic updating progress possible. Thus the scientific quality of the results is considered very high, as the field work can be carried out very flexible, following the evolving geologic interpretation of an area.

Apart from the iterative work cycle between field work and digital field office the cooperation between DGM expert and team leader shows some significant differences compared to more traditional approaches. This cooperation proved as very effective as the person having the regional geologic picture in mind could be responsible for the compilation of the digital field work results and preliminary maps. By creating this team leader position it is much easier to identify areas that need more attention or to highlight areas that need intensive rock sampling or further structural examination. This information can be directly discussed with the responsible field teams and the coordination of the teams is facilitated and optimized. As the team leader is working closely with the DGM expert (⑨, ⑩) the gathered information and the digital interpretation layers of the field teams can be used to create a final digital field map and database (⑫) that contains all information and that is directly usable by the GIS cartographer in the final production phase of the survey. This position requires obviously more time spent in the field office by the team leader and a proper training in the digital office (⑦), but it greatly improves the efficiency of the field campaign and hence the quality of the results. In addition, between the digital field office sessions both the DGM expert and the team leader can contribute much to field work as additional field geologists (chapter 4.3.). In reality it showed that the necessity of the DGM expert to stay in the digital field camp for technical support of the field teams or the team leader decreases quickly as all work flow procedures are relatively simple and straight forward.

Nevertheless the work with a DGM system in the field requires some time to get used to the digital operations, slowing down the working speed a bit in the beginning. A schematized direct comparison of the DGM approach and common CGM survey setups in the various phases of field work is given in Figure 48, Figure 49, Figure 50 and Figure 51.

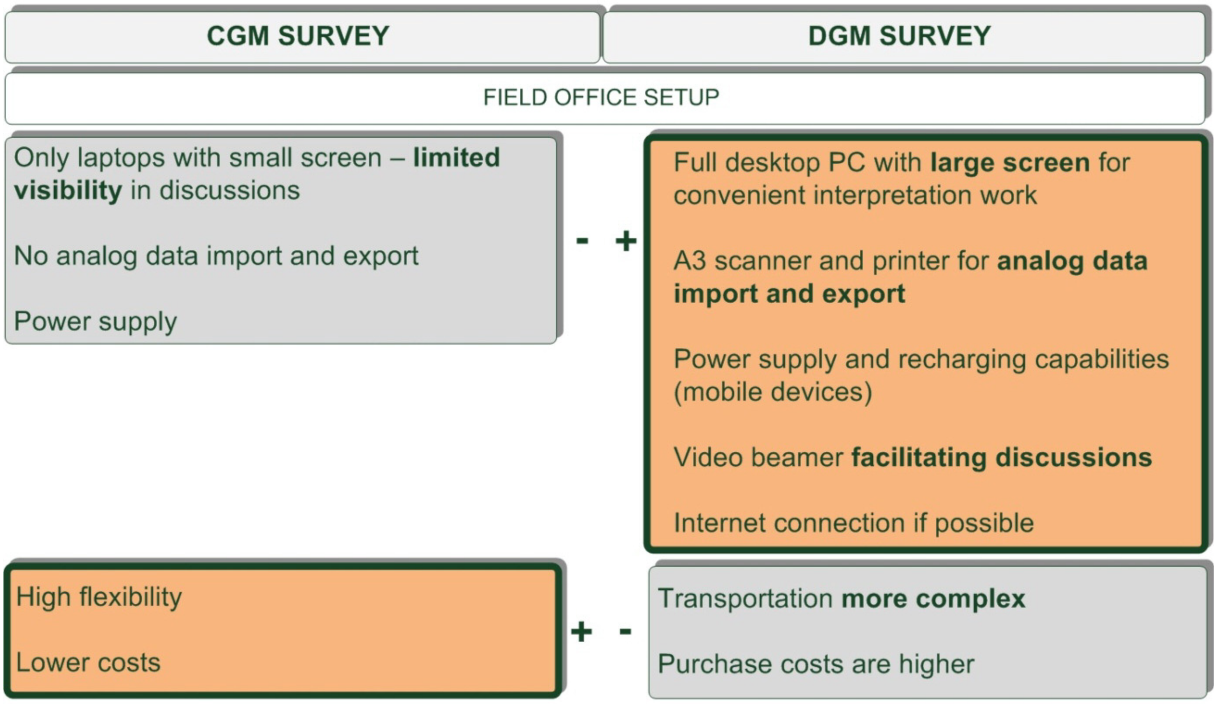
	CGM SURVEY	DGM SURVEY
Team Leader	**Coordinates field teams** mainly in the beginning by assigning work areas Integrates the **results into final products** (maps, reports)	Creates **final digital field map** already in the field Can **coordinate** the field teams **very flexible** according to digital field map progress (gaps, special interests etc.) Constant **supervision of the field teams** and their progress
Field Geologists	Work in their assigned areas **individually or in teams** Drop off their data and reports at the **end of the survey** Produce maps with GIS assistance **after fieldwork**	Are **integrated** in the whole interpretation process Produce **digital results** in the field Constantly contribute to and benefit from the **growing knowledge base** Receive constant **feedback** from chief geologist
DGM Expert		**Assists** in all technical, GIS and remote sensing questions **Supervizes** the DGM workflow in the field and camp **Communicates** with software engineer - updating process **Supports** the field geologists as additional mapper whenever possible

Figure 48: Involved key personnel in CGM and DGM approach during field work phase. Main duties and differences between the key personnel.



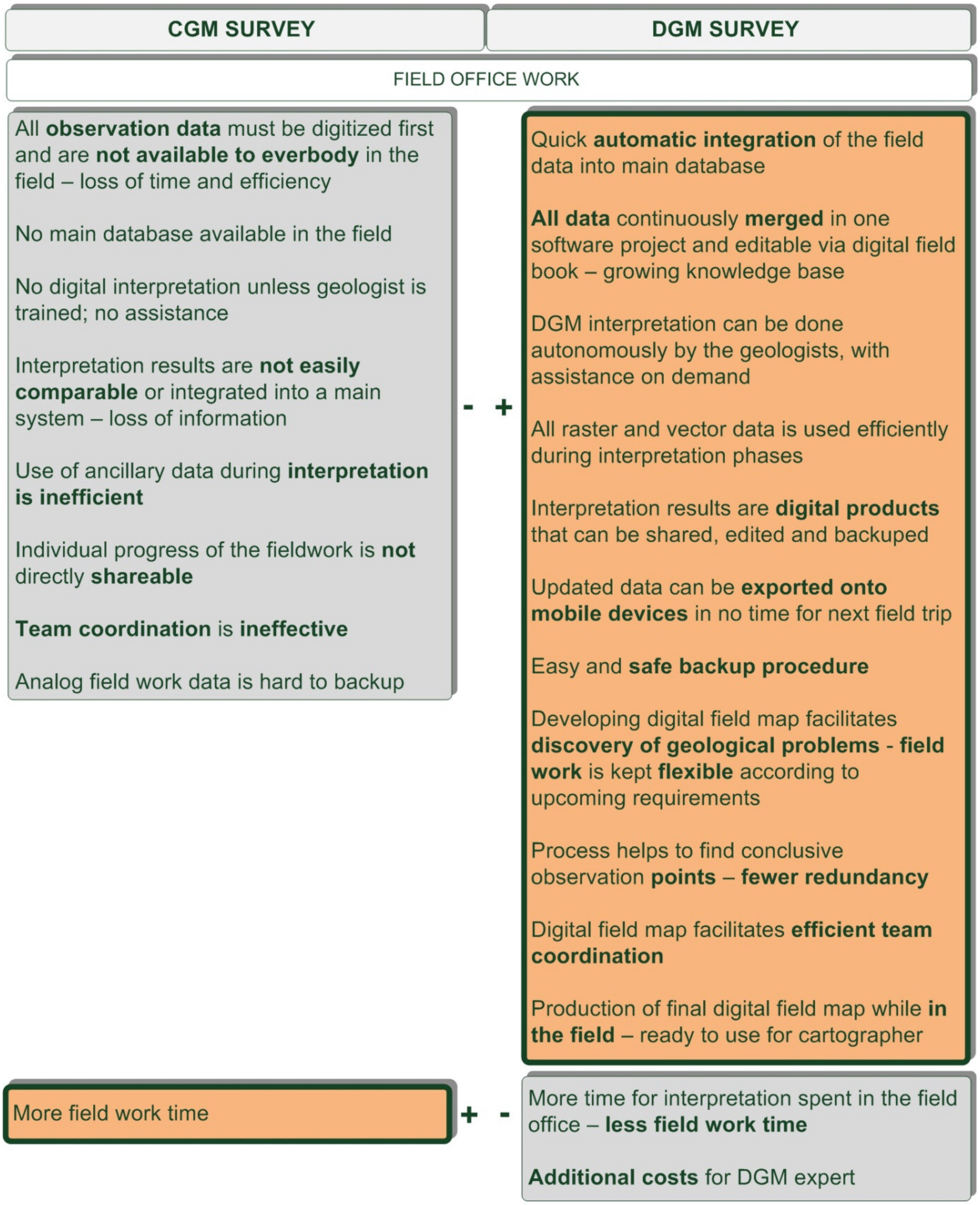
CGM SURVEY			**DGM SURVEY**
Navigation with print out **paper map only** Points have coordinates only – no attributes Field observations are made on paper observation form sheets with little standardisation – **poor comparability** and fixed format **Observation** form sheets are not shareable and normally **digitized at a later stage** from handwritten entries – source of errors Visualization has to be done manually **Photos** have to be sorted and put into context with the observation point **manually** in the field office Sketches have to be digitized later and connected with the point manually **Observation points** of other teams are **not easily shareable** Only **analog maps** available **at the outcrop** Interpretation **problems** are often **not seen** prior to GIS work in the office, when **returning to the field is complicated**	**-**	**+**	Split-screen **navigation tool** for finding and directing to relevant observation points Points are instantly geocoded and **digitally attributed in the field** Digital field book allows quick standardized entries via **drop-down menus**, comparable in digital queries Drop-down menus can be **updated** according to field work proceedings Digital field book makes data **instantly shareable** Entries are directly visualized and symoblized **Photos and sketches** geographically **connected** with observation points Access to observations of other teams **Access** to all geocoded ancillary data (topography, geology, satellite imagery, geophysics etc.) **directly at the outcrop** Data access helps to **instantly attend to interpretation problems** while still in the field
Free text entries force the geologist to formulate and rethink theories Stand-alone pen&paper method is **independent** Geologist is **used to** the workflow Sketching and brainstorming is done easier in paper format	**+**	**-**	Drop-down menu lists tend to favor fast and **unreflected decisions** DGM methods are depending on **batteries** and/or **electricity** Additional **training** sessions needed Working with digital data input needs some extra **customization time**, slowing down the data entry in the beginning

Figure 49: Major advantages (+/orange) and disadvantages (-/grey) between CGM and DGM approach during daily field work procedures.



CGM SURVEY		DGM SURVEY
FIELD OFFICE SETUP		
Only laptops with small screen – **limited visibility** in discussions No analog data import and export Power supply	- +	Full desktop PC with **large screen** for convenient interpretation work A3 scanner and printer for **analog data import and export** Power supply and recharging capabilities (mobile devices) Video beamer **facilitating discussions** Internet connection if possible
High flexibility Lower costs	+ -	Transportation **more complex** Purchase costs are higher

Figure 50: Major advantages (+/orange) and disadvantages (-/grey) between CGM and DGM approach concerning the field office setup.



CGM SURVEY			DGM SURVEY
FIELD OFFICE WORK			
All **observation data** must be digitized first and are **not available to everbody** in the field – loss of time and efficiency No main database available in the field No digital interpretation unless geologist is trained; no assistance Interpretation results are **not easily comparable** or integrated into a main system – loss of information Use of ancillary data during **interpretation is inefficient** Individual progress of the fieldwork is **not** directly **shareable** **Team coordination** is **ineffective** Analog field work data is hard to backup	-	+	Quick **automatic integration** of the field data into main database **All data** continuously **merged** in one software project and editable via digital field book – growing knowledge base DGM interpretation can be done autonomously by the geologists, with assistance on demand All raster and vector data is used efficiently during interpretation phases Interpretation results are **digital products** that can be shared, edited and backuped Updated data can be **exported onto mobile devices** in no time for next field trip Easy and **safe backup procedure** Developing digital field map facilitates **discovery of geological problems - field work** is kept **flexible** according to upcoming requirements Process helps to find conclusive observation **points – fewer redundancy** Digital field map facilitates **efficient team coordination** Production of final digital field map while **in the field** – ready to use for cartographer
More field work time	+	-	More time for interpretation spent in the field office – **less field work time** **Additional costs** for DGM expert

Figure 51: Major advantages (+/orange) and disadvantages (-/grey) between CGM and DGM approach concerning the field office work.

4.1.3 Final Production Phase

The final production phase is characterized by the transition from field observations to the production of final results – normally maps, reports and databases. The assessment of the DGM approach considers its ability to smoothly and effectively integrate the preliminary results into: a) the final map and database production in the cartography section and, b) the final reports of the geologists. The close up evaluation of the various stages in the final production phase is given in the following (numbers in brackets refer to the task numbers in Figure 52):

The position of the DGM expert is again a major advantage as the interaction between GIS cartographer and team leader is mediated by someone familiar with the field observation work *and* the requirements of GIS cartography. Therefore the DGM expert can manage the transfer of field data and maps to the GIS cartographer in an efficient way (①). By utilizing the presented DGM approach the final field map is transferred to the cartographer as a set of topologically correct geodatabases, containing all necessary information for the final map production with advanced GIS cartography software.

As the digital data is already finalized during field work, the final production can start from a finished field map sheet that was the result of several interpretation cycles all based on full access to all available data during field work (chapter 0). In other CGM approaches the digitization of field work results and the effective GIS work starts in the final production stage, most probably leading to new insights into the geology that cannot be easily verified by going back into the field. Furthermore, these new insights into the digital field observation database will more likely make changes on the final map necessary that have to be implemented by the cartography expert. But even if the DGM approach is used, the biggest challenge during the final production phase remains the limitation of necessary updates of the final map. These updates are often needed due to new geologic information derived from laboratory results (chapter 3.1.3) and further interpretation work (③-⑨) done in the meantime.

Although the proposed DGM approach gives the possibility to uncouple the geologic interpretation from the finalizing schedule of the GIS cartographer – by allowing the team leader to update the geology with the DGM software self-dependently (⑦, ⑧) – these integration processes remain problematic. However, the approach allows for

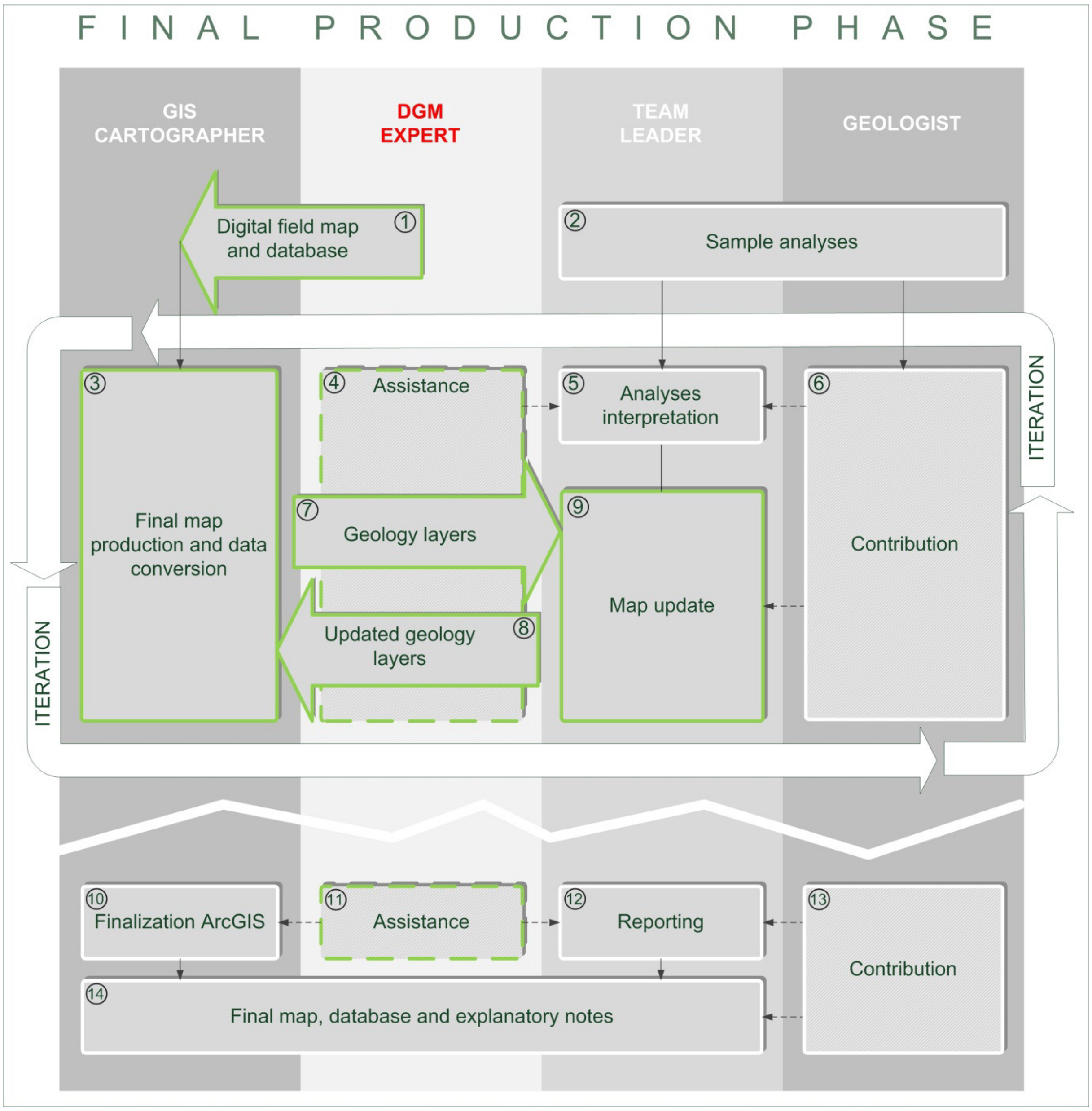


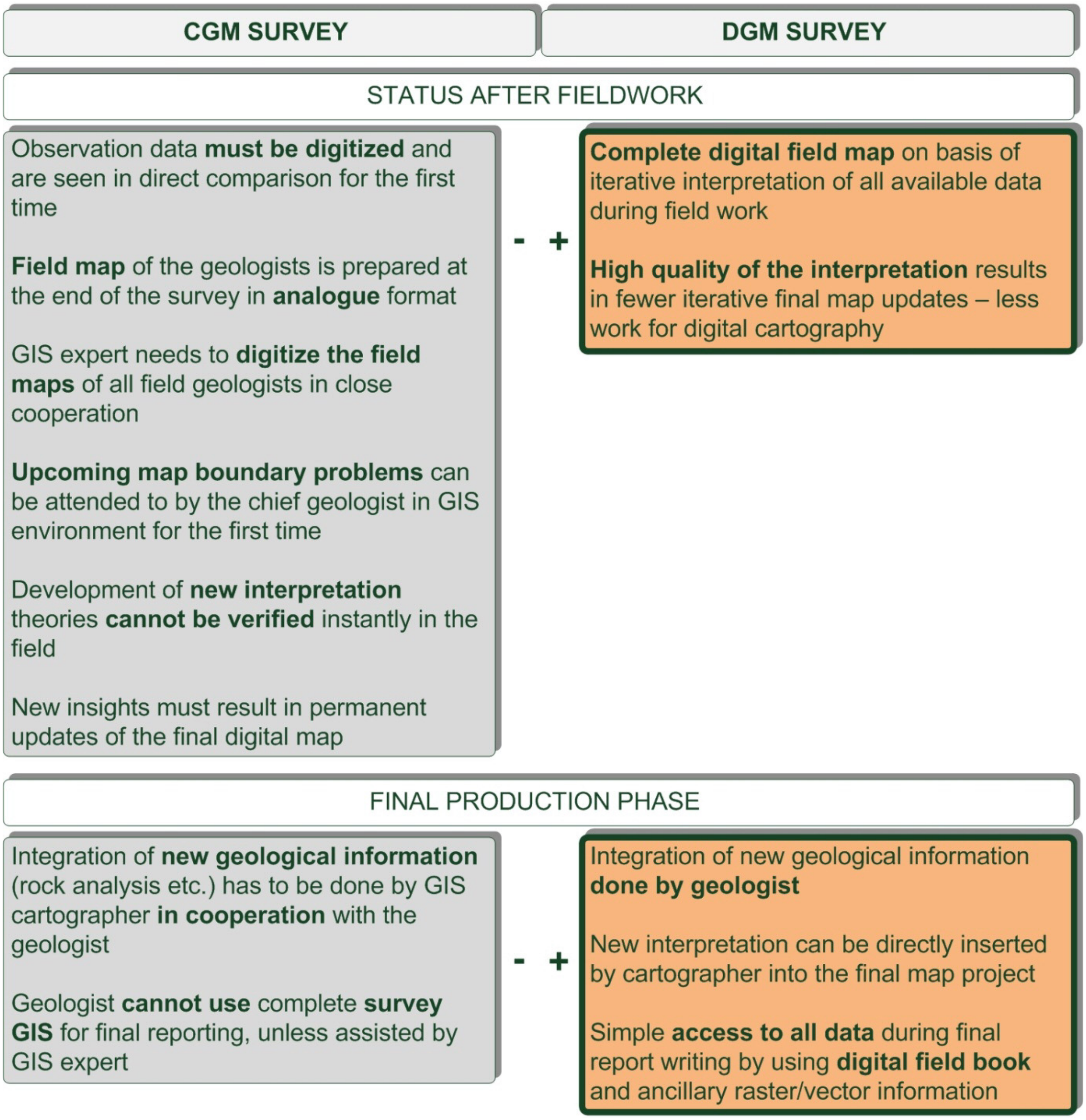
Figure 52: DGM work flow analysis of the final production phase.

Highlighted according to their effects on quality, time and costs in comparison to modern CGM methods (red: extra time/cost effort; green: quality improvement and/or time/cost savings; white: little to no difference); dashed outlines symbolize details that are commented in the text); dashed pattern resemble a part-time function; the task numbers are referred to in the text in brackets.

the majority of the production time a parallel work of both parties according to their expertise. Nevertheless a deadline for updates and changes has to be set prior to the map finalization in any approach to create final products.

In parallel with the work on the geologic map, the team leader normally prepares a final report, containing all geologic information regarding the map. The digital geologic field book, containing all of the observational data, linked photographs, and the ability to search this digital resource for particular features, makes this work considerably faster, more convenient, and generally of a higher quality as all information is quickly at hand.

It can be postulated that all extra time and effort that is put into the DGM approach in the field work and especially during the preparation phase pays off significantly in the final preparation phase. It saves an enormous amount of time at that stage while keeping a high quality standard of the geologic interpretation and the final products (⑭). A brief summary of the comparison in the final production phase is given in Figure 53.



CGM SURVEY			**DGM SURVEY**
STATUS AFTER FIELDWORK			
Observation data **must be digitized** and are seen in direct comparison for the first time **Field map** of the geologists is prepared at the end of the survey in **analogue** format GIS expert needs to **digitize the field maps** of all field geologists in close cooperation **Upcoming map boundary problems** can be attended to by the chief geologist in GIS environment for the first time Development of **new interpretation** theories **cannot be verified** instantly in the field New insights must result in permanent updates of the final digital map	-	+	**Complete digital field map** on basis of iterative interpretation of all available data during field work **High quality of the interpretation** results in fewer iterative final map updates – less work for digital cartography
FINAL PRODUCTION PHASE			
Integration of **new geological information** (rock analysis etc.) has to be done by GIS cartographer **in cooperation** with the geologist Geologist **cannot use** complete **survey GIS** for final reporting, unless assisted by GIS expert	-	+	Integration of new geological information **done by geologist** New interpretation can be directly inserted by cartographer into the final map project Simple **access to all data** during final report writing by using **digital field book** and ancillary raster/vector information

Figure 53: Major advantages (+/orange) and disadvantages (-/grey) between CGM and DGM approach concerning the final production phase of a survey.

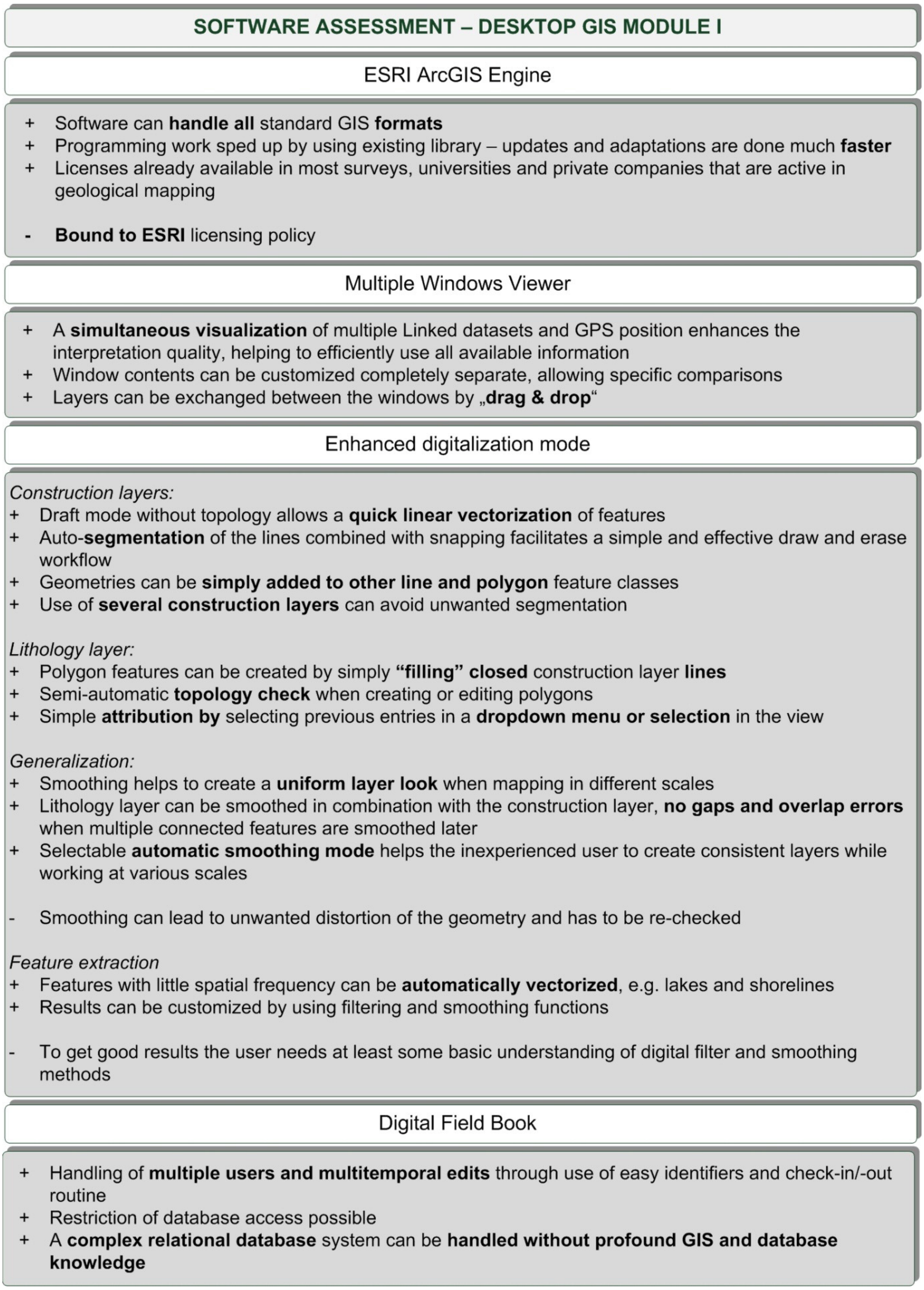
4.2 Assessment of the Digital Geologic Mapping System

The software development went hand in hand with the experiences gathered during the survey work and resulted from the input and ideas that were analyzed and evaluated by the author during the different working stages. Observations made in the office, but especially during field work, were directly used to adapt the software to the specific needs and to further improve the work flow performance as being described in chapter 3.2. The conceptual development was always aiming at keeping the software simple – designed to the specific needs of the geologist – and to smooth the work flow in geologic mapping surveys. Complex GIS and cartographic layout functionalities were left aside for the benefit of an intuitive DGM system, filling the gap between office and field work without re-inventing already existing solutions. As the presented DGM work flow is predominantly based on the use of the specific GeoRover software and as the overall advantages and disadvantages of DGM are described in the previous chapters, some of the specific software's tools and configurations will be assessed in relation to DGM techniques. Following the description in chapter 3.2, the assessment is based on the two main columns of the software, the *desktop GIS module* and the *mobile GIS application*.

4.2.1 Desktop GIS Module

As shown above, the desktop GIS module shows a number of improvements (Figure 54 and Figure 55) compared to other GIS software that were born from geologic survey work requirements. Some of the basic features were already implemented in the early versions of the software, but during every subsequent study (chapter 2) improvements were made through the evaluation of experience and through analysis of the feedback from all involved personnel. This particular development cycle made the presented DGM approach as such and the desktop GIS module in specific mature and effective in the long run.

As the software was primarily programmed in C++ in 2003, the developments in the GIS sector lead to the decision to implement the whole work flow into a more common ESRI environment, which allowed a relatively quick programming procedure, using C# .NET framework and ESRIs ArcObjects library. The unique features of the software were kept, but a compatibility with all modern data formats



SOFTWARE ASSESSMENT – DESKTOP GIS MODULE I

ESRI ArcGIS Engine

+ Software can **handle all** standard GIS **formats**
+ Programming work sped up by using existing library – updates and adaptations are done much **faster**
+ Licenses already available in most surveys, universities and private companies that are active in geological mapping

- **Bound to ESRI** licensing policy

Multiple Windows Viewer

+ A **simultaneous visualization** of multiple Linked datasets and GPS position enhances the interpretation quality, helping to efficiently use all available information
+ Window contents can be customized completely separate, allowing specific comparisons
+ Layers can be exchanged between the windows by „**drag & drop**“

Enhanced digitalization mode

Construction layers:
+ Draft mode without topology allows a **quick linear vectorization** of features
+ Auto-**segmentation** of the lines combined with snapping facilitates a simple and effective draw and erase workflow
+ Geometries can be **simply added to other line and polygon** feature classes
+ Use of **several construction layers** can avoid unwanted segmentation

Lithology layer:
+ Polygon features can be created by simply **“filling” closed** construction layer **lines**
+ Semi-automatic **topology check** when creating or editing polygons
+ Simple **attribution by** selecting previous entries in a **dropdown menu or selection** in the view

Generalization:
+ Smoothing helps to create a **uniform layer look** when mapping in different scales
+ Lithology layer can be smoothed in combination with the construction layer, **no gaps and overlap errors** when multiple connected features are smoothed later
+ Selectable **automatic smoothing mode** helps the inexperienced user to create consistent layers while working at various scales

- Smoothing can lead to unwanted distortion of the geometry and has to be re-checked

Feature extraction
+ Features with little spatial frequency can be **automatically vectorized**, e.g. lakes and shorelines
+ Results can be customized by using filtering and smoothing functions

- To get good results the user needs at least some basic understanding of digital filter and smoothing methods

Digital Field Book

+ Handling of **multiple users and multitemporal edits** through use of easy identifiers and check-in/-out routine
+ Restriction of database access possible
+ A **complex relational database** system can be **handled without profound GIS and database knowledge**

Figure 54: Software assessment of the desktop GIS module in table form, part one.

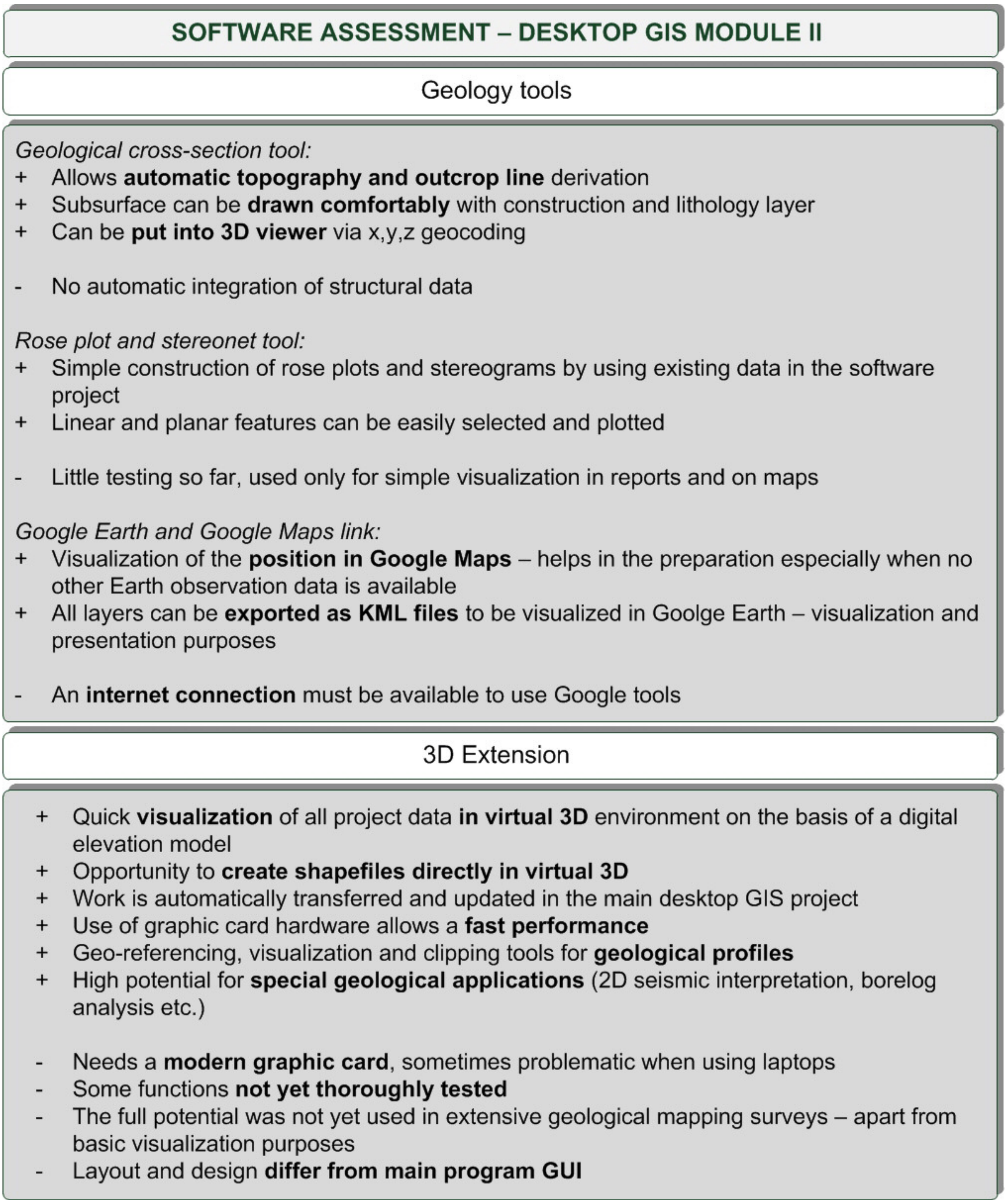
+ and - are referring to advantages and disadvantages.

and with general requirements of the GIS community was achieved. Additionally, some standard features could be implemented that would have meant enormous efforts when being rebuilt in C++, e.g. an editor functionality with undo option.

Although the software is now dependent on ESRI licensing, another advantage of using ArcObjects is the fact that most companies or institutes working on geologic mapping surveys already own ArcGIS licenses and these can be used for the without further licensing costs.

One of the oldest and perhaps most useful features of the software is the multiple windows viewer allowing a simultaneous visualization of multiple datasets. With it the huge amount of available raster and vector data, relevant for a thorough geologic interpretation, can be much better organized and analyzed. The full potential of this functionality becomes obvious in the field, combined with the GPS functionality of the software. Analyzing the various information layers simultaneously and in direct relation to the present position makes the use of geologic information and the development of theories much easier. Analysis and comparison is further facilitated with a common mouse cursor displayed in all working windows at once.

As the software is meant to support geologists, the digitizing work flow was customized according to geologic working procedures. The geologist is normally looking at point observations from field work, outlines linear lithological boundaries or structural features in a second step and finally fills lithological units in between the boundaries, as areas with the same symbols. The software works in a similar way, helping to create topologically correct digital layers in a process that the geologist is familiar with. Especially when attributing the lithological polygons, an intelligent, expandable drop-down menu facilitated the fast and easy production of complete geologic map layers. A supervized classification tool speeds up the digitization process of certain features, helping specifically in the data compilation phase during preparation of a survey. The application helps to quickly outline areas with a similar pattern and to implement these new features into the polygon or line inventory of a map. In the presented surveys it could often be used to limit sea or lake shorelines and monochromatic units in geologic maps. Especially when working with RADAR data the strong differences between outcropping material and Quaternary cover often could be used to outline geologic units with the extraction tool (Figure 41, page 101).



SOFTWARE ASSESSMENT – DESKTOP GIS MODULE II

Geology tools

Geological cross-section tool:

- \+ Allows **automatic topography and outcrop line** derivation
- \+ Subsurface can be **drawn comfortably** with construction and lithology layer
- \+ Can be **put into 3D viewer** via x,y,z geocoding

- \- No automatic integration of structural data

Rose plot and stereonet tool:

- \+ Simple construction of rose plots and stereograms by using existing data in the software project
- \+ Linear and planar features can be easily selected and plotted

- \- Little testing so far, used only for simple visualization in reports and on maps

Google Earth and Google Maps link:

- \+ Visualization of the **position in Google Maps** – helps in the preparation especially when no other Earth observation data is available
- \+ All layers can be **exported as KML files** to be visualized in Goolge Earth – visualization and presentation purposes

- \- An **internet connection** must be available to use Google tools

3D Extension

- \+ Quick **visualization** of all project data **in virtual 3D** environment on the basis of a digital elevation model
- \+ Opportunity to **create shapefiles directly in virtual 3D**
- \+ Work is automatically transferred and updated in the main desktop GIS project
- \+ Use of graphic card hardware allows a **fast performance**
- \+ Geo-referencing, visualization and clipping tools for **geological profiles**
- \+ High potential for **special geological applications** (2D seismic interpretation, borelog analysis etc.)

- \- Needs a **modern graphic card**, sometimes problematic when using laptops
- \- Some functions **not yet thoroughly tested**
- \- The full potential was not yet used in extensive geological mapping surveys – apart from basic visualization purposes
- \- Layout and design **differ from main program GUI**

Figure 55: Software assessment of the desktop GIS module in table form, part two.
+ and – are referring to advantages and disadvantages.

When working at various scales and with different users it is generally important to harmonize all digital vector results, otherwise final map products might look inconsistent as unintended edgy features or unnatural straight lines distort the results. To avoid this, simple generalization functions are often implemented in GIS software systems. When working with polygon layers, in which all features share their borders with adjacent polygons, these smoothing tools can lead to topological gap and overlay errors when used at a later stage of the digitizing process. This is a common and known problem in GIS technology. As software engineers invented a special smoothing operation in the presented software, outline and polygon filling are smoothed simultaneously, avoiding these topological errors (Annex III). However, this function is still in its testing phase and not yet fully applicable.

The main advantages of the digital field book concerning field work and the other phases of a survey are already described in detail in chapter 4.1. From a more technical point of view it is worth mentioning that the import/export routine can handle multiple user entries and multi-temporal edits by a versioning algorithm, making it perfectly usable in larger groups of geologists, working on various devices. To avoid unwanted changes in the database of the digital field book, its access can be restricted. For example allowing only editing of the own observation points and not those created by other geologists. This feature is particularly useful when working in mapping projects without a coordinating DGM expert or team leader. Summarizing, it can be said that the digital field book is designed to allow the handling of a complex relational database system without experience in GIS and database systems, a fact that makes the software an effective link between geologists and GIS experts.

Geologic applications like the cross-section and rose plot diagram/stereonet tools help to create diagrams and imagery products that can be used for interpretation and implementation into the final reports or maps. These tools were implemented in the late phases of the thesis work and although they combine all advantages of the presented digitizing mode with the corresponding scientific requirements, they lack the testing in extensive survey work.

The simple but effective tool for the export of KML files and the instant visualization of the cursor position in Google Maps both proved very helpful. This was especially true in the preparation phase of the surveys when additional information of the Google Earth community could be used for the logistical preparation. As more and more users are becoming familiar with virtual globes, the link to external similar software will be part of future updates although probably bound to further licensing costs.

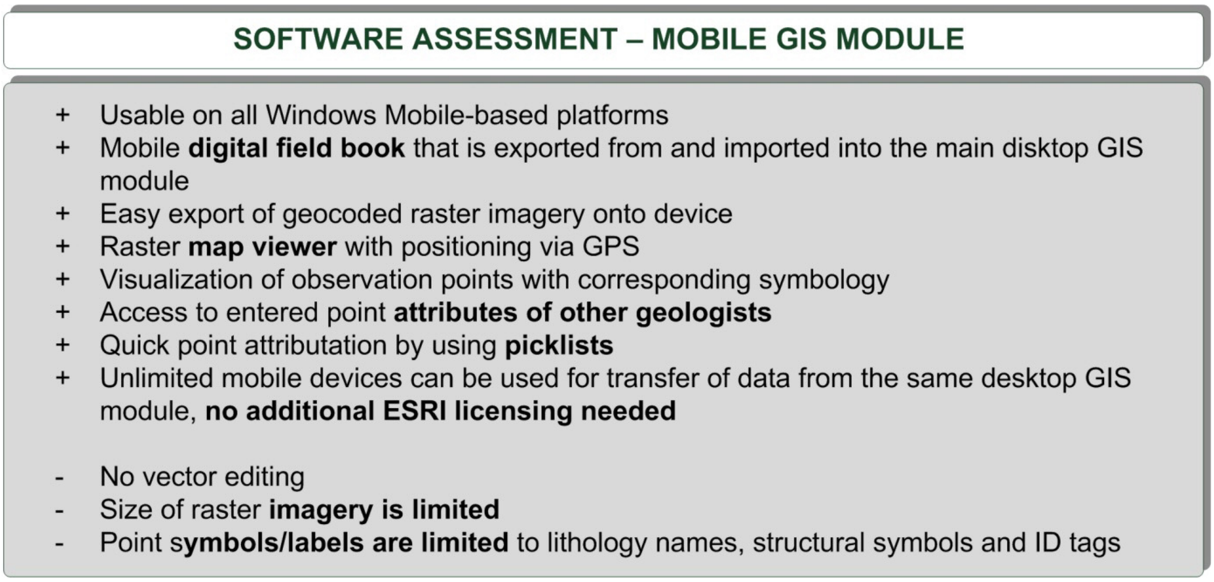
The integrated 3 D application is of great help when quickly in need of a perspective view of datasets. All data containing altitude information can be used as underlying surface models to drape additional imagery on. The application was developed and programmed completely independent from the presented software (Gocke, 2008)) but proved as very useful for the visualization in the process of geologic mapping surveys. Although geologists are traditionally trained to transfer 2D information into three dimensions, virtual 3 D views make it often easier to detect pattern and features as they resemble the natural observation in the field much better. In addition its use makes discussions and presentations amongst geologists and non-geologists much more effective. Especially the fast performance of the tool – based on the use of graphic card power instead of CPU – makes it highly profitable in the mapping process of all survey phases. The tool itself shows much more potential in various fields as it was designed for the specific use in the hydrocarbon industry. For example the geocoded visualization of seismic imagery and borelogs allows a fast interpretation of the subsurface, the modeling of interpolated planes and basic volume calculations. Nevertheless, due to the specialty of these applications and their lack of practical utilization in the presented geologic mapping surveys, they are not evaluated as part of this thesis. However, the trend to 3 D applications in the geosciences is clearly observable and appreciated by a growing community, making further developments of that tool very likely.

4.2.2 Mobile GIS Application

The biggest achievement of the mobile GIS application is the fact that the digital field book of the desktop GIS database, containing all project data, can be transferred onto a mobile device (Figure 56). It can be filled and edited in the field, with the assistance of additional raster information, and afterwards be integrated again into the main database without producing relational errors of the entries.

Built as a version for mobile devices it is meant to be an improvement for the work in areas that are not easily accessed by car and where battery power and weight are limiting factors. That means the assessment must be based on the software’s capability to support the geologist in remote and complicated surveys in the best way while being contained by hardware limitations of the mobile devices (chapter 3.2.3).

Therefore vector layers cannot be exported onto the mobile device and there is a limit to the size of raster imagery. The latter was improved by implementing an image tiling algorithm that made bigger image sizes manageable but a limit still exists. The former was not found too problematic as most geologists did not see an advantage in doing delicate editing of vectors with a stylus pen on tiny hand-held touch screens in the field. Above all, this work could be done much more efficient in the digital field office on a bigger screen with mouse and keyboard.



SOFTWARE ASSESSMENT – MOBILE GIS MODULE

+ Usable on all Windows Mobile-based platforms
+ Mobile **digital field book** that is exported from and imported into the main disktop GIS module
+ Easy export of geocoded raster imagery onto device
+ Raster **map viewer** with positioning via GPS
+ Visualization of observation points with corresponding symbology
+ Access to entered point **attributes of other geologists**
+ Quick point attributation by using **picklists**
+ Unlimited mobile devices can be used for transfer of data from the same desktop GIS module, **no additional ESRI licensing needed**

\- No vector editing
\- Size of raster **imagery is limited**
\- Point s**ymbols/labels are limited** to lithology names, structural symbols and ID tags

Figure 56: Software assessment of the mobile GIS module in table form.
+ and – are referring to advantages and disadvantages.

Even with these limitations the possibility to take the most important raster information into the field and the easy access to a GPS map viewer, interlinked with the mobile digital field book is still an enormous improvement compared to the work with a simple GPS and analog field book (Figure 45, page 112).

A very practical advantage of the application in the survey is the fact that an unlimited number of hand-held devices can be filled from the main desktop GIS program, without any special software needed. That allows the quick integration of additional field teams with very limited costs, even by using Windows Mobile based smart phones.

Apart from the GeoRover software other systems became available over the time and two should be mentioned here, without intending to be exhaustive. The brief description and estimation of the two software packages is built merely on a comparison of published information, not extensive practice. A competitive comparison of DGM software systems is not the intention of this study but rather the explication of the similarity of various approaches.

A software called MAP IT (De Donatis and Bruciatelli, 2006) was developed in 2005, mainly built as a DGM tool for the use of tablet PCs in the field, programmed using Microsoft Visual Basic (VB). Due to several problems (Antonello et al., 2010) MAP IT development came to an end and the software was rebuilt and improved under the name BeeGIS, using uDig, an open source application framework (Antonello et al., 2010). The software is free to use and offers a lot of tools that are comparable to the GeoRover system, without being bound to ESRI licensing. A system of using geo-referenced notes that can be placed on a background raster image and the possibility to insert sketches, photos and other media data seems to be straight forward and is pursuing the same objective as GeoRover: To provide the geologist with a tool that is easy to learn without profound GIS knowledge and to follow the classic pen & paper working methods of geologists. However, published information about the work with BeeGIS in huge mapping campaigns with several geologists and a final integration of field mapping results into ArcGIS are still lacking, as are detailed descriptions on the solving of vector topology issues and multiple user management.

The SIGMAmobile DGM software that is being developed by the British Geologic Survey (BGS) since 2005 can be seen as a geologic extension to ArcGIS connected to a database management built around Microsoft Access. GIS tools are used from ArcGIS directly and several basic geologist tools requiring an extra installation have been developed. Due to the close relation to ArcGIS the system seems to imply a good knowledge of GIS techniques and from the descriptions in the user manual some features might be error-prone when executed by inexperienced users. The tool has seen extensive testing and improvement periods according to the BGS and it is free to use, in case an ArcGIS license is available – comparable to GeoRover.

All three systems, BeeGIS, SIGMAmobile and GeoRover are built to serve a certain mapping workflow and are therefore strongly influenced by the developers, thus all of them require a proper training to be efficiently used. BeeGIS seems to be a very good open source alternative when an integration into the ESRI world is not desired or wanted. SIGMAmobile appears to be advantageous in geologic mapping campaigns of national geologic surveys.

However, for the presented types of geologic mapping projects, the GeoRover is considered as the best solution, principally due to the concurrency of a mobile and desktop GIS solution, the use of multiple working windows, an easy but topologically correct digitizing workflow, specific geologic tools, an integrated 3D modeler and a simple and reliable multiple user management.

4.2.3 Hardware Systems

For evaluation purposes it has to be pointed out that the specific field work conditions have to be analyzed prior to any recommendations. With the presentation of the studies in Madagascar, Uganda and Oman three significantly different types of field work are observed. The mapping in Madagascar occurred under generally very tough environmental conditions with extensive traverses by car and foot. In Uganda the conditions were much easier with most work done within a small working radius around the car with daily return to the field camp. The setup in Oman was strictly limited to verification field checks and the field work could be best described colloquially as “car geology”. Taking these various preconditions into account it was tried to customize the hardware setup according to the needs with the best price-performance ratio. The evaluation components of the different hardware systems are schematized in Figure 57. The ranking is based on many discussions with field geologists and the compilation of the biggest concerns and requirements. Different field work conditions require different DGM setups and therefore the following detailed descriptions and rankings are referring to the specific hardware systems that were used in the presented projects (chapter 2). The selection of the main ranking criteria is based on other publications (Soller, 2000-2012; McCaffrey et al., 2005; Clegg et al., 2006; De Donatis and Bruciatelli, 2006; Athey et al., 2008; De Donatis and D'Ambrogi, 2009; Whitmeyer et al., 2009; Whitmeyer et al., 2010) and the interrogation of field geologists. The valuation is based on this interrogation and the personal field work experience of the author.

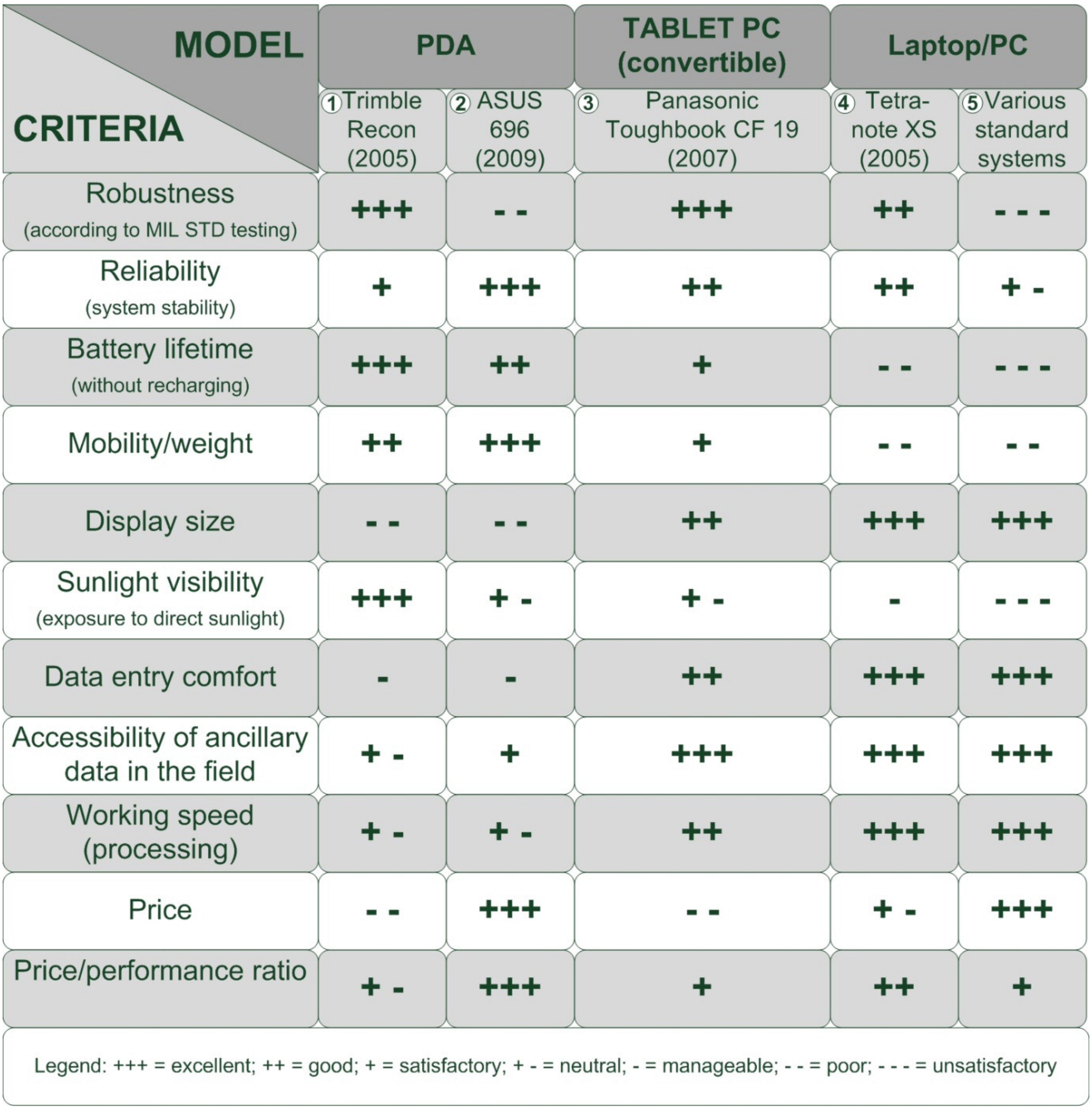
Hardware manufacturers offer very robust electronic outdoor equipment (Annex V) as it is needed under various job conditions. To rank the degrees of robustness the U.S. Department of Defense provided tests for all equipment, described as the Military Standards related to reliability and robustness abbreviated as MIL STD (U.S. Department of Defense, 2000). As the geologist is confronted with challenging outdoor conditions quite regularly using equipment with MIL-STD tag seems to be a logic step. The rugged systems employed in Madagascar, Uganda and Oman were all tested according to MIL-STD regulations and undoubtedly performed well in difficult terrain. Within the projects, the Trimble PDAs were used in pouring rain, incidentally dropped several times and covered in dust and dirt without an obvious negative effect on their performance. Concerning the tablet PC convertible and laptops, the rugged versions (③, ④ Figure 57) where of great advantage when taken into the car and used while being driven through the working area or staying in a field camp with limited facilities. Shock-absorbing hard drives that were usable in motion, fan-free cooling for leaving the dust outside the hull, stable lid hinges and improved sunlight readability made these computers more convenient and much less prone to crashes. Especially because of their screen's poor sunlight readability normal laptops were found inapplicable for this job, apart from driving on very good pavement roads or staying in field camps with almost dust-free conditions and moderate climate. Although the tablet PC convertible was quite expensive, the Tetranote XS laptops remained in the price range of normal high-end laptops and were found worth the money as they never showed any hardware problems.

The systems were almost exclusively affected by GPS connection failures. Whereas all systems were relatively reliable, the Trimble PDA had minor problems, most often related to the CF-card GPS mouse connection loosening when used on bumpy roads or carried in a bag for a longer time. Although that could be fixed by reconnecting the mouse that often resulted in broken connection pins, when done without maximum caution. The Trimble PDA also lacked a hold button avoiding the unintentional use of the on/off button, resulting in faster loss of battery power. The GPS connection of the tablet PC convertible and laptops via USB cable proved quite reliable although sometimes unhandy when taken into the outcrop but that is avoidable by using Bluetooth or other connections. The in-built GPS of the ASUS obviously showed the best reliability although not changeable for projects with a higher precision requirement.

One of the major factors in the assessment of DGM methods is the power supply in the field. In the field camp and during car rides this is hardly relevant but when taken into remote areas, battery power becomes a big issue. This is up to now the single exclusion criterion for the use of tablet PC convertibles and laptops in remote field work. Although short return trips from car to outcrop can be managed easily, longer foot traverses are not possible. Even if manufacturers state a battery life of several hours, this was not observed in the field under testing conditions. With active GPS and other software running the tablet PC convertible's battery power was run down in less than 3 hours. The use of PDAs is therefore highly advisable due to a better battery lifetime and the fact that spare batteries are small and easy to transport. In Madagascar the Trimble PDAs were used on ten days foot traverses in rough environment and lasted with one battery if switched on at outcrop points to enter observations and for quick orientations in the field.

The weight of the system is the second most important factor when planning foot traverses with DGM equipment and obviously that is another advantage of the PDAs. An often stated objection concerning DGM technology in the field is the display size and with it the readability under various conditions. The screen size definitely is an important factor when using DGM techniques but bound to the above stated restrictions of mobility and power supply one that has to be weighed carefully. In the particular way the PDAs were used in the studies, the screen size sufficed to orientate and interpret ancillary data on the spot in close relation to the outcrop surroundings. Questions of broader scale had to be attended to on printed maps or similar material. Even though the bigger screens of tablet PC convertible and laptop obviously helped, they were restricted when dealing with large-scale overview issues. As all described studies were carried out in tropical to desert environments the poor visibility of digital screens in bright sunlight was one of the more important issues to overcome. Although the manufacturers of the tablet PC convertible, the rugged laptops and PDAs all promised sunlight-readability for their screens, the long term tests under bright light conditions proved them wrong. Apart from the Trimble PDA readability, that was in fact increasing the more sun hit the screen, all other systems had to be somehow shaded to be used in an acceptable way in the field. Due to the small size and strong backlight capability the ASUS PDA could handle this situation better than the other systems. Normal laptops could not cope with that issue at all; even inside a car they were hardly usable.

When observations in the field had to be integrated into the digital database on the outcrop the various input devices were tested in relation to their use with the specific setup of the database. The PDAs provided with a sensitive touch-screen could both be operated with almost every pointing device but were naturally lacking a keyboard.



MODEL / CRITERIA	PDA		TABLET PC (convertible)	Laptop/PC	
	① Trimble Recon (2005)	② ASUS 696 (2009)	③ Panasonic Toughbook CF 19 (2007)	④ Tetra-note XS (2005)	⑤ Various standard systems
Robustness (according to MIL STD testing)	+++	- -	+++	++	- - -
Reliability (system stability)	+	+++	++	++	+ -
Battery lifetime (without recharging)	+++	++	+	- -	- - -
Mobility/weight	++	+++	+	- -	- -
Display size	- -	- -	++	+++	+++
Sunlight visibility (exposure to direct sunlight)	+++	+ -	+ -	-	- - -
Data entry comfort	-	-	++	+++	+++
Accessibility of ancillary data in the field	+ -	+	+++	+++	+++
Working speed (processing)	+ -	+ -	++	+++	+++
Price	- -	+++	- -	+ -	+++
Price/performance ratio	+ -	+++	+	++	+

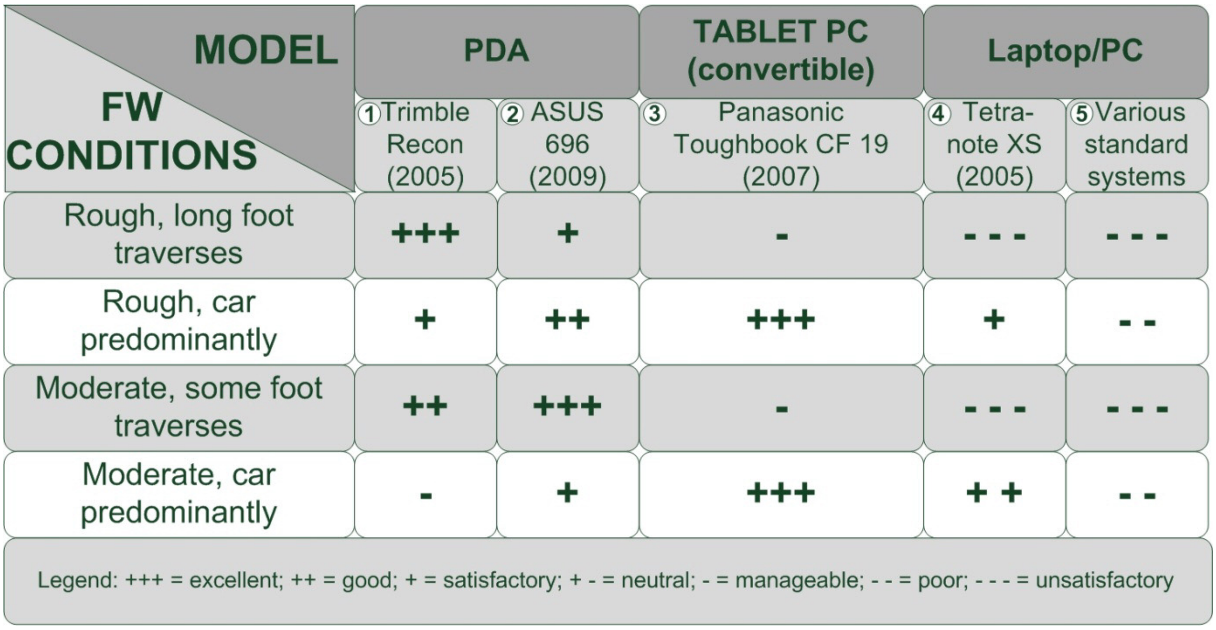
Legend: +++ = excellent; ++ = good; + = satisfactory; + - = neutral; - = manageable; - - = poor; - - - = unsatisfactory

Figure 57: Assessment of the various hardware systems used in the presented surveys according to field work relevant aspects.
The valuation is based on the interrogation of field geologists and personal experience of the author.

However, as the developed digital form sheets (chapter 4.1.1) minimized the use of free text, the problem of data entry with digital on-screen keyboard remained manageable. After getting into the routine, most geologists entered long free text in the designated note fields within short times. Nevertheless, the input of text can be described in general as inconvenient. The tablet PC convertible combined all methods of input devices but in its form as a tablet PC it was bound to a special active pen. As the tablet was running the full desktop GIS version, the active pen had to be used as mouse substitute. On the outcrop operations were manageable although the small stick and the tiny right mouse-click button on it hardly felt comfortable or precise. Easy operations in a moving car became relatively complex and by far less convenient than the handling of the normal PDA touch-screens under these conditions. For most users the classic input devices of mouse and keyboard proved as the most effective in the car and if possible on the outcrop. The tablet PC convertible used with keyboard and mouse as a small field laptop thus was found very effective when working not too far from the car. In more remote areas the limitations mentioned above favored the PDAs with the dropdown lists and short field entries.

Accessing ancillary data in the field, while standing on the outcrop, was granted by all systems although bound to several restrictions. When using the full desktop GIS capabilities on the laptop and tablet PC convertible, combined with their much better processor performance and hard disk space, access on all project data was granted. The hardware limitations of the PDAs – combined with only limited GIS functionalities – minimized the use of ancillary data in the field to predefined subsets copied on the device prior to field work. Although that helped a lot for the well-prepared daily working schedule, those subsets were not usable for overview questions and were sometimes outrun by an unforeseen change of the field schedule. In later software versions the tiling of raster layers allowed bigger amounts of data to be processed and taken to the field. Nevertheless the data access and editing with PDAs in the field remained pretty basic but in combinations with the other capabilities served the DGM purpose very well.

Evaluating the use of the various systems in the presented studies (chapter 2), the price-performance ratio labels the cheap Asus PDAs in combination with semi-rugged or rugged laptops as the best field work setup for most project parts Figure 58). When working in large teams, a handy DGM tool for every mapping geologist is needed that could deal with the standardized data entries and provide the geologist with additional information in the field. The experience gathered during the described projects suggests that the cheap PDA versions could cope with most environmental situations if treated responsibly. In addition, the price made it possible to provide the field camp with several spare units of cheaper PDAs in case of a hardware failure, as the prices for rugged PDAs were approximately five times higher. The working procedure described in chapter 2 and chapter 3 normally allowed a constant backup of the gathered data at least on a daily basis, further diminishing the effect of a possible hardware failure. Thus the failure of one component would not end up in a severe loss of data, but in the loss of one field day maximum. Additionally, if an analogue paper backup is taken in the field the data could be even entered in the field camp later on. The relatively long battery life of the ASUS PDAs along with the easy transportation of several spare batteries and an integrated GPS also argue for their choice.



MODEL	PDA		TABLET PC (convertible)	Laptop/PC	
FW CONDITIONS	① Trimble Recon (2005)	② ASUS 696 (2009)	③ Panasonic Toughbook CF 19 (2007)	④ Tetra-note XS (2005)	⑤ Various standard systems
Rough, long foot traverses	+++	+	-	- - -	- - -
Rough, car predominantly	+	++	+++	+	- -
Moderate, some foot traverses	++	+++	-	- - -	- - -
Moderate, car predominantly	-	+	+++	+ +	- -

Legend: +++ = excellent; ++ = good; + = satisfactory; + - = neutral; - = manageable; - - = poor; - - - = unsatisfactory

Figure 58: Specific hardware recommendations based on the experience with various field work conditions.

All additional work that could not be done in the field due to the limited GIS capabilities of the PDAs was done in the field camp or car, using rugged laptop systems of moderate prices. Consequently it can be said that the PDAs were used as standardized digital field books and the field map production was done in the camp using full desktop GIS facilities with comfortable input devices, screen size, visibility and without power issues – a general work flow that is in accordance with the proposed field work procedures by the Ad-hoc committee on geology (Schwarz et al., 2004).

4.3 Exemplary Time and Cost Analysis

To create a reasonable comparison between the developed DGM approach and CGM methods, a fictional geologic mapping project is analyzed according to the involvement of key personnel for both setups. The example is built around a field work campaign of six weeks, with similar lengths for preparation and final production. Personnel activity is measured in person days (PD) and work power is treated as equal for all individuals (field geologists, GIS expert etc.) in both work setups. Whereas the positions of DGM expert, team leader and GIS expert are referring to one person each, geologists are calculated as a group of five individuals. A working week consists of six days. These frame conditions are based on the experiences gathered during various geologic mapping projects and are considered as realistic for the proposed assessment. The total PD amount is summarized for all three survey phases separately, facilitating the comparison.

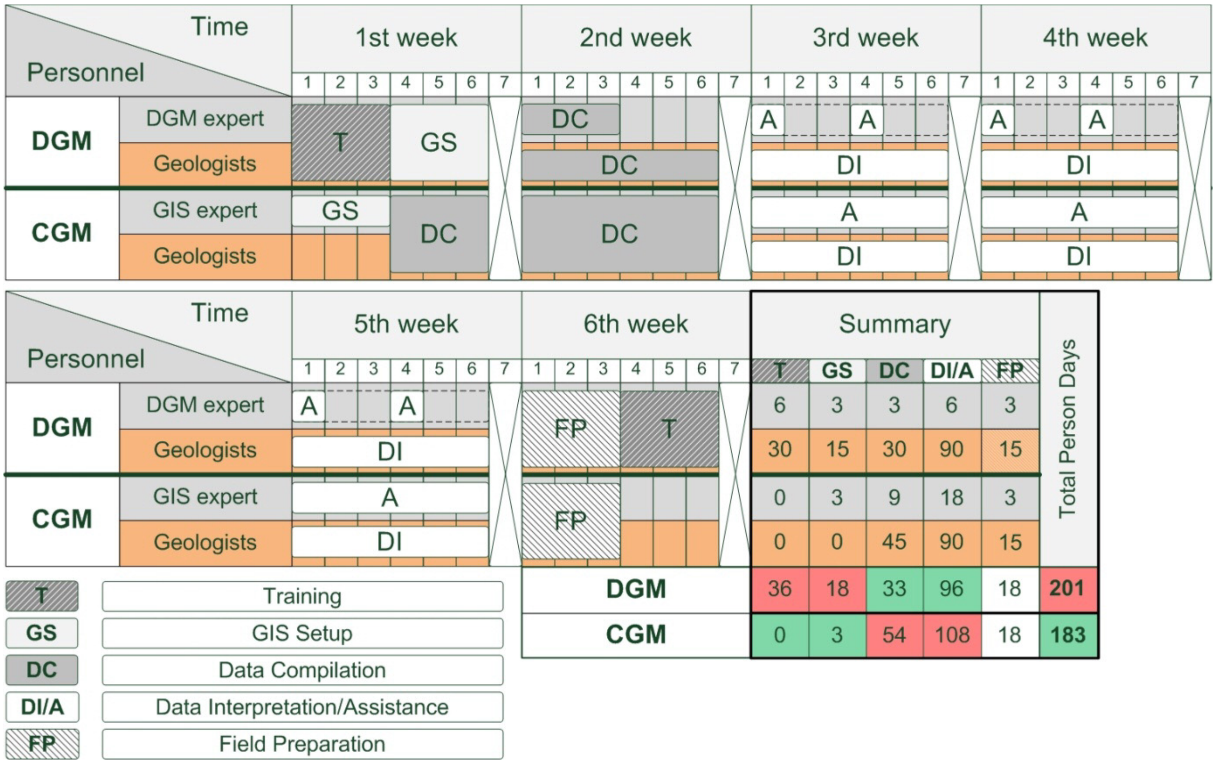
During the preparation phase obviously the biggest cost discrepancies in both working approaches reflects the additional costs of having a full time DGM expert within the DGM approach. This pivotal position set between geology and digital cartography facilitates the efficient interaction between both fields and offers proper support and training sessions.

Although this position in some phases produces extra costs – notably during field work – it grants the maximum of support and assistance for the geologists, enabling them to fully contribute with digital results to the advancement of all phases. Thus, apart from raising interpretation quality by working autonomously with the software, full work power of all groups is unleashed, minimizing unproductive waiting periods. During the preparation phase this affects directly the data compilation and interpretation. As the individual work with the software cannot be done without proper training of the personnel, the DGM approach requires extra time spent on training sessions mainly in the beginning and at the end of the preparation phase. Once the geologists are capable of working independently, the work power of the DGM expert can be channeled to other tasks, assisting only on demand. Naturally the longer the preparation phase, the sooner the stated benefits will outrun the extra efforts and costs put into training.

In CGM surveys the geologists are normally assisted full-time by GIS experts for transferring their ideas into the digital world. Not only is this procedure cumbersome and not ideal for developing scientific theories but it inefficiently doubles the work. In detail (Figure 59) the data compilation uses only half of the time from the middle of the second week onwards. In analogy to the DGM approach, the extent of this effect is proportionally linked to the duration of the preparation phase.

The biggest differences can be seen in the training sessions (advantage CGM) and data interpretation assistance (advantage DGM). As the geologists work independently in the DGM approach, the work load of the DGM expert can be reduces in contrary to the GIS expert in the CGM approach.

However, during the preparation phase there is a slight advantage of the CGM approach visible (18 days) that is mainly relating to the short interpretation time of three weeks. When this phase is elongated the advantages of independent work of the geologists outruns the extra efforts of training in the beginning and the slight advantage of the CGM approach.

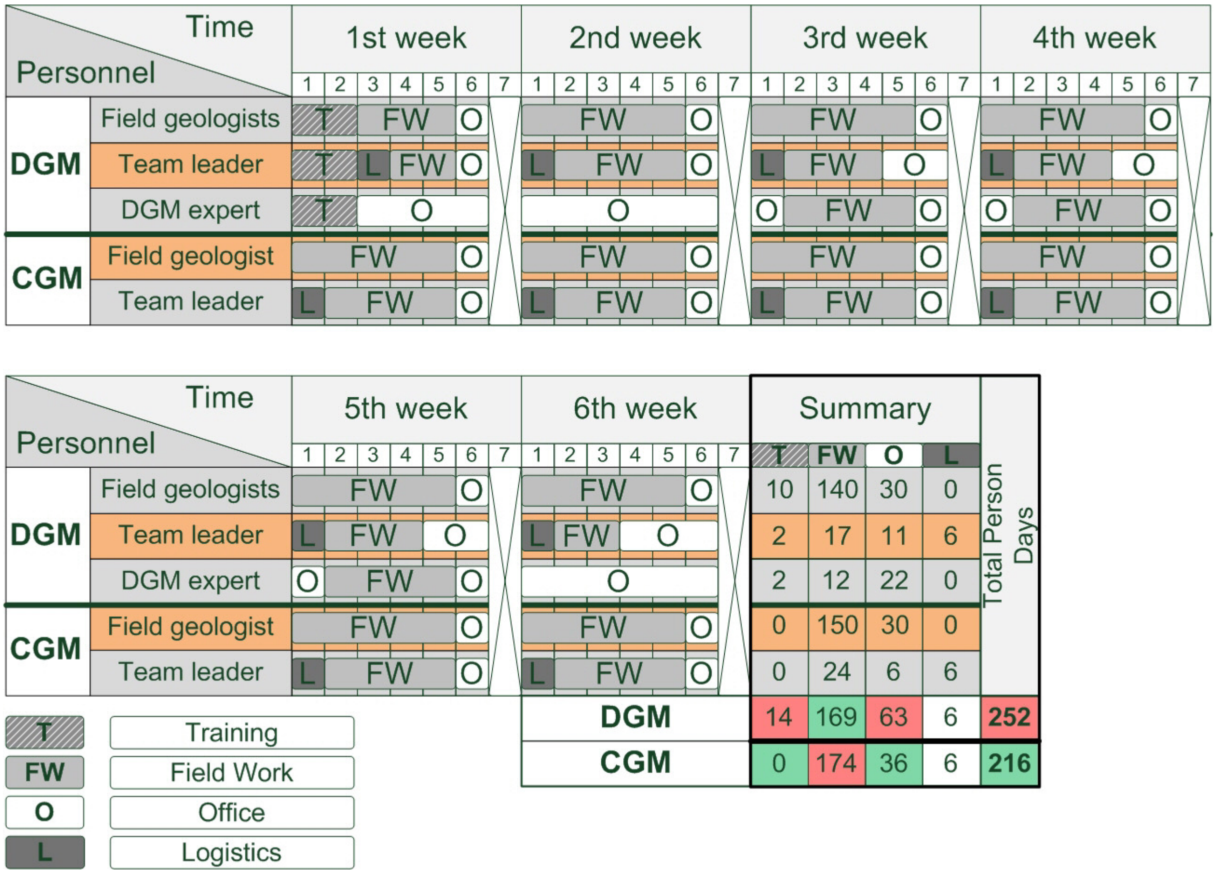


		T	GS	DC	DI/A	FP	Total Person Days
DGM	DGM expert	6	3	3	6	3	
	Geologists	30	15	30	90	15	
CGM	GIS expert	0	3	9	18	3	
	Geologists	0	0	45	90	15	
DGM		36	18	33	96	18	201
CGM		0	3	54	108	18	183

Figure 59: Simplified comparison of DGM and CGM time schedules during the 6 weeks preparation phase of a geologic mapping test project;

Collaboration of DGM expert and geologist (DGM approach) is directly compared to the collaboration of GIS expert and geologists (CGM approach) Outstanding differences refer to training sessions and data interpretation assistance.

As for the preparation phase, the training component during field work requires extra PDs in the beginning of a DGM field work campaign. However, the full-time position of the DGM expert throughout the complete field work campaign (Figure 60) is primarily responsible for the higher amount of PDs (252) compared to the CGM approach (216). Whereas the DGM expert is responsible for the training (both theory and on the job) and the setup of a digital field office in the beginning, his duties are progressively transferred to geologic field work, according to the group's progress.



Summary		T	FW	O	L	Total Person Days
DGM	Field geologists	10	140	30	0	
	Team leader	2	17	11	6	
	DGM expert	2	12	22	0	
CGM	Field geologist	0	150	30	0	
	Team leader	0	24	6	6	
DGM		14	169	63	6	**252**
CGM		0	174	36	6	**216**

Figure 60: Simplified comparison of DGM and CGM time schedules during the field work phase of a geologic mapping test project;

Collaboration of DGM expert, team leader and geologists (DGM approach) is directly compared to the collaboration of team leader and geologists (CGM approach). Additional PDs are bound to the full-time position of the DGM expert, training phases and digital mapping work in the office.

However, at the end of the phase, the specific support of the team leader with remote sensing and GIS techniques is assured on demand when the production of a digital field map begins. This production forces the team leader and DGM expert to contribute less PDs to field work in favor of the digital mapping in the office (27 PDs more, compared to CGM approach). The time spent by the team leader on logistics can be considered as equal in both survey setups. Apart from the training phase in the beginning, the same holds for the field work contribution of the geologists.

In summary, the DGM expert is the major difference of both approaches. However, this role is likely to contribute almost full-time to geologic mapping between the third and fifth week, whereas supporting other team members in the first, second and sixth week. A longer campaign would result in a higher amount of field work days in the DGM approach, as digital mapping (team leader) and assistance (DGM expert) efforts would remain more or less the same and the DGM expert could be used as additional field geologist in between.

During the final production phase the time benefit of the DGM approach becomes remarkably visible. The time that has been spent in the field on digital mapping, digital data entry and training results in a seamless continuation from the field work phase into the final production phase. In comparison, the CGM approach needs several working steps after field work to achieve the same level. The analog observation form sheets have to be first digitized and then all information can be used to start the production of a final digital field map. That map has to be realized in close collaboration of a GIS expert with each of the geologists. In this calculation it is assumed that an average of eight observation points is gathered by each geologist per day. Taking the field work days from Figure 60 into account, a total of 1392 observation points are inferred to have been collected in the CGM project. The digitization of all information related to each point is estimated to take 15 minutes on average. Thus the overall time for the production of a geo-referenced field book database equals 348 hours or approximately 44 PDs (Figure 61). The preparation of a final digital field map is estimated to take three days for each geologist to sit together with the GIS expert. That adds up to 15 PDs for the geologists and another 15 PDs for the GIS expert, resulting in 30 PDs total. This sums to 74 preparation days, before even starting the production of the final production phase. This time is completely saved in the new DGM approach.

The fact that the team leader is working independently with little assistance from the DGM expert, saves some additional time, as all work in the CGM approach has to be done as a collaboration of team leader and GIS cartographer. In both approaches the contribution of the field geologists and the reporting is considered equal.

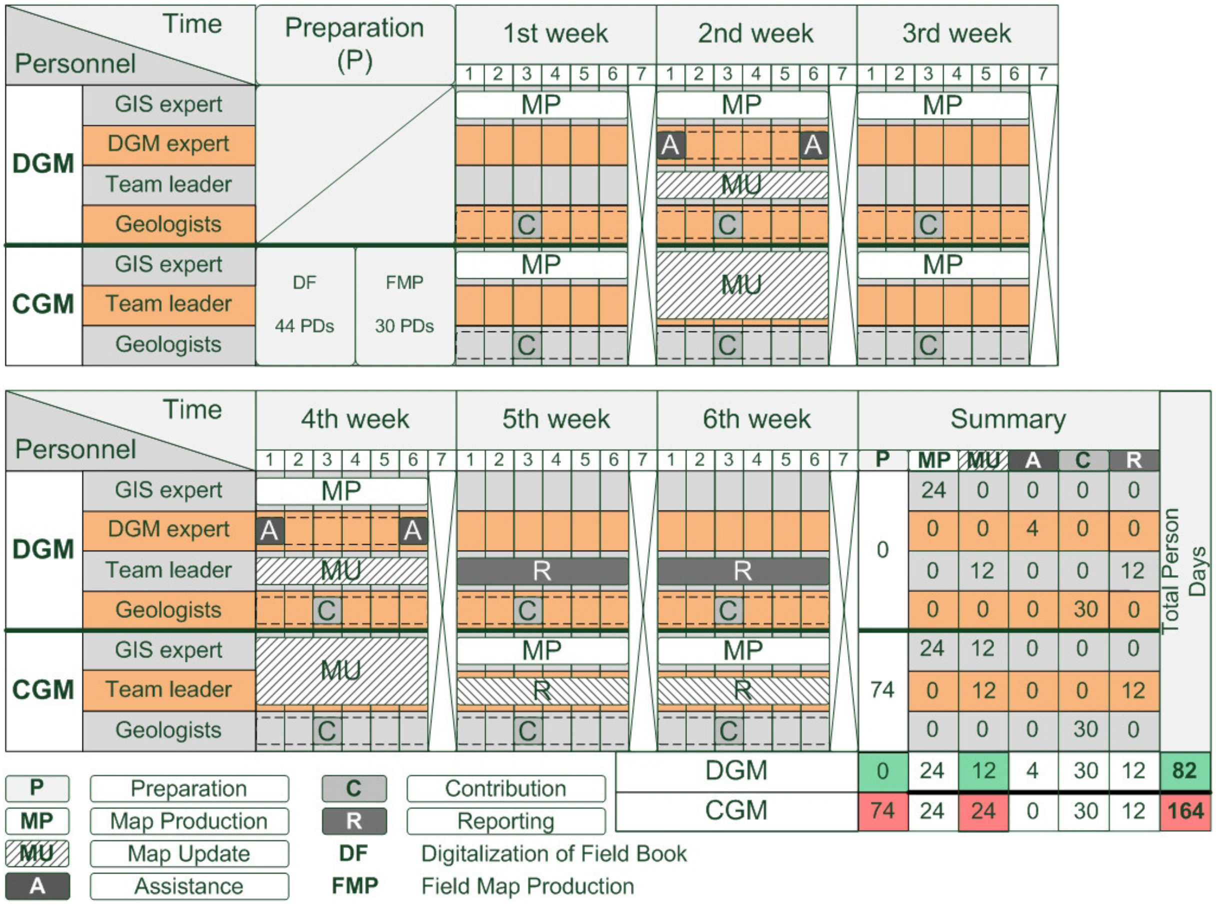


Figure 61: Simplified comparison of DGM and CGM time schedules during the final production phase of a geologic mapping test project.

Collaboration of DGM expert, team leader, geologists and GIS expert (DGM approach) is directly compared to the collaboration of team leader geologists and GIS expert (CGM approach). Main difference is the additional time that is needed for the transfer of field data in the CGM approach.

In summary, when comparing all project phases, the DGM approach produces a total of 535 PDs with 169 field work days whereas the CGM approach ends up with a total of 563 PDs with 174 field work days. This calculation takes only the working time into account, regardless of the quality improvement related to DGM working methods (chapter 4.1). Although even in short-term projects of six weeks an advantage of DGM methods can be seen already, the time savings of the DGM approach are proportional to the length of the project and are considerably higher for long-term projects as described in chapter 2. Software and hardware costs are not implemented in this analysis as they are considered minor compared to the working costs, especially when working with open source systems and very basic hardware devices.

5 Conclusion

The main ambition of this study is the presentation and analytical assessment of a new digital geologic mapping (DGM) approach that was actively developed by the evaluation of geologic field work studies, the requirements of involved experts and software engineers with the pronounced goal to create a modern mapping approach that suits the challenging standards of international geologic mapping projects. The study is based on first-hand experience the author gathered during the accomplishment of numerous international geologic mapping projects, when involved iteratively in the design, analysis and improvement of the approach from 2004 to this date. The resulting digital geologic mapping work flow is built around the GIS software package GeoRover that was continuously improved in close collaboration with software engineers as part of this thesis. Three key steps in the development history of the DGM approach are highlighted by presenting study experience gathered in Oman, Madagascar and Uganda. The critical comparison of the emerged methods with conventional geologic mapping approaches delivers advantages and disadvantages in relation to modern mapping requirements. It becomes obvious in the assessment that the innovative methods for the most part raise the quality and time-efficiency of geologic mapping results to a great extent; hence this study is seen as a contribution to the acceptance of specific DGM methods in the geoscientific community, by being based on a long-term practical experience and iterative assessment, not overreliance on technological progress.

An evaluation of DGM methods cannot be done in general without looking at specific survey setups and goals. Thus the evaluation and conclusion at hand are based on the experiences made during particular types of geologic mapping projects and can only partly be transferred to projects or surveys with completely different preconditions. The results consider the developed work flow that is strongly correlated to the constantly updated software system and naturally the hardware that was available at the various stages.

It can be stressed out that the presented DGM methods not only contribute to a faster and more time-efficient project work but can greatly improve the general quality of the field work and the geologic interpretations in specific. The cyclic work flow built around the standardized capturing of data in the field, their storage and interpretation in a mobile, easy-to-use GIS in combination with the instant shareability of the data proved as a major advantage in direct comparison with conventional methods in Madagascar and Uganda. Although other mobile GIS applications and DGM methods exist, the strength of the developed work flow is the consideration of all aspects from associated disciplines in GIS, remote sensing and geology, while aiming at the efficient conduction of geologic mapping campaigns from preparation to final production on an expert level. Specifically the interwoven needs and requirements of all participating technical and scientific experts are taken into account to streamline handovers and maximize efficiency. The most important benefits of the new DGM approach can be summarized as such:

- **Streamlining** of the work process from beginning to end of a mapping survey.
- **Easy setup** of the DGM system minimizes the GIS training needed for inexperienced users; **digital geological interpretation** can be done **directly by the geologist**.
- Preliminary interpretation results can be **taken directly into the field**.
- Field observations can be interpreted and precisely compared to **other auxiliary information at the outcrop**; the **interpretation quality is raised** by testing hypotheses and preliminary interpretations while being in the field.
- All geologic observation data entries are **comparable, homogenous** and at always easily accessible via **integrated digital field book**.
- Geologists contribute with their data integration to a constantly **growing GIS**, showing always the actual status of the mapping progress
- Large groups of geologists can be easily managed by granting **transparency and easy supervision of the field team**'s schedules.
- Improved geologic interpretation through **advanced analysis tools**, e.g. cross-section, supervised classification and rose diagram applications.
- Production of **digital field maps** by every responsible geologist is encouraged by **simple GIS tools**.
- Field work results return to the GIS cartographer in the format of digital maps and databases that can be **directly integrated into the final map production** in the office.

Although the presentation of the work flow and software evolution over a project time span of seven years documents numerous problems, most of them were solved quickly and represent a learning curve of the approach. The benefit of having today an efficient digital operating cycle from the preparation phase till the final map production cannot be overemphasized, when today in all tendered geologic mapping projects the final delivery products have to be in a digital geologic database format.

Even though the study is built around the specific setup of having a DGM expert and several GIS cartographers at hand, it is possible to implement the DGM approach to various extents. Whereas it is considered relatively easy for individual geologists to simply enter observation points in the field and visualize them with the presented soft- and hardware solutions, it gets more complex as a function of raised GIS and remote sensing demands and the number of simultaneous users involved. However, this study proves that such complexity can be overcome successfully with the supervision by a regulating expert in larger projects.

Nevertheless, DGM techniques – especially mobile GIS applications for field work – are still faced with an attitude of skepticism by a remarkable number of geologists, organizations and institutes. The geologist as "[…] tough natural scientist operating in the field without technology" (De Donatis and D'Ambrogi, 2009) and the quote of a colleague: "I became a geologist to get rid of computers in the first place!" are both reflecting an image of geology that will slowly but surely vanish with succeeding generations of geologists, used to integrate mobile technology – not for the sake of itself – but if considered as an advancement. In other words:

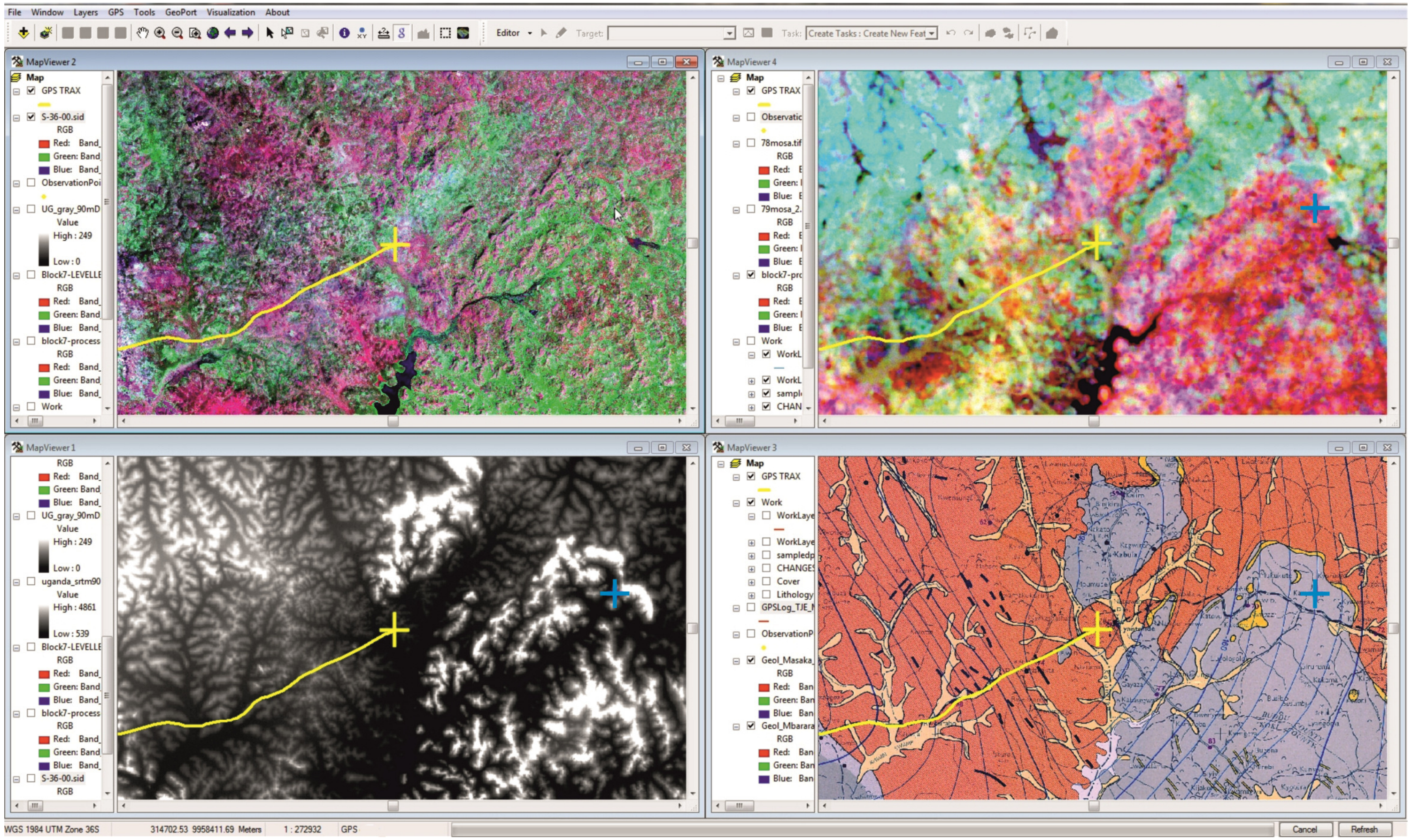
Uganda's regional geology is still easier discussed with an A0 print-out of the geologic map laid out on the hood instead of ten people sitting around an 8" display in bright sunlight. In this context it shall be underlined that the developed DGM techniques must not replace traditional geologic field work methods as such but should support the geologist in conducting efficient and high quality field work while facilitating the integration of the results into the modern digital standard of mapping projects and surveys.

6 OUTLOOK

It seems realistic to say that modern digital mapping techniques will continue to find their way not only into geologic mapping surveys but into all scientific disciplines that require field work and the fast and easy processing and analysis of observed and collected data. A new public awareness of geo-referenced data through GPS related developments in car and cell phone navigation systems or virtual globe applications such as Google Earth will surely lessen the skepticism of younger geologist generations towards DGM methods. As GPS receivers are today common standard and processing power and battery lifetime are improving constantly in smart phones, tablets and netbooks, a huge variety of adequate and user-friendly hardware systems seem to be at hand for that task. In addition, software solutions keep becoming more applicable and developers try to minimize the need for GIS expert knowledge, making them straightforward usable by field geologists without strong GIS background. Thus, as a promising future of DGM techniques seems set, it is now in the hands of the respective organizations and individuals to implement the methods in the best suiting way and deliver constructive scientific feedback for a fast evolution of useful DGM methods. The intention of international surveys and state departments to develop common digital standards for geologic mapping (Soller and Stamm, 2008) and initiatives to make digital geologic information accessible to everyone (e.g. OneGeology, 2011) can be seen as a step towards this direction.

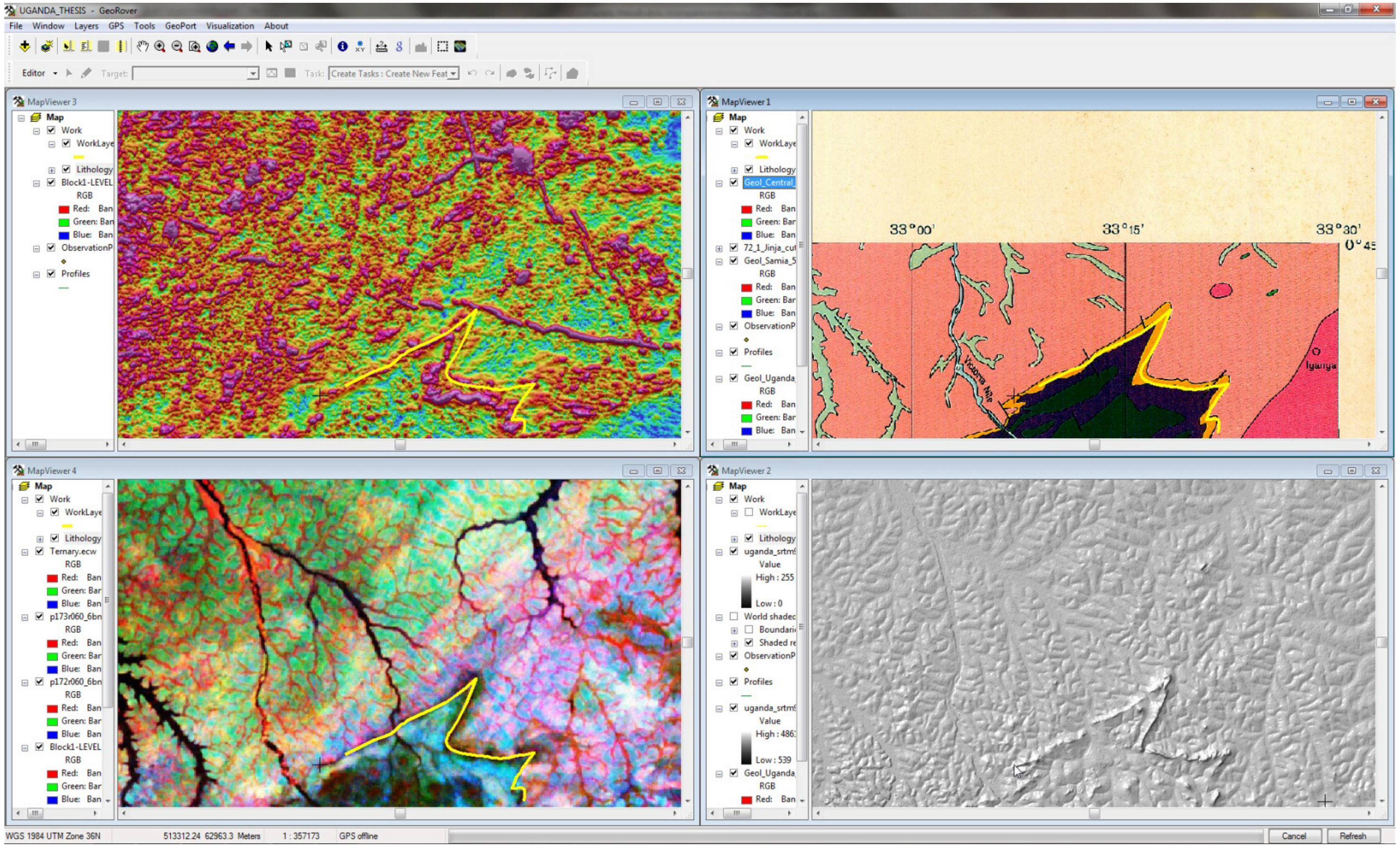
Whereas in this thesis the complex relationship of large teams in geologic mapping projects is described, countless other geoscientific DGM setups are imaginable in national geologic surveys, mineral and mining exploration organizations, the hydrocarbon industry and especially at universities. For the author it appears to be highly advisable to strengthen the implementation of DGM methods in university courses as they will become undoubtedly an important part of future geologic working routine. These courses surely must not replace the training of traditional working methods but should be integrated into field excursions as a practical introduction of new tools for preparation, conducting and interpretation of geologic surveys, thus contributing greatly to the substantiated education of future geologists.

ANNEX



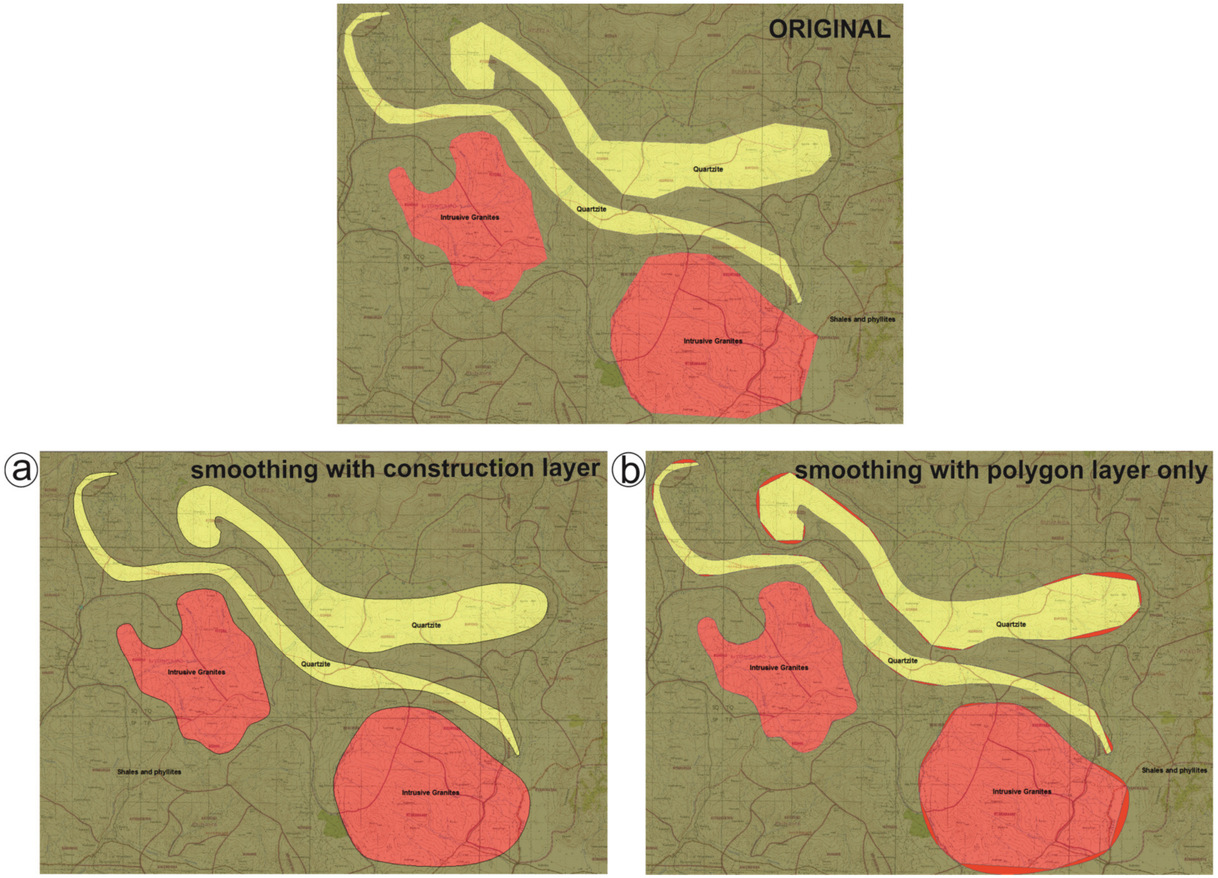
Annex I: Improved Multiple Windows Mode.

Actual GPS position (yellow cross) and Multicursor (blue crosses relating to white mouse cursor, upper left window); clockwise from upper left: LANDSAT ETM (741 RGB); ternary radiometry image; geologic map of the Masaka area, Uganda, scale 1/ 250 000; SRTM elevation data; raster images by courtesy of the Department of Geologic Survey and Mines, Uganda and GAF AG, Germany.



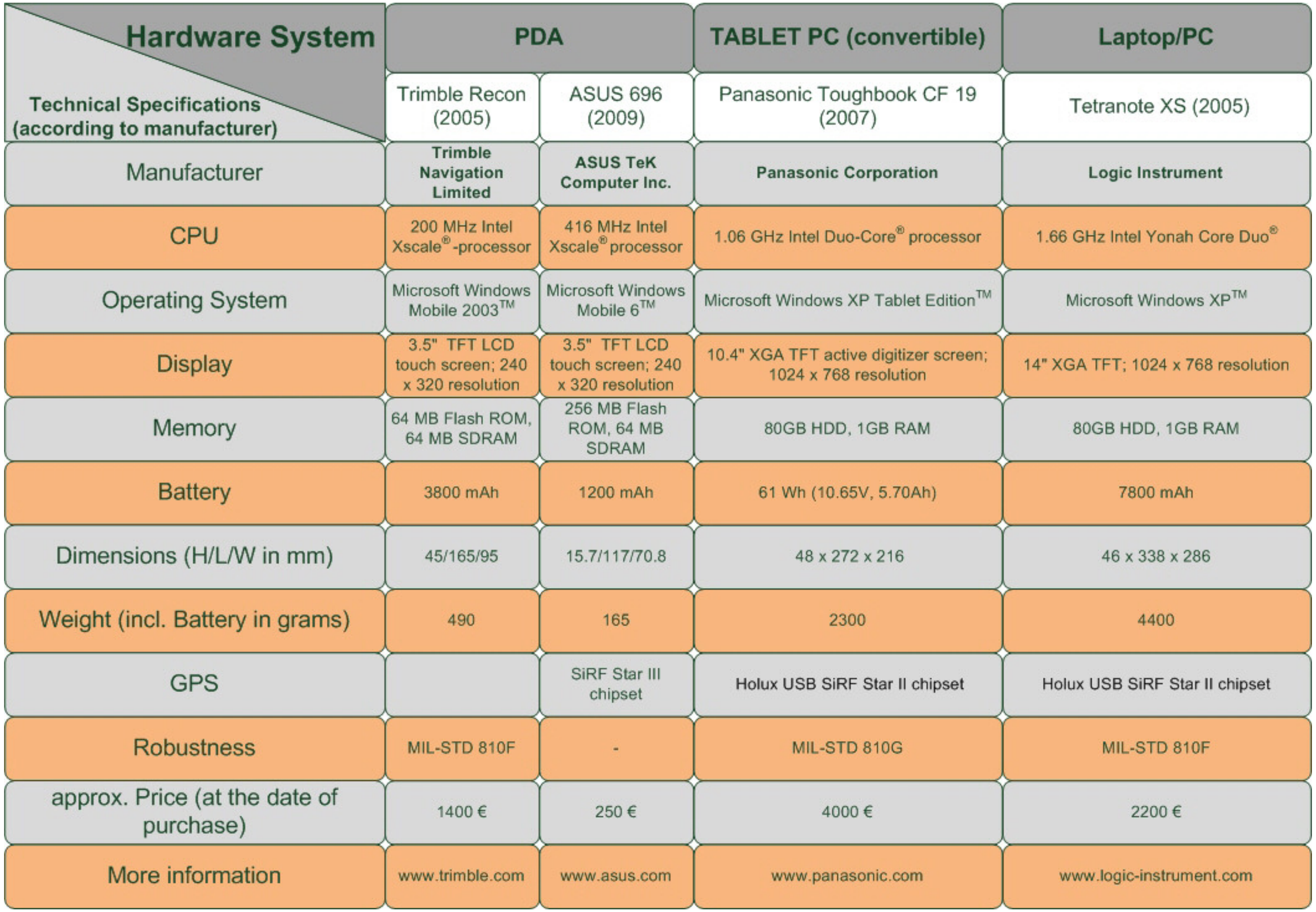
Annex II: Improved detection in Multiple Windows Mode.

Detection of features in multiple information layers, here a quartzite ridge close to Jinja, Uganda; clockwise from upper left: aeromagnetic data; geologic map of the Jinja area 1/500 000, produced by BGR; SRTM elevation data displayed as hillshade image; ternary radiometry image; raster images by courtesy of the Department of Geologic Survey and Mines, Uganda and GAF AG, Germany.



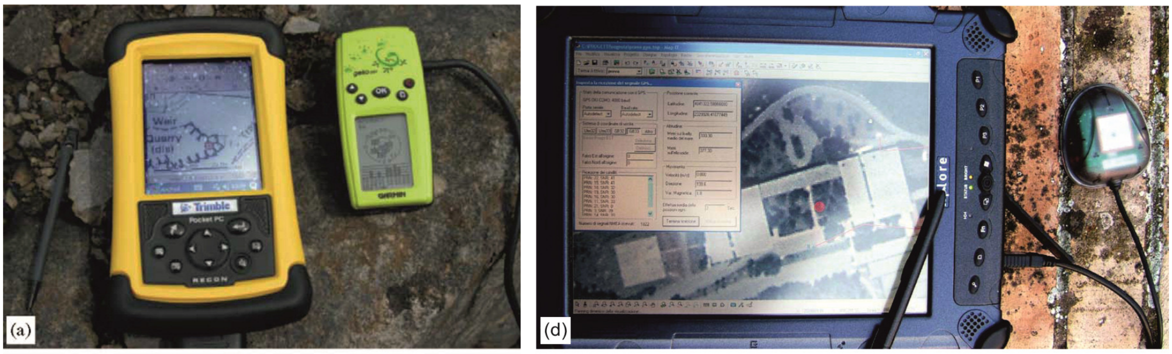
Annex III: Generalization by advanced smoothing technique.

An original polygon vector layer is smoothed by using ⓐ outline in combination with the polygon or ⓑ polygon layer only (bottom right); the feature is still in its testing phase.



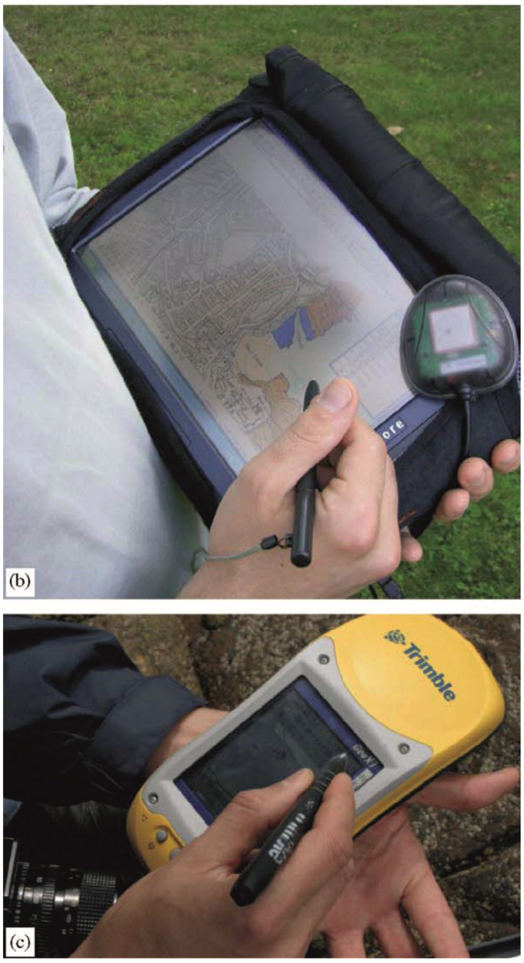
Hardware System Technical Specifications (according to manufacturer)	PDA		TABLET PC (convertible)	Laptop/PC
	Trimble Recon (2005)	ASUS 696 (2009)	Panasonic Toughbook CF 19 (2007)	Tetranote XS (2005)
Manufacturer	**Trimble Navigation Limited**	**ASUS TeK Computer Inc.**	**Panasonic Corporation**	**Logic Instrument**
CPU	200 MHz Intel Xscale®-processor	416 MHz Intel Xscale® processor	1.06 GHz Intel Duo-Core® processor	1.66 GHz Intel Yonah Core Duo®
Operating System	Microsoft Windows Mobile 2003™	Microsoft Windows Mobile 6™	Microsoft Windows XP Tablet Edition™	Microsoft Windows XP™
Display	3.5" TFT LCD touch screen; 240 x 320 resolution	3.5" TFT LCD touch screen; 240 x 320 resolution	10.4" XGA TFT active digitizer screen; 1024 x 768 resolution	14" XGA TFT; 1024 x 768 resolution
Memory	64 MB Flash ROM, 64 MB SDRAM	256 MB Flash ROM, 64 MB SDRAM	80GB HDD, 1GB RAM	80GB HDD, 1GB RAM
Battery	3800 mAh	1200 mAh	61 Wh (10.65V, 5.70Ah)	7800 mAh
Dimensions (H/L/W in mm)	45/165/95	15.7/117/70.8	48 x 272 x 216	46 x 338 x 286
Weight (incl. Battery in grams)	490	165	2300	4400
GPS		SiRF Star III chipset	Holux USB SiRF Star II chipset	Holux USB SiRF Star II chipset
Robustness	MIL-STD 810F	-	MIL-STD 810G	MIL-STD 810F
approx. Price (at the date of purchase)	1400 €	250 €	4000 €	2200 €
More information	www.trimble.com	www.asus.com	www.panasonic.com	www.logic-instrument.com

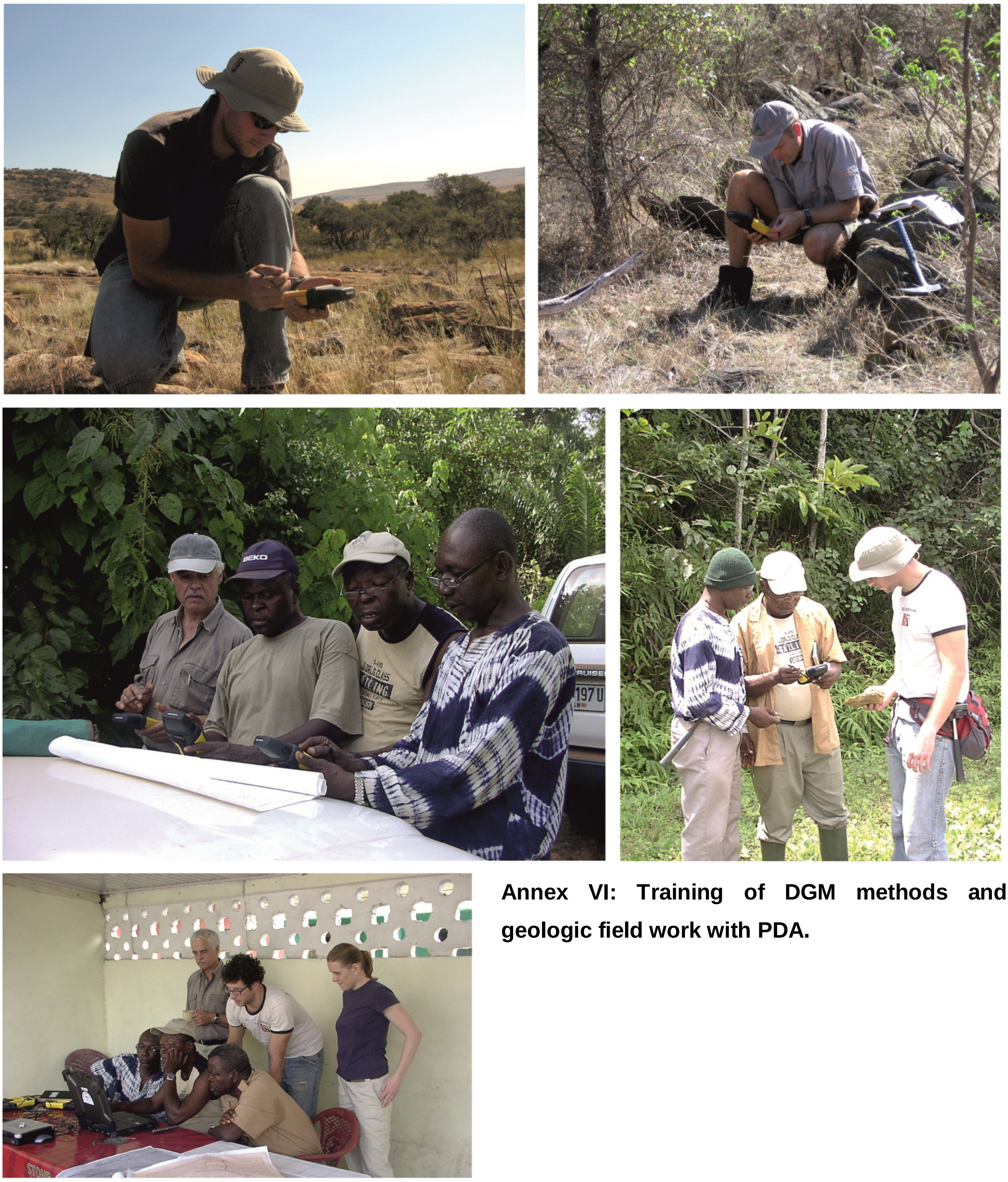
Annex IV: Summary of the most important technical specifications of the described hardware systems (according to manufacturer's information).



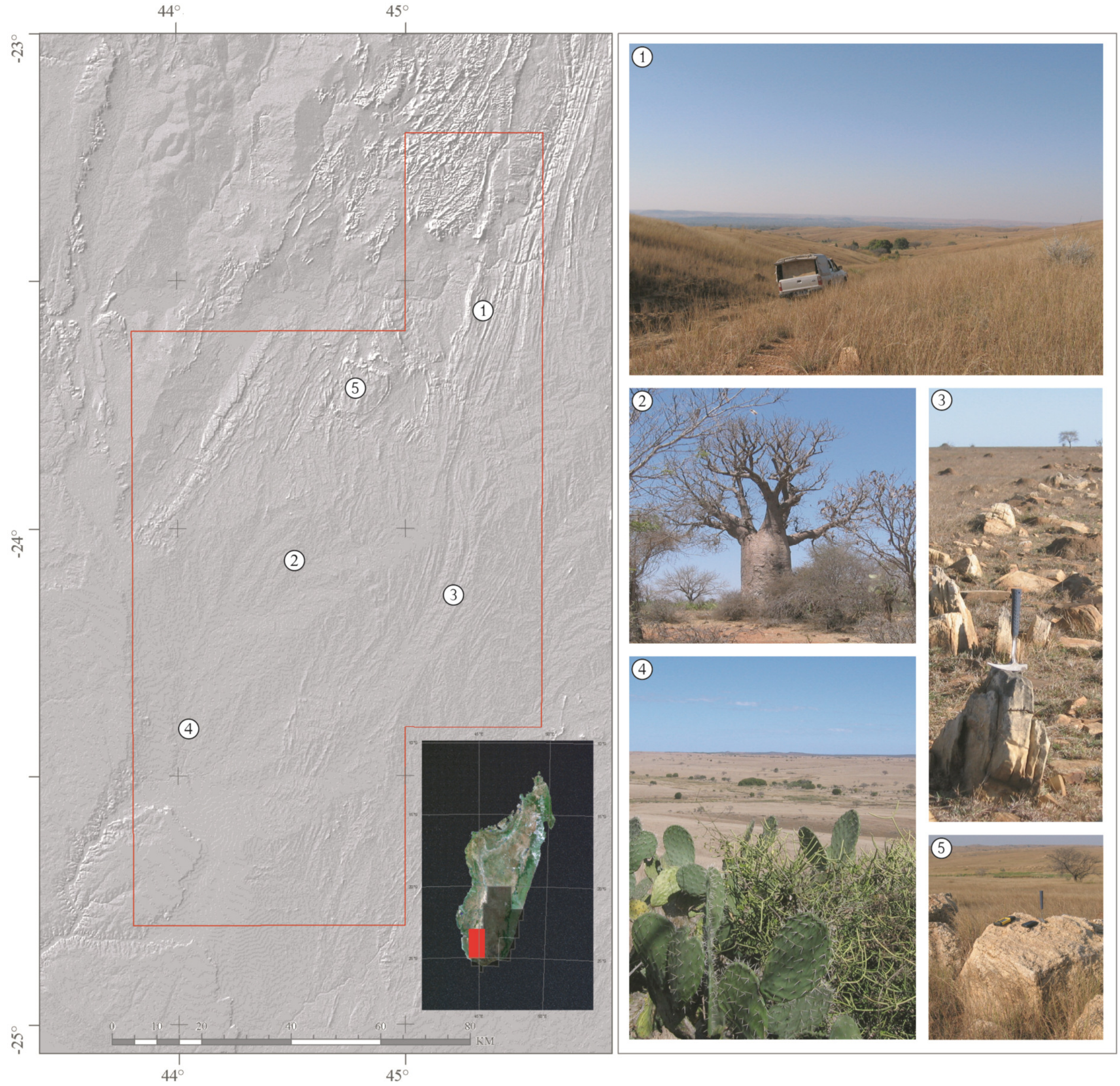
Annex V: Other possible DGM hardware for field work.

Reprinted from "Digital geological mapping with tablet PC and PDA: A comparison" by Clegg et al. (2006) (a-c), and "MAP IT: The GIS software for field mapping with tablet PC" by De Donatis & Bruciatelli (2006) (d). All images reprinted with permission of Elsevier.



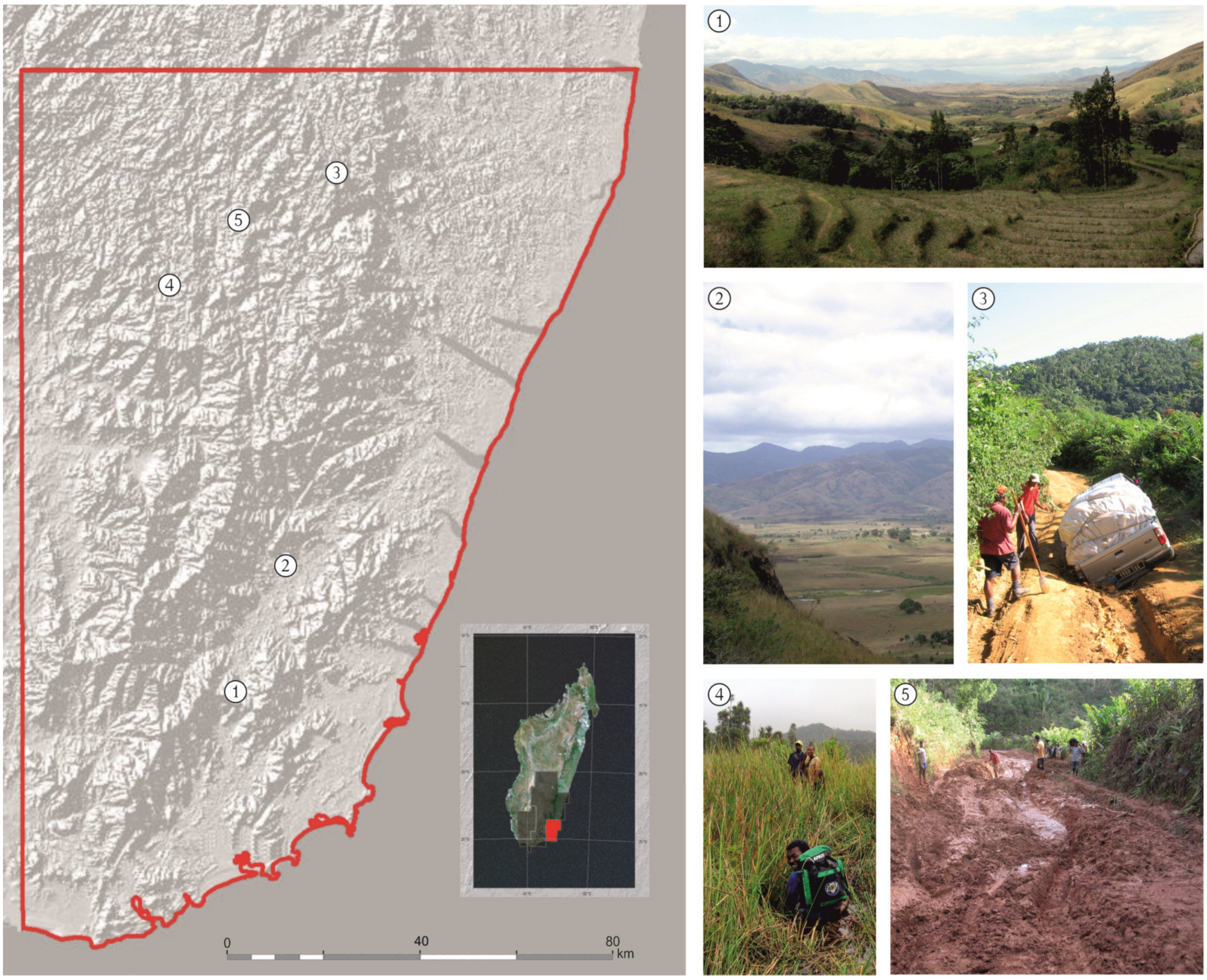


Annex VI: Training of DGM methods and geologic field work with PDA.



Annex VII: Topographical overview of the Vohibory domain in Madagascar.

Some representative landscape photographs taken during field work show a generally well accessible area, favoring “car-geology” and a very convenient DGM setup.



Annex VIII: Topographical overview of the Tôlanaro domain in Madagascar.

Some representative landscape photographs taken during field work show the poor access and road conditions, especially during or close to the rainy season. Most field work had to be done by longer foot-traverses, an aspect that had to be considered in the DGM setup.

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CURRICULUM VITAE

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