Developing a geoscience knowledge framework for a national geological survey organisation.

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Abstract

Geological survey organisations (GSOs) are established by most nations to provide a geoscience knowledge base for effective decision-making on mitigating the impacts of natural hazards and global change, and on sustainable management of natural resources. The value of the knowledge base as a national asset is continually enhanced by exchange of knowledge between GSOs as data and information providers and the stakeholder community as knowledge 'users and exploiters'.

Geological maps and associated narrative texts typically form the core of national geoscience knowledge bases, but have some inherent limitations as methods of capturing and articulating knowledge. Much knowledge about the 3D spatial interpretation and its derivation and uncertainty, and the wider contextual value of the knowledge, remains intangible in the minds of the mapping geologist in implicit and tacit form.

To realise the value of these knowledge assets, the British Geological Survey (BGS) has established a workflow-based cyber-infrastructure to enhance its knowledge management and exchange capability. Future geoscience surveys in the BGS will contribute to a national, 3D digital knowledge base on UK geology, with the associated implicit and tacit information captured as metadata, qualitative assessments of uncertainty, and documented workflows and best practice.

Knowledge-based decision-making at all levels of society requires both the accessibility and reliability of knowledge to be enhanced in the grid-based world. Establishment of collaborative cyber-infrastructures and ontologies for geoscience knowledge management and exchange will ensure that GSOs, as knowledge-based organisations, can make their contribution to this wider goal.

Keywords

Geological mapping, 3D models, knowledge management, cyber-infrastructure, ontology

1. Introduction

1.1 National Geological Surveys as knowledge-based organisations

Geological survey organisations (GSOs), including the British Geological Survey (BGS), are established by most nations to provide a geoscience knowledge base that enables effective decision-making on mitigating the impacts of natural hazards and global environmental change, and on sustainable management of mineral, energy, water and land resources. The knowledge base held by GSOs typically comprises a range of data and information gathered by strategic geoscientific survey programmes, and may also include datasets obtained from (or held on behalf of) industry, government and the academic community. The knowledge base may be held by a single, national GSO or, in some countries, may be distributed among several regionally-based agencies that, together with an 'umbrella' federal agency, collectively provide the national GSO function.

While GSOs usually have responsibility for managing the knowledge base and making it widely accessible, knowledge of the context, application and relevance of that data and information extends way beyond the boundaries of the GSOs to a broad community of users and stakeholders in education, research, industry and government. The value of the knowledge base as a national asset is continually enhanced by exchange of knowledge between GSOs as data and information providers and the stakeholder community as knowledge 'users and exploiters'. Consultancy work, information and advisory services, outreach programmes and collaborative research projects are highly effective methods of knowledge exchange, and are carried out by many GSOs as part of their remit. Such GSOs are therefore 'knowledge based' organisations that not only acquire and manage geo-environmental data and information, but also understand its context, application, value and limitations and can communicate these to users and stakeholders. Effective knowledge management - the creation and subsequent management of an environment that encourages knowledge to be created, shared, learned, enhanced, organized and utilized for the benefit of the organisation and its customers - is therefore essential in GSOs to enable them to fulfil their national capability role. This paper presents a case study of how the BGS has implemented a workflow-based cyber-infrastructure to enhance its knowledge management and exchange capabilities, and places this progress in the context of international efforts to develop collaborative cyber-infrastructures and ontologies to discover, exchange and exploit geoscientific knowledge.

2. Geoscience knowledge: definitions and requirements from the BGS perspective

Many definitions of what is meant by data, information and knowledge have been published within the last decade. The consensus has been summarised by Schreiber (2000) and more recently by Nickols (2000). In this paper, we refer to three types of knowledge:

- *Explicit* - knowledge that has been recorded, communicated or articulated in some tangible way;
- *Implicit* – knowledge that is capable of being communicated or articulated, but is yet to be made explicit;
- *Tacit* – knowledge that cannot be articulated, but is acquired and exchanged by experience-based learning.

Figure 1 expands on these definitions and provides some geoscientific examples (see also Jones et al., 2004).

As the United Kingdom's GSO, the BGS operates a 'mixed economy' business model, with approximately half of its income derived directly from government for a 'national capability' programme of strategic surveying, monitoring and information management, and the other half from commissioned research contracts and from the sale or licensing of data and information. Collectively, these activities establish the BGS at the centre of the UK's national geoscience knowledge infrastructure (Figure 2).

In 2000, the BGS implemented a new organisational strategy to enhance its capabilities and national value as a knowledge-based organisation. This involved a major re-engineering of the organisational structure and human resource management functions in BGS to improve inter-disciplinary sharing of knowledge, and development of a workflow based cyber-infrastructure to enhance geoscience knowledge management and engender a more business-like approach to project management. The cyber-infrastructure has not only focussed on identifying and capturing implicit knowledge assets, but also elements of spatial knowledge, know-how and experience that have conventionally been regarded as tacit, stored in the geoscientists' minds, and difficult to articulate.

As a brief checklist to guide the infrastructure design, BGS adopted the following approach to identify and capture the more implicit and tacit forms of its knowledge assets, along the lines described by Al-Hawamdeh et al. (2000):

- Recognise why the business model requires such a knowledge base;

- Identify core functions along its geoscientific workflow and ensure that collaborative knowledge gathering and interpretative procedures are in place;

- Encourage innovation to flourish and new best practice to be captured in an organised and timely manner.

The following section describes key components parts of the BGS cyber-infrastructure, relating specifically to management of knowledge acquired by geological survey programmes, and discusses some of the lessons learned and future developments.

3. Geological surveying and knowledge management

3.1 Geological maps as explicit knowledge

Since the first national examples produced by William Smith (1815), geological maps have been used to synthesise and communicate explicit knowledge on the stratigraphy, structure and composition of the Earth's surface and shallow subsurface.

Together with the map marginalia, which typically include a scale cross-section and a generalised vertical section of the stratigraphy, a geological map provides a 2 dimensional representation of a 4 dimensional domain (considering geological time as the 4th dimension). In the hands of a trained geologist, the third and fourth dimension can be partially reconstructed from the stratigraphical and structural information presented on the map and marginalia, without reference to other information.

Geological maps, together with associated narrative publications, have therefore been the principal form of explicit knowledge output of GSOs, and form the core of a national geoscience evidence base. However, basic differences in national geology and socio-economic drivers have led to different approaches to national geological survey programmes, especially in terms of priorities, resolution and the downstream deliverables. In the UK, factors such as the highly varied geology, high degree of urbanisation, long legacy of industrial development and a complex regulatory and planning framework combine to create a demand for high-resolution geological mapping at 1:10,000 scale. From the late 1970s onwards, demand increased in the UK to produce thematic geological maps, mainly based on 1:10 000 scale mapping, aimed specifically at planners and developers (Smith and Ellison, 1999). The objective of these products was to unlock and communicate some of the additional, implicit knowledge on resources, hazards and constraints that are 'hidden' on a standard geological map. Initially these demands were met by providing packages of environmental geology maps and associated guidance reports but, in the 1990s, GIS and decision-support systems began to replace these products (Culshaw, 2005). This has driven the development in BGS of cartographic production systems designed to digitally capture information from pre-existing paper geological maps, including both pre-existing published maps and geologists' hand-drawn draft maps created by new surveys. This stimulated major investments in digital capture of the entire dataset of 1:50 000 scale geological maps (DiGMapGB50) of Great Britain, which was completed in 1999 (Jackson and Green, 2003), and the subsequent capture of 1:10 000 maps, currently in progress.

Although geological and thematic maps have served the geoscience user community effectively for nearly 200 years, they have some basic deficiencies as a communication medium for explicit, spatially located 3D geological information

(Loudon, 2000). In particular, the knowledge they convey is explicit in 2D, but largely implicit in 3 and 4D. The most serious knowledge gaps are in shallow superficial deposits, and at depth in the bedrock below major unconformities. Superficial deposits, especially those of glacigenic origin, can be highly complex stratigraphically and geometrically, and are characterised by the presence of many disconformities and high lenticularity of individual depositional units. Much of the UK is covered with such deposits, which vary in thickness from less than 1 metre to several tens of metres. Geological maps conventionally show the superficial deposits mapped at surface but may provide a very unreliable prediction of the subsurface, even at depths of only one or two metres. Similarly, typical bedrock geology maps do not indicate the subsurface geology below major unconformities. For example, below the south-eastern part of Great Britain and adjacent offshore areas, the published geological maps provide little, spatially located information on the geology below the unconformable base of Permian and Triassic rocks, despite the considerable amount of interpreted information available on the underlying Carboniferous rocks available from borehole and seismic data. The latter information is published in narrative memoirs and generalised subsurface geology maps at much lower resolutions.

Unfortunately, these information gaps coincide with those parts of the subsurface where information is in greatest demand from the user community (Walton and Lee, 2001). Shallow (less than 20 metre depth) 3D geological knowledge, associated with a holistic understanding of processes, is required by a diverse community of users, including engineering, waste management, environmental assessment, planning and environmental regulation and aggregate mineral exploration and exploitation (Fookes, 1997; Culshaw, 2005). Deeper, spatially accurate geological information, once mainly required for exploration and management of hydrocarbon, coal, groundwater and metalliferous mineral resources, is now in increasing demand for implementation of newer technologies such as clean coal, underground gas storage, nuclear waste containment, and deep storage of carbon dioxide. For all these applications of geological knowledge, an indication of the level of confidence in the 3D interpretation is required to enable users to make appropriate ‘risk-informed’ decisions, but is commonly not available except in the most rudimentary of forms.

3.2 Geological mapping and knowledge capture

The capability to visualise subsurface geology in 3 and 4 dimensions is an essential skill for a mapping geologist. Geological mapping involves an iterative process of observation, recording, conceptualisation and interpretation (Loudon and Laxton, 2007). From the first moment of fieldwork, a geologist assembles a mental 3 and 4 dimensional model of stratigraphy and structure, and this is then iteratively adjusted as more observational evidence is accumulated (Jones et al., 2004; Kastens and Ishikawa, 2006). As this model develops, the geologist continues to test and refine their interpretation against the available prior information, including his or her own knowledge and understanding of geological processes and concepts (Loudon and Laxton, 2007). The mapping geologist will also develop an appreciation of the interdependencies (and inconsistencies) between data and interpretation, and will also evolve an impression of their confidence (or degree of certainty) in their model, though this may be highly subjective, dependent on previous experience or bias, and may even be influenced by pressures to conform with fashionable concepts and scientific trends (Jones et al., 2004; Bowden, 2004; Baddeley et al., 2004). While in the field, the geologist will also acquire, though not necessarily formally record, a range of other contextual geoscience knowledge including relationships between geology and the built environment, hazards, land use, ecology and heritage. In the BGS, much of this contextual knowledge is developed by experience of working on other knowledge exchange activities elsewhere in the BGS programme (see above).

Figure 3 illustrates a generic workflow for a typical geological survey project in BGS and the explicit knowledge captured at each stage. Traditionally, knowledge management in the workflow has typically focussed on the archiving of all data and information that contributes directly to the delivery of the published or released, digital and analogue map and text outputs, but this has left much implicit knowledge remaining in the minds of the geologist (Figure 4).

During the last 5 years BGS has invested heavily in its IT infrastructure and data digitisation, investing capital to upgrade its storage area networks (SANs) and increasing the bandwith for its internal communications between itself and with other nodes on JANET, the UK’s Joint Academic NETwork that links universities, research centres and other higher education establishments. In parallel, three major new components of the BGS cyber-infrastructure have been developed and implemented that help make explicit much of the implicit knowledge acquired by new geological surveys. These are:

- BGS Project Management System
- SIGMA (System for Integrated Geoscience MApping)
- DGSM (Digital Geoscience Spatial Model)

These systems were originally developed with separate, specific objectives in mind, but are gradually converging, though continual development, into an integrated knowledge management system with the following main objectives (cf. McCaffrey et al., 2006):

- Capture and communicate geologists' 3 and 4D perception of subsurface geology acquired by geological survey projects
- Ensure all data and knowledge is recorded using common, documented standards to promote wider interoperability and data and knowledge exchange
- Speed up the process of data and knowledge capture and delivery
- Ensure knowledge capture is carried out in the context of prior information, i.e. it builds on and augments prior information, without re-inventing it
- Ensure that the data and knowledge capture process is verifiable, repeatable and auditable
- Record a greater proportion of implicit knowledge
- Differentiate observation from interpretation, as far as practically possible
- Record and communicate the sources of information and uncertainty involved in the interpretation process.

Figure 4 illustrates the implicit knowledge captured by the main components of the infrastructure, which are described in the following section.

4. BGS Cyber-infrastructure for geological survey knowledge management

4.1 BGS Project Management System (PMS)

This was developed and implemented in 2003 as a workflow-based information system to help formalise the approach to project management in BGS, and manage the associated project information. It holds information on business case, project initiation, aims and objectives, project plans, financial information, and project review. The PMS workflow leads project teams through the key steps in the life cycle of a project based on the PRINCE2 project management method, which is now widely recognised as the de facto standard for project management in the UK[1]. The PMS was designed around an Oracle 9 instance and customised using ColdFusion.

While the PMS might appear peripheral, at first sight, to the objective of geoscience knowledge management, it contains project planning information on the approach, methodologies, resources and expertise deployed that is critical for understanding the value, limitations and certainty of the geological interpretations delivered by a BGS survey project. In particular, all objects (e.g. field observations, geological boundaries, outcrop polygons, geological surfaces) captured in BGS digital maps and models using the SIGMA and DGSM systems (see below), are linked to the knowledge held in the PMS by a unique project code attribute. It is therefore possible, for example, to interrogate individual objects in the BGS digital map and model databases and determine, through cross-reference to the PMS, whether the object was recorded by a field geological survey, an air photo reconnaissance, or by a desk revision carried out as part of an applied geoscientific project commissioned by a specific client. The PMS also stores knowledge of lessons learned and new methods adopted by the survey project that contribute to the upgrade of procedures and best practice in the SIGMA and DGSM systems. A major upgrade to the PMS in 2008 will strengthen its integration with these other cyber-infrastructure systems.

[1] PRINCE2 – Projects In a Controlled Environment - http://www.ogc.gov.uk/methods_prince_2__overview.asp

4.2 System for Integrated Geoscience MApping (SIGMA)

SIGMA is a Geographic Information System (GIS) application that links spatial search and assembly, digital field data recording, digital geological map compilation and map production[2]. The system was designed around the geological survey workflow (Figures 3 and 4) and integrates with the PMS and the 3D modeling systems in the DGSM. The system is built around the ESRI ArcGIS 9.x software suite, and captures geological data and knowledge into a relational, feature/attribute data model implemented in an ArcGIS geodatabase. Following validation at key stages in the workflow, the geodatabase is uploaded and managed in the corporate BGS Oracle relational database, and provides the data for subsequent production of both digital and printed BGS geological maps and a range of other, derived information services and products. Customisation of the ArcGIS desktop was performed using ArcObjects (the ArcGIS software component library), mainly with VBA and vb.NET development tools. Within this system application, most parts of ArcGIS suite are used in the workflow development (ArcMap, ArcCatalog, ArcGlobe and ArcSDE). Corporate data from Oracle and other sources are loaded to and from the BGS SAN as shapefiles, grids, SDE feature classes and SDE raster datasets and catalogues.

SIGMA is designed for use by all BGS survey geologists and replaces the former paper-based map and notebook systems for recording field data and compiling geological maps. The digital field data capture component (MIDAS – Mobile Integrated Data Acquisition System), which operates on a ruggedized Tablet PC, has been deployed to 66 individual mapping geologists, with an equipment ‘pool’ of 20 further systems available for other uses (e.g. landslide surveys, field sample recording). All BGS mapping geologists now use SIGMA on their desktop for map compilation and, at the delivery end of the workflow, the system is used by GIS specialists, data managers and cartographers for data quality control and map production. MIDAS uses a ‘digital field map’ interface linked to a ‘digital field notebook’ application consisting of data recording forms, freeform notes, sketches and photograph annotation (Figure 5) to encompass the full range of structured and

[2] SIGMA - http://www.bgs.ac.uk/science/3dmodelling/sigma.html

contextual data and knowledge captured by fieldwork (Jordan et al., 2005). The 'digital field map' uses a customised ArcMap interface to enable geological notes, features and boundaries to be recorded against a range of backdrop reference data including existing geological maps (raster and vector), aerial photographs, digital terrain models and topographic maps. A simple sketch tool enables rapid drawing of freeform sketch objects (e.g. topographic features), which are subsequently converted to attributed geodatabase objects by selecting a single icon on the customised digital field map interface. The 'digital field notebook' application is launched from the field map window by selecting from a set of icons, each of which represents a specific notebook 'page' for recording data such as structural measurements, section logs, sketches, or sample metadata records. Each notebook record is positioned either by selecting a map location or by a Global Positioning System (GPS) location. A relational data model enables multiple entries to be recorded at a specific site and also allows explicit links between objects, for example one or more photographs or sketches of a logged section. Earlier versions of the system implemented on a palmtop PDA (Personal Digital Assistant) platform did not provide the geologist with a large enough screen for map-based observations or the capability for creating relational links between the diverse data and knowledge types captured during fieldwork (Jordan et al., 2005; see also Clegg et al., 2006).

All objects in the SIGMA data model have a unique identifier constructed from the date, time and the user's identifier code. Each object can also be attributed with information on certainty, information sources, and freeform contextual notes, so that explicit knowledge on lineage of interpretations can be captured. The system enables observations and interpretations made in the field – 'in full view of the geology'- to be distinguished from interpretations made at the field base or on return to the office, based on other geological data. This distinction can commonly be blurred on paper-based systems (Jones et al., 2004). Prior information imported into the system and considered in the interpretation process is also recorded in the ArcGIS .mxd project workspace file. Hierarchical classification schemes and nomenclature for key attributes of stratigraphy[3] and lithology[4] used in the system are published on the BGS

[3] BGS Lexicon of Named rock units - http://www.bgs.ac.uk/lexicon/lexicon_intro.html
[4] BGS Rock Classification Scheme - http://www.bgs.ac.uk/bgsrcs/home.html

website, and documentation of the other standards used is currently in progress for eventual release.

SIGMA was initially designed to support knowledge capture for 2D geological mapping, but will continue to be adapted and integrated with the 3D modeling systems in the DGSM to augment its capability for 3D and 4D knowledge capture in the fieldwork environment. At present, the 3D geological model is not captured until the geologists have returned from the field and recorded the bulk of their conceptual model in 2D form, resulting in some loss of knowledge and potential inconsistencies with observations made in the field. While 3D field data capture methods such as terrestrial laser scanning (Hodgetts et al., 2004; McCaffrey et al., 2005) are advancing rapidly, capture of geologists' implicit 3D knowledge in the field remains a significant challenge and is likely to await the development of more effective, portable 3D and augmented reality visualisation systems (McCaffrey et al., 2005)

4.3 Digital Geoscience Spatial Model (DGSM)

Proficient mapping geologists will always have some kind of 3D representation in their mind as they develop an understanding of an area they are investigating (Kastens and Ishikawa, 2006). During the last 25 years, computing technology and the cyber-infrastructure that goes hand in hand with its development have progressed to allow the geologist to encode this implicit mental image, along with the tacit 'experience and know-how' that constructed it, into an explicit information product. Although many commercial companies in the petroleum and mining industries have developed their own 3D cyber-spaces, GSO organisations have taken only limited steps towards the construction of national scale 3D frameworks. It was clear that a leap of faith was required to build such a national scale knowledge base, and incorporate forms of knowledge that have conventionally been regarded as tacit.

The DGSM was originally mooted in BGS in the late 1970s in an unpublished internal report by Vic Loudon, and conceived as a hypermedia repository for 3D geological knowledge of the UK. However, it has taken well over a quarter of a century for the necessary information technology to become available and affordable, and the understanding of human computer interactions to become sufficiently mature, to make this vision a practical proposition (Loudon, 2000). In 2005, BGS published a strategy for development of a National Geoscience Framework (British Geological Survey, 2005), which will eventually establish 3D spatial models or 'LithoFrames' (Smith, 2005) at the core of the evidence base for UK geology, replacing the geological map. The DGSM research and development project commenced in 2000 to establish the modeling methodology and cyber-infrastructure required to begin work on this long-term objective, with deployment of the completed system in 2005.

The knowledge framework of the DGSM has 7 main components, summarised below and described in more detail by Smith (2005). Figure 6 illustrates the flow of information between various parts of the system.

Data portal. This provides an essential bridge between the BGS corporate databases and the modeling software used by the geologists. The portal utilizes web-based GIS systems to interrogate, preview, download and convert data such as terrain models and borehole data into the formats required for use in specific 3D modeling software packages.

Information and software standards. Geoscientific data standards, dictionaries and thesauri for geoscientific description, classification and mark-up of the spatial models and associated texts, and for the software used in the modeling process, are an essential part of the DGSM knowledge framework. Many of these standards have been in place in BGS for over two decades, and have been updated and adapted to meet the DGSM requirement. The standards allow the knowledge content of the spatial models to be attributed, communicated and reproduced in a consistent way, and facilitate its wider interoperability. Mark-up standards have contributed to the international collaboration to develop a generic XML schema called GeoSciML (Geoscientific Mark-up Language) (Cox et al., 2005, see also section 6 below).

Geoscience large object store. The GLOS provides storage for 3D models, visualizations and associated metadata in their individual proprietary software format. Depending on the software used, the modle may consist of a single file or (as in GoCAD) a number of separate files, each representing a single object or groups of similar objects in the model. Metadata for each object (see below and Figure 7) is stored alongside the model in the GLOS.

Geoscience spatial framework — The GSF provides a non-propriety data store for models to ensure that their geometric form and geoscientific properties are shareable and preserved. It is a relational database that stores the complete set of 3D points contained in each model, linked where applicable to the geological surface identifier and, via the standard BGS dictionaries, to their geoscientific attributes (Hatton et al., 2005). Although it is recognized that storage in the GSF can result in loss of some information and knowledge, it provides secure long term storage and delivery of information in software independent format.

Metadata. DGSM metadata is the key component of the DGSM that captures the experts' implicit knowledge about the source and lineage of the spatial interpretation embodied in the model (Figure 7). In the survey and modeling workflow, geologists examine data from many external sources; this is recorded in the metadata, together with the associated reasoning and reconciliation processes. The resulting knowledge base can be filtered for relevant material, and searched with a variety of spatial or text-based queries. The metadata system has four main components. 'Data' metadata describes the data subset used to create the model, its derivation and the criteria for including or excluding data items. 'Model' metadata provides information describing the model, and the purpose for which it was constructed. This is also linked via a project code identifier to knowledge about the objectives, conduct and purpose of the project held in the PMS (see above). 'Inference' metadata describes how particular data was interpreted and interpolated to create the model, and a qualitative assessment of the fitness of the data for that purpose. All three metadata types have been mapped onto the ISO 19115 international metadata standard, and implemented in a relational database structure. Finally, 'keywords' provide a simple way of finding the model and describing its content. A Geoscience Thesaurus, based on that of the Australian Mineral Foundation, is under continued development in BGS to enable the knowledge embedded in models to be linked semantically to its wider scientific and environmental context (see section 6 below).

Uncertainty. The DGSM system for communicating the inherent uncertainty in a 3D model focuses on a combination of geostatistical analysis methods and capture of qualitative, implicit knowledge from the geological and technical experts who built the model. Work is continuing on methods of communicating knowledge about uncertainty to the model user. Qualitative uncertainty assessment involves an initial brainstorming meeting of the survey and modeling project team to exchange knowledge and catalogue the sources of uncertainty feeding into the modeling process, involving construction of a 'fishbone' or Ishikawa diagram. A fuzzy logic rule set analyses the components of uncertainty derived from the Ishikawa analysis to characterise every point or object in the model with a numerical value, which can then be visualised in 3D alongside the model. Since the risks associated with geological uncertainty vary from user to user, the outputs of the DGSM uncertainty system will be evaluated by users of BGS models to provide feedback on their suitability for input into their risk assessment procedures.

Best practice. The DGSM best practice system enables procedures adopted by the technical experts in building models to be documented, shared, and where appropriate, flagged as 'best practice'. In the present system, documents are captured conventionally by word processor and held in a text database linked to a web-based search and retrieval system, which also enables model outputs to be linked to the 'best practices' used to create them. Wiki-type systems are currently being trialled to develop a more consensus based-approach to developing and documenting best practice.

The DGSM is adaptable to inter-operate with a range of commercially available software for 3D modeling. Software was evaluated extensively at the start of the DGSM development project and has been kept under review since then. To facilitate 3D knowledge capture and delivery, BGS has sought to implement software that is simple and intuitive enough for deployment to its entire complement of survey geologists. A key requirement is that the software must allow the geologist to remain in control of the spatial interpretation by easily combining input of interpolations based on their own knowledge and experience with the more rapid mathematical interpolation provided by the software. In this way, the tacit knowledge of the geologist and the computational power of the software can combine cost effectively and harmoniously to capture and communicate the spatial geological model. The DGSM knowledge management system enables the manual and computerised interpolations to be clearly distinguished. At present, the BGS has deployed Insight GmBH GSI3D (Geological Surveying and Investigations in 3D) software for 3D modeling to meet the above requirements. GSI3D's current limitations to geological domains of low structural complexity are being addressed with a major software upgrade, due for completion and deployment in BGS from 2010. GoCAD software is currently used in BGS for 3D modeling of regional extensional basins and structurally complex areas, and for specialised volumetric and properties modeling applications.

To draw the DGSM knowledge capture components together into a coherent system, a workflow based application has been developed that leads the user through the spatial modeling process, via a series of key steps (Figure 8). These ensure contextual and timely capture of metadata and information about uncertainty and best practices. Checklists built into the workflow system enable repeatability and audit of the modeling and knowledge capture process. The DGSM workflow system and its various components were deployed in 2005 and have been used routinely since then on all BGS 3D modeling projects for a variety of clients.

As population of the BGS 3D knowledge base proceeds, the technologies developed by DGSM will, with continual development, enable the BGS to offer a more comprehensive spatial geoscientific interpretation, linked to more relevant and accurate contextual knowledge. DGSM extends the national geoscience knowledge base, ready for the next wave of technology. The internet is evolving into the grid — a ubiquitous knowledge infrastructure, supporting web services that hide complexity from the users, but to be shared by all and increasingly taken for granted. Geological survey knowledge management may evolve in parallel, to occupy a future niche as a set of web services integrated within the mainstream standards of the global knowledge system. Taken together, the DGSM, SIGMA and related components of the BGS cyber-infrastructure provide an example of the initial steps that GSOs will need to take to enhance their knowledge management capabilities and prepare for this revolution.

5 Cyber-infrastructures for geoscience knowledge exchange and management

From its position as a single national GSO, BGS has focused on developing, capturing and exploiting its implicit and tacit knowledge assets. Other countries with regional GSOs have needed to respond to additional challenges to exchange and utilize their collective datasets and knowledge bases.

The national organisational model of regional GSOs, with or without an over-arching federal GSO, has tended to develop in countries with more distributed regional governance and regulatory systems, and where the large size of the country presents major logistical challenges for execution of national survey programmes. In these countries, a more diverse range of standards, practices and data models have emerged, over decades of systematic survey and data collection, that have constrained the potential for collaborative knowledge management. It is therefore not surprising that these countries are now leading the way in the development of inter-agency cyber-infrastructures, common standards and vocabularies for geoscience knowledge discovery and exchange.

In the last decade, large geoscientific organisations such as the national, state and provincial GSOs in Canada (Canadian Geoscience Knowledge Network, CKGN[6]) and Australia (Solid Earth and Environment GRID, SEEGRID[7]) have been developing their knowledge networks with notable success. National, state and provincial surveys in North America have joined forces to develop the North American Geologic Map Data Model, with the goals of standardizing methodologies for the management and distribution of digital geologic-map information, and developing common vocabularies, data standards and interchange formats to make the knowledge contained in these maps accessible and useable by all. Globally, a number of GSOs have also adopted a collaborative approach to attempt to identify and codify their knowledge bases in a logical and consistent manner. To achieve this, much international, collaborative effort has gone into standardizing geological data interchange models, using the IUGS Commission for the Management and

[6] The Canadian Geoscience Knowledge Network. - http://cgkn.net/cur/index_e.html
[7] Solid Earth and Environment GRID, SEEGRID - https://www.seegrid.csiro.au/twiki/bin/view/Main/WebHome

Application of Geoscience Information[8] initiative as a major driver (Cox et al., 2005). The work completed by the CKGN, the CGI and other international geoscience networks has enhanced the capture and sharing of explicit and implicit knowledge within the geoscience realm and its accessibility to more diverse scientific collaborators and the wider stakeholder community.

Again in North America, the Geosciences Network (GEON)[9] project illustrates how collaborative geoscience knowledge cyber-infrastructures may evolve in future, and demonstrates their exciting potential for the eventual globalisation of geoscience knowledge exchange. GEON is led mainly by a consortium of universities in the United States, but is gradually broadening its associations with national and regional GSOs, other agencies and industry across North America. GEON's aim is to drive a more quantitative understanding of the 4D evolution of the North American lithosphere by using advanced information technologies to support "intelligent" search, semantic data integration, and visualization of multidisciplinary information and 4D earth science data. Currently, GEON offers a range of resources including 3D and 4D geoscience data and software tools for interpretation and visualisation. In the future, it will provide controlled vocabularies, hierarchical classifications and ontologies for knowledge representation, discovery and exchange.

6 An ontology-based knowledge management future for the geosciences

Discovering and exploiting the wealth of knowledge available on the World Wide Web, whether offered by GSOs, formal geoscience knowledge networks or the wider geological research and user community, involves extending the role of ontologies (Agarwal, 2005). Ontology development focuses on representing concepts or objects and their properties, relationships and hierarchies, and typically expresses explicit and stable or uncontested knowledge. As already discussed, there is considerable value to be gained from capture of implicit knowledge, and new types of geoscience products such as digital 3D models can tease out and crystallize some of the tacit, experience-based knowledge formerly hidden in conventional outputs such as geological maps.

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[8] IUGS Commission for the Management and Application of Geoscience Information - http://www.cgi-iugs.org/welcome.html

[9] The Geosciences Network (GEON) - http://www.geongrid.org/

If this implicit knowledge can be captured by effective knowledge management, and exchanged in collaborative cyber-infrastructures, the future of geoscience may see ontology-based, computational agents discovering new emergent knowledge from these ever-expanding oceans of information, crossing disciplinary boundaries and reasoning with competing knowledge sources.

Loudon and Laxton (2007) provide a roadmap of how ontologies can be implemented by GSOs to help capture and exploit knowledge assets, and develop 3D digital knowledge bases. Ontologies can also help with automated processes to discover and harness knowledge locked within the often huge archives of paper records and publications held by GSOs. The National Borehole Information Capture (NBIC) project in BGS is deploying ontologies to assist with conversion of paper borehole records into digital formats that can be used for 3D Modeling applications. BGS holds in excess of 1.5 million paper borehole records donated by third parties and drilled for various purposes, such as geotechnical investigations and exploration for mineral resources, groundwater, coal and oil. Major investment has already been made to scan these data, but use in 3D modeling projects still requires time-consuming, manual coding of each record into a structured data format that is useable by modeling software. For NBIC, the scanned data is first converted into machine-readable format using Optical Character Recognition. A domain-specific ontology is being developed to support the capture of lithological information from these boreholes and codify the output, together with depth, into the BGS Borehole Geology digital downhole database. The original paper databases contain records accumulated over many decades, with highly variable lithological terminology and, in some cases, use of obscure, vernacular terms. The ontology is being developed from the hierarchical BGS Rock Classification Scheme and the BGS Geoscience Thesaurus (see above), augmented by translations of older vernacular terminology. The project is in its early stages, but it is expected that the ontology will develop and grow to enable wider, environmental data and knowledge to be discovered and captured from a wider set of historical text-based datasets held by BGS, and allow information to be codified for web delivery and for downloads to BGS clients in various industry-standard digital formats. More widely, BGS is participating with many other GSOs in the development of GeoSciML[10] (Geoscientific Mark-up Language). This is a major international initiative, led by the IUGS Commission for the Management and Application of Geoscience Information, to develop and codify agreed concept definitions for the geosciences. The semantics of these definitions are not yet being formalised, however the objective of this work is that it will lead eventually to the development of formal geoscience ontologies, and support the discovery and use of objects referenced with those ontologies within and across agencies.

Knowledge gains value when it can be used in some way, such as in a scientific workflow that supports decision-making by a client. There is much knowledge about how to analyse, manage, visualise and apply geological information that either lies latent in a scientist's mind or is expressed in a software specific language. Being able to express the semantics of that knowledge in ontologies is critical to support the future of geological research in a grid environment (Loudon and Laxton, 2007). Research into expressing the semantics of scientific workflows provides the first steps to converting this type of knowledge into a form that can enhance scientific research, facilitate interoperability and provide cross-disciplinary access to new data and new services (Berkley et al., 2005).

Recent developments in the World Wide Web community have raised the question of knowledge reliability. In a Web 2.0 world, where users of the web are also providers of information and knowledge, we see the emergence of unregulated knowledge bases that are likely to compete with those provided by authoritative sources, including GSOs. Nevertheless, knowledge of this sort can be of huge value, and applications such as Wikipedia illustrate how a neutral and authoritative point of view can emerge organically from a wide community of knowledge contributors. An ontology-based framework that takes into account issues of trust, reputation and authority may provide a way for supporting the integration of this distributed, community-based knowledge with institutional knowledge in order to exploit their complementary attributes and enhance knowledge use in a scientific context. Collaborative research tools such as Wikis and virtual environments also support this new approach towards knowledge creation for geographically distributed participants (Page et al., 2005), and

[10] GeoSciML - https://www.seegrid.csiro.au/twiki/bin/view/CGIModel/WebHome

can be assimilated into a knowledge base when their content attains an appropriate level of confidence.

Ontologies will form the basis for grid-based scientific research, from service discovery (Klien et al., 2006) to model component composition (Reitsma and Albrecht, 2005), and also advance the automation of menial scientific research activities. The vision of ontology-based knowledge management and use is that we will be able to pose complex queries or research tasks to a software environment or Web Service, and rapidly get sensible results that help us answer our questions or complete our research.

But how do we automatically integrate such information in an emergency scenario, requiring rapid and informed decisions utilising resources of variable and possibly questionable reliability, provided by different service and knowledge providers? Knowledge becomes more powerful when interconnecting threads can be pursued, developed and applied by innovative, creative and lateral thinking. Such queries and tasks will involve connecting independently developed knowledge repositories or services without requiring global agreement of terms and concepts (Berners-Lee et al., 2006). Knowledge-based decision-making at all levels of society requires the accessibility, reliability and usability of knowledge to be enhanced in a grid-based world. Effective knowledge capture, management and exchange will ensure that GSOs, as geoscience knowledge-based organisations, can make their contribution to this wider goal.

Conclusions

Assembling the national geoscientific knowledge base, and exchange of its content with stakeholders to support decision-making, are key roles of national geoscience surveys. Effective knowledge management and exchange require not only effective data and information management, but also an analysis of those ‘missing’ implicit and tacit knowledge assets that need new methods to capture and exploit. These assets include knowledge of the 3D geology, approach, inferences, uncertainty, wider context and best practice acquired during the process of geological mapping.

A coherent and well-designed corporate cyber-infrastructure, linked to a familiar workflow of core functions in the geological mapping and modeling process, together with software that enables the geologists to easily transfer their experience and know-how into 3D interpretations, enables capture of the key elements of this implicit and tacit knowledge. Effective management of this knowledge within GSOs will prepare them for the knowledge revolution of collaborative cyber-infrastructures and grid-based technologies.

Participation of GSOs in wider, national and international geoscience cyber-infrastructures enables discovery, exchange and exploitation of this implicit knowledge and is driving the development of common data standards, interchange formats, best practices, workflows and scientific vocabularies that will lead eventually to development of geoscience ontologies.

An ontology-based future for the World Wide Web will enable greater access to tacit and implicit knowledge in shared geoscience knowledge bases and the wider web community. By automating data discovery and conditioning tasks, ontologies will also help GSOs to unlock and harness the considerable knowledge assets within their traditional paper records and archives. Sustained investment and international collaboration is needed to capture this valuable intellectual capital and to continue development of the cyber-infrastructures required for wider knowledge exchange and exploitation.

Acknowledgements

We thank our many colleagues at the BGS who have been involved in the development, testing and deployment of the DGSM and SIGMA systems since 2000. In particular, Vic Loudon and Ian Smith are acknowledged for their clearly articulated vision and management in converting these systems from a tacit mental image to explicit reality. Colm Jordan is thanked for comments on the manuscript. The two anonymous referees are thanked for their constructive comments on the original submission, which have helped us to make substantial improvements to the paper. Andrew Howard, Bill Hatton and Ken Lawrie publish with the permission of the

Executive Director, British Geological Survey (Natural Environment Research Council, UK).

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Figure captions

Figure 1. Definitions of explicit, implicit and tacit knowledge, with examples from geoscience.

Figure 2. Knowledge development and exchange model for British Geological Survey (BGS). A range of knowledge exchange activities, involving two-way communication and development of mutual understanding between BGS teams and external stakeholder community, continually enhances value and relevance of national geoscience knowledge base. Tacit knowledge is acquired and exchanged both internally and externally as staff work in multi-disciplinary projects for clients and stakeholders.

Figure 3 Generic workflow for a traditional ('pre-cyber-infrastructure') geological survey project, and explicit knowledge typically captured at each stage. 'Accessibility' includes external availability, ease of understanding, use of familiar terminology etc. Data and knowledge management pervades all stages of workflow.

Figure 4. Implicit knowledge not usually captured (or captured in forms with low external accessibility) by traditional geological survey processes, and parts of new BGS cyber-infrastructure designed to capture and communicate this knowledge. PMS = BGS Intranet-based Project Management System, SIGMA = System for Integrated Geoscience Mapping, DGSM-W = Digital Geoscience Spatial Model workflow.

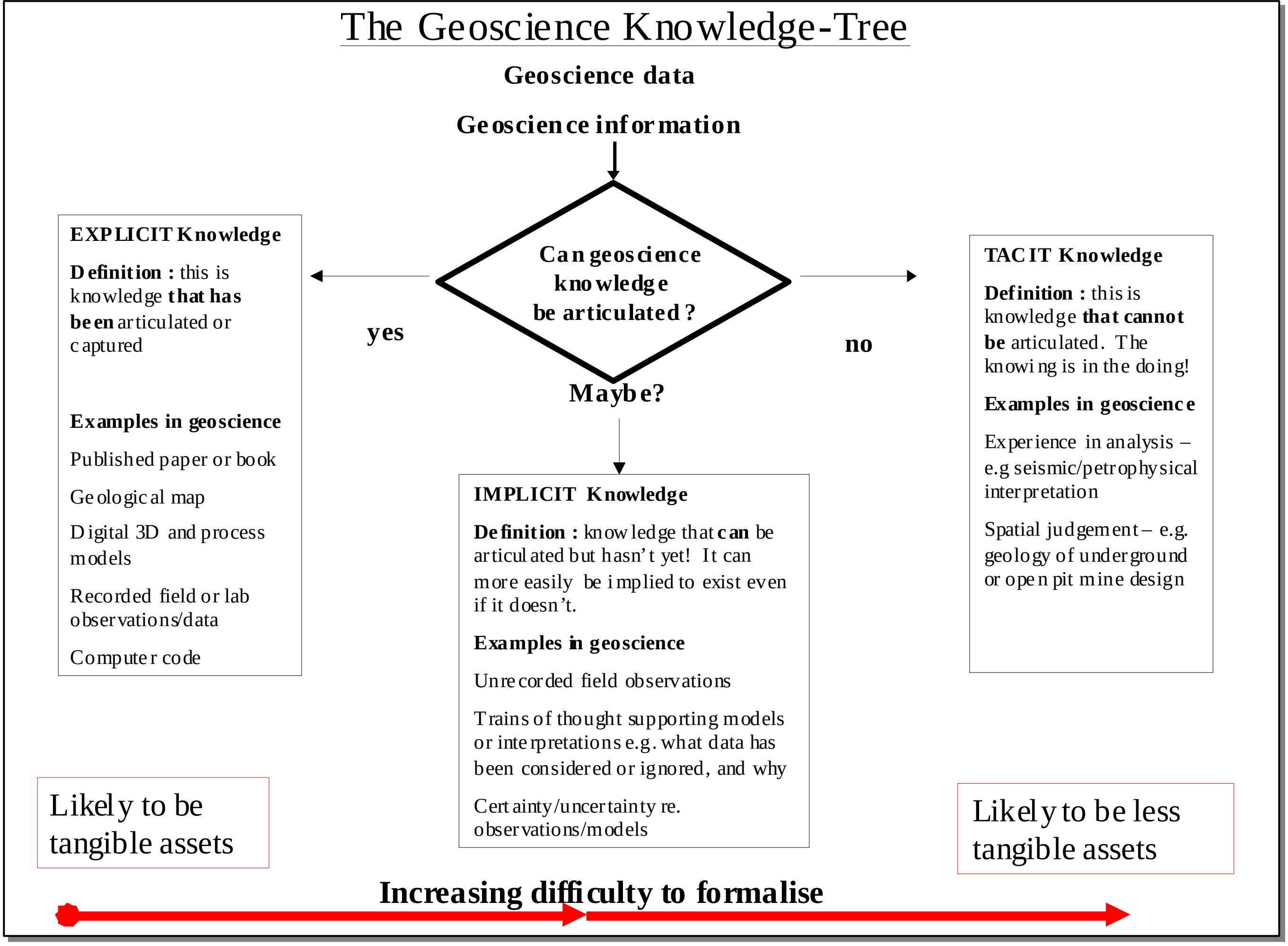
Figure 5. Montage of screenshots showing examples of data entry, notes and sketches 'pages' in BGS MIDAS digital field data recording application. A. 'Digital field map' interface with digital geological map backdrop; B. Launch screen for 'digital field notebook' application; C. Data review screen showing sketch captured at a field locality; D. Application for predicting outcrop position of a dipping surface based on a structural dip measurement or three known points.

Figure 6. Data, information and knowledge flow within BGS Digital Geoscience Spatial Model system (after Smith, 2005). EarthVision, GSI3D, GoCAD and Vulcan

are various third party 3D modeling software packages used by BGS during development and testing of DGSM system.

Figure 7. 3-dimensional geological model of part of central England, constructed using GoCAD software to assist with groundwater management applications. Approximate model dimensions 75km. x 30 km. x 0.4 km. Metadata screen illustrates discovery metadata for whole model. More detailed DGSM metadata for each stratigraphic surface and groups of faults can be selected and interrogated individually.

Figure 8. Screenshot example of web-based interface to BGS Digital Geoscience Spatial Model workflow application, illustrating main workflow tasks and sub-tasks. Clicking on each link in workflow takes user to best practice documents that recommend methodologies to be used for each task. A checklist is then automatically populated and stored along with metadata for each model, recording practices used.



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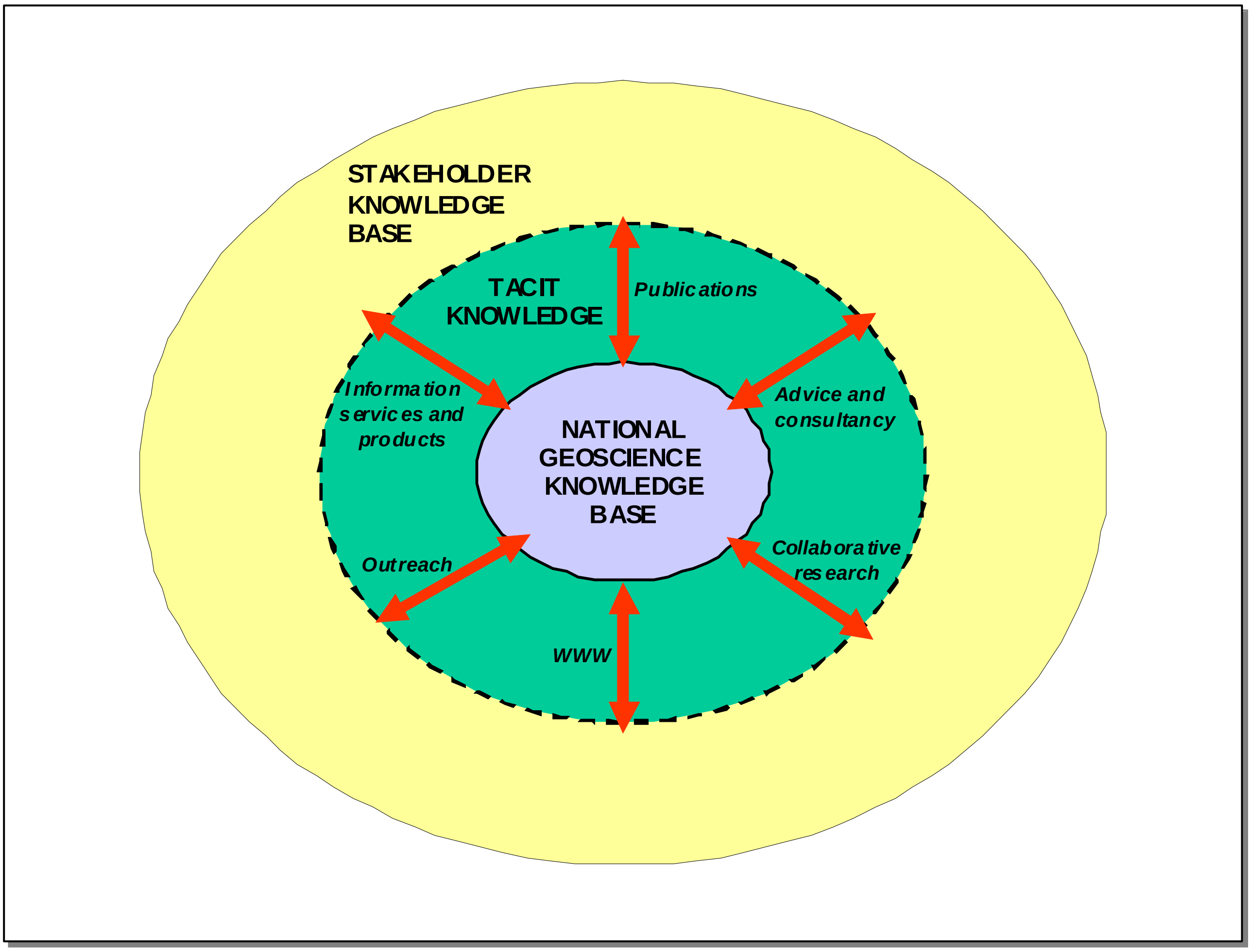

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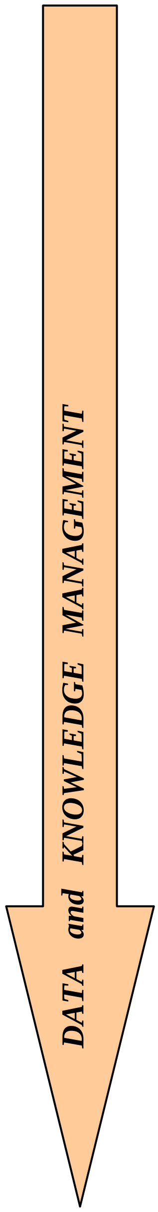
Geological Survey workflow		Explicit knowledge	
		Types captured	**Access-ibility**
1. Plan project	Agree aims and objectives, plan project, assign resources, staff and equipment	Project plan and files	Low
2. Assemble prior knowledge	Assemble available data and information	Project database, bibliographies	Low
3. Evaluate prior knowledge	Evaluate quality and relevance of existing knowledge, identify gaps in knowledge, standards and nomenclature	Selected subset of information, annotated maps and notes	Variable
4. Update project plan	Update objectives and project plan to address knowledge gaps	Project plans and files, survey plan	Low
5. Acquire and interpret data	Complete field-based and remote investigations to acquire and interpret new observations and data	Field maps and notebooks, samples, photos and captions	Low to moderate
6. Draft and validate interpretation	Draft maps and reports, check, refine and correct new data and interpretations	Draft versions of maps, reports, papers	Low
7. Publication	Publish or release new, validated data and interpretations	Maps, digital maps and GIS, reports, papers, posters, presentations	High
8. Review	Review outcome of project, identify lessons learned, refine procedures and best practice, update standards and nomenclature	Project review report, updated procedures and specifications	Low



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Workflow stage	Implicit knowledge (not traditionally captured and/or with highly limited availability)	Cyber-infrastructure		
		PMS	SIGMA	DGSM-W
1. Plan project	Are the resources, skills and equipment fit for purpose? What is the experience of the survey geologist and how might this influence interpretation?			
2. Assemble prior knowledge	How thorough was the knowledge search? Has any data or knowledge been overlooked?			
3. Evaluate prior knowledge	What data and knowledge was rejected for input into the survey process, and why?			
4. Update project plan	What type of survey was conducted (e.g. full survey, revision, reconnaissance)? How thorough was it?			
5. Acquire and interpret data	How were interpretations derived? How do information and observations support the interpretations? How certain are the interpretations? What alternatives were considered? What conceptual models (3D/4D, processes) underpin the interpretation?			
6. Draft and validate interpretation	How were draft publications refined and why? What generalisations/simplifications were made?			
7. Publication	What 3D/4D knowledge lies ‘behind the 2D geological map’?			
8. Review	What new or improved practices can be adopted in future?			

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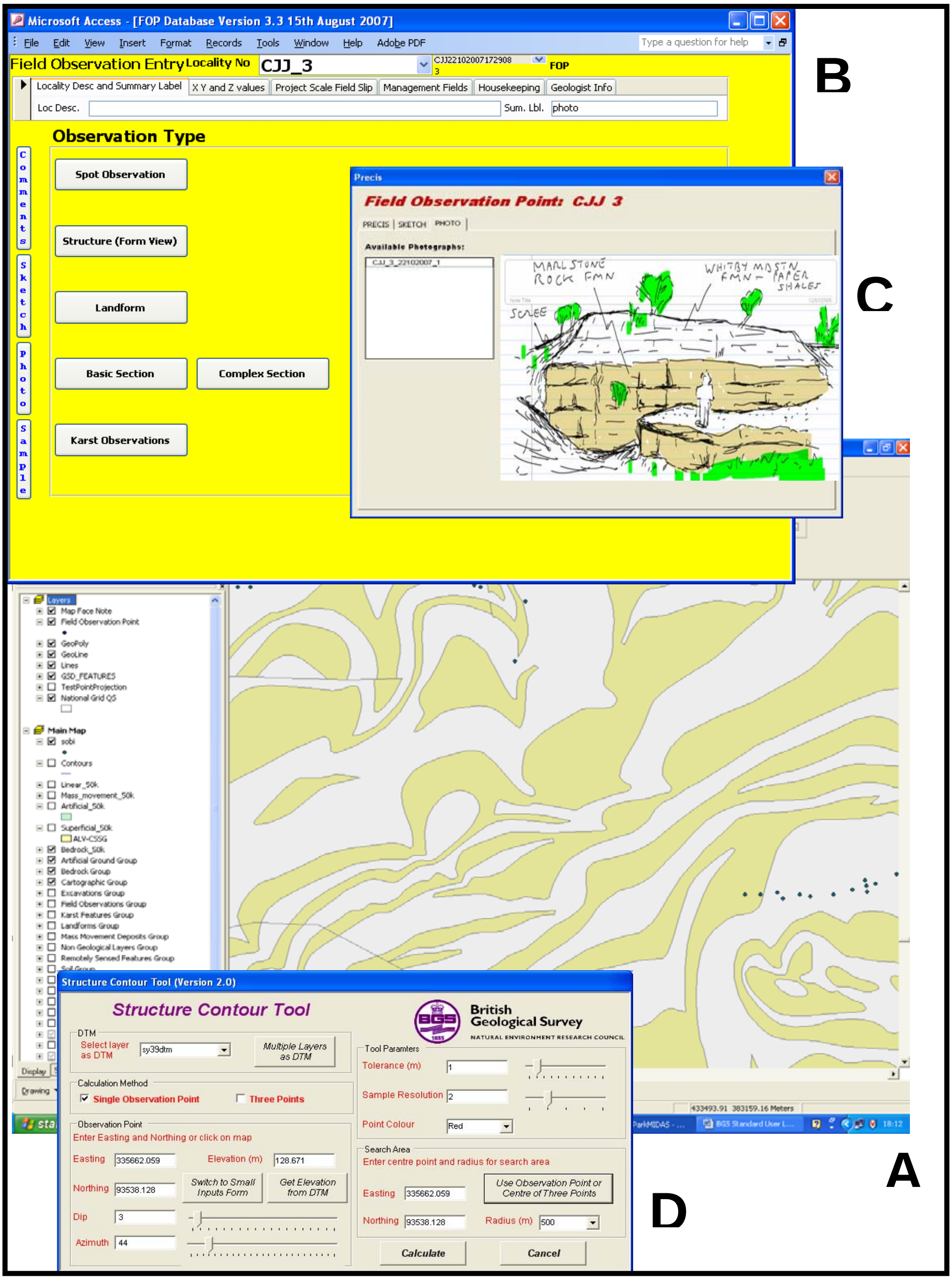

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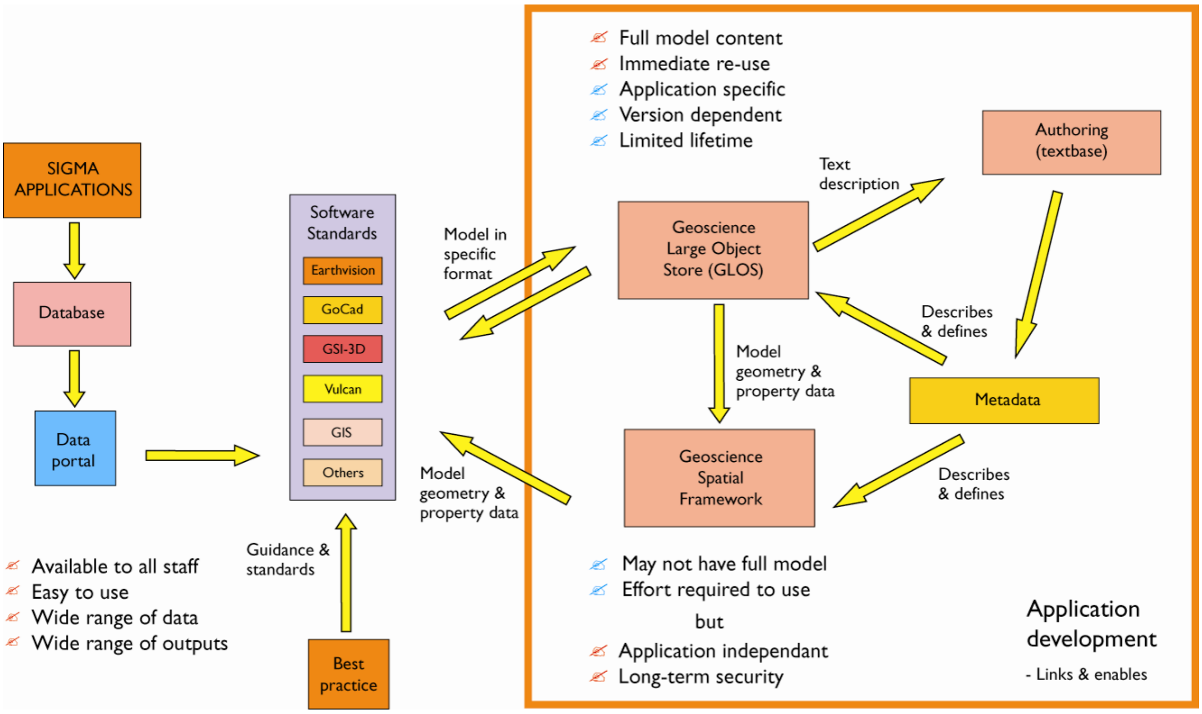

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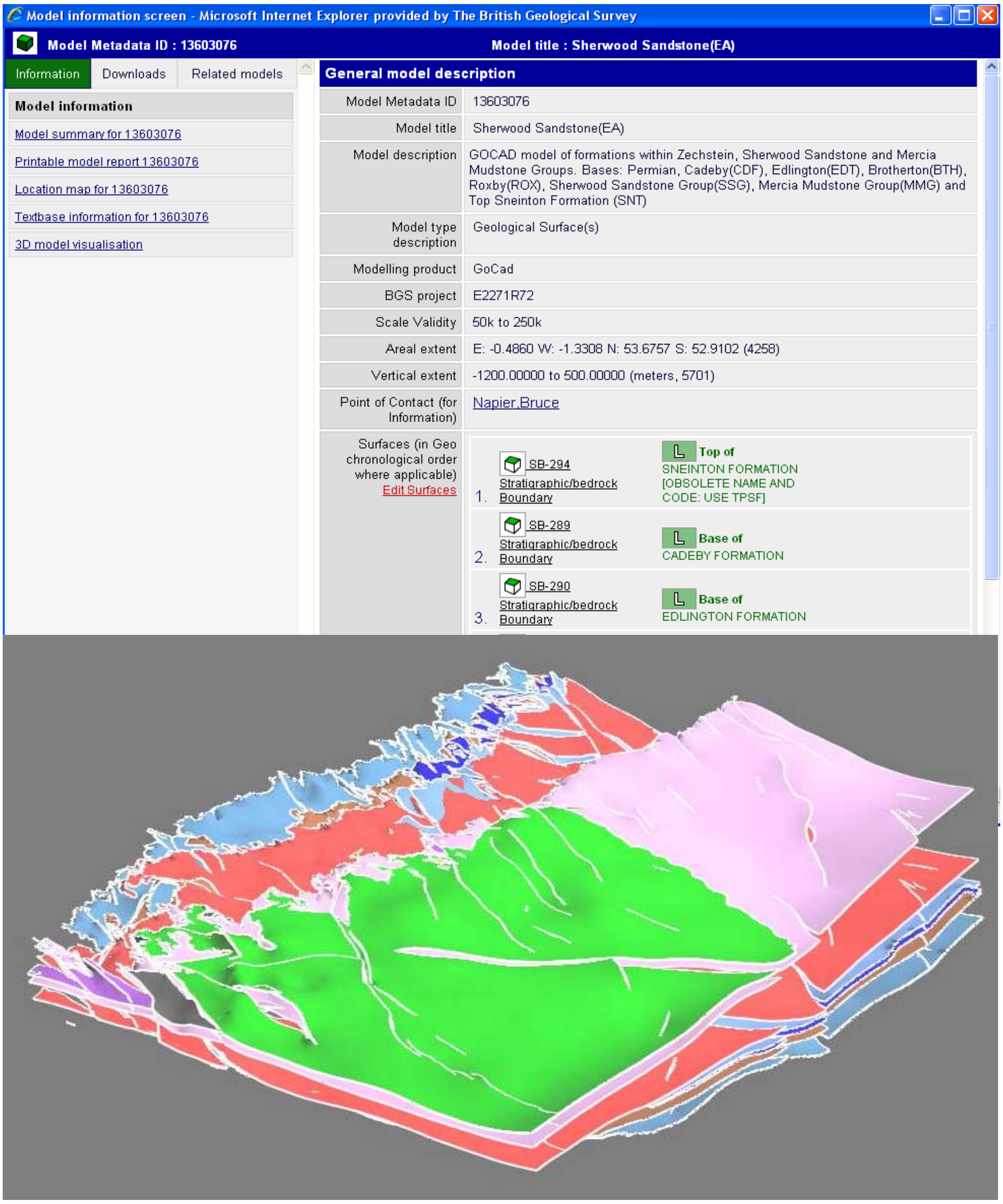

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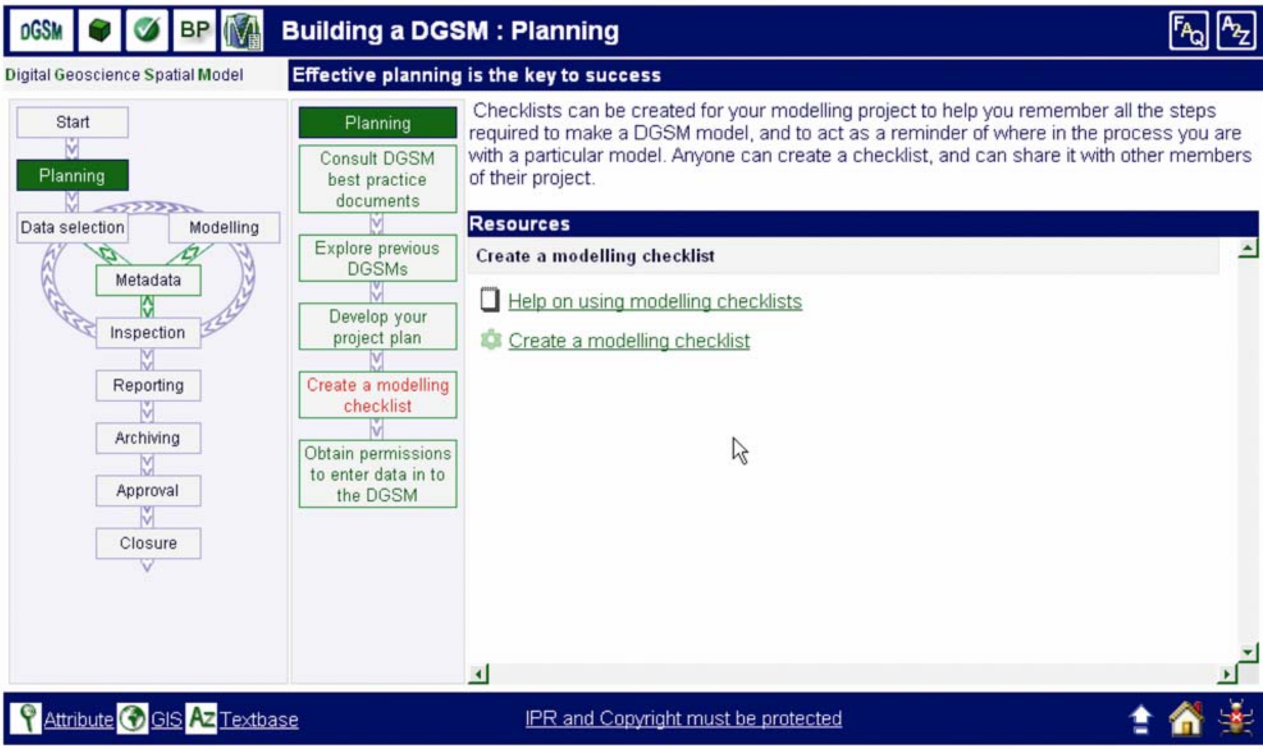

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