# Proceedings of a Workshop on Digital Mapping Techniques: Methods for Geologic Map Data Capture, Management, and Publication

Edited by David R. Soller

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*Hosted by the*
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# FOREWORD

If American citizens want a balanced and acceptable quality of life that is economically and environmentally secure, the states and the nation must provide a reliable geologic-map foundation for decision-making and public policy. In this time of government downsizing, the state geological surveys and the U.S. Geological Survey are confronting a severe geologic- mapping crisis. Less than twenty percent of the United States is adequately covered by geologic maps that are detailed and accurate enough for today's decisions. Critical ground-water, fossil- fuel, mineral-resource, and environmental issues require accurate and up-to-date geologic information—almost always in the form of maps—to arrive at viable solutions. There are hundreds of examples of the important role geologic mapping plays in our society.

In 1988, the Association of American State Geologists (AASG) and the United States Geological Survey (USGS) began to draft legislation that would require and fund a major, cooperative, nationwide geologic-mapping program to be administered by the USGS. The National Cooperative Geologic-Mapping Act was signed into law in 1992. It authorized major federal funding for a four-component geologic-mapping program. FEDMAP comprised geologic mapping to be conducted by the USGS. SUPPORTMAP included the background geologic research needed to accomplish the FEDMAP mapping. The STATEMAP component included geologic mapping to be done by the state geological surveys. EDMAP was the program that supported geologic mapping and training to conduct mapping by the academic community. The National Geologic Mapping Act of 1992 also required that a National Geologic-Map Database be established in order to make geologic-map information available to the public in digital format.

Legislation is pending in the Congress to reauthorize the National Geologic-Mapping Act. As of this writing, the measure has passed the House, and the same legislation is pending in the Senate as S317. The Act requires the establishment of a **National Geologic-Map Database**. The reauthorization bill contains the following language:

> *(¶ 1) Geologic maps contributed to the national archives shall have format, symbols, and technical attributes that adhere to standards so that archival information can be accessed, exchanged, and compared efficiently and accurately, as required by Executive Order 12906 (59 Fed. Reg. 17,671 (1994)), which established the National Spatial Data Infrastructure.*

The reauthorization bill further requires that

> *(¶ 2) Entities that contribute geologic maps to the national archives shall develop the standards described in paragraph (1) in cooperation with the Federal Geographic Data Committee[FGDC], which is charged with standards development and other data coordination activities as described in Office of Management and Budget revised Circular A–16.*

At the 88th Annual National Meeting of AASG in 1996, the Association established the Digital Geologic Mapping Committee with the following charge:

> *The Digital Geologic Mapping Committee shall represent all of the state geological surveys to help establish and construct the National Geologic Map Database as required by the National Geologic Mapping Act of 1992, and by federal legislation reauthorizing the Act. The Committee will work in direct cooperation with the U.S. Geological Survey (USGS) where the national database is to reside. The Committee will work with the USGS to establish and meet digital standards to be developed in concert with the Federal Geographic Data Committee (FGDC). The Committee shall, with the approval of the [AASG] Executive Committee establish subcommittees to deal with digital mapping issues such as metadata, attribution, costs, and topo-*

> *graphic mapping. It will also report on activities of the FGDC, the NAS/NRC Mapping Science Committee, and other groups from government, private industry, and academia involved with digital mapping standards.*

In response to the mandates of the National Geologic-Mapping Act and the charge to the AASG Digital Geologic Mapping Committee, a meeting was convened in August of 1996, at St. Louis, Missouri, to begin work on the development of national digital geologic-map standards. Six working groups were established, and their responsibilities are elaborated by David Soller in the introduction to this collection of papers presented at the ***Digital Mapping Techniques '97*** (DMT'97) conference held at Lawrence, Kansas. That conference and this USGS Open-File report are only one result of the work of the *Data-Capture Working Group*. Those who attended the DMT'97 conference overwhelmingly agreed that this should become an annual conference to share the outcomes of members of the geoscience community who are engaged in digital geologic mapping and digital geologic-map production. We look forward to DMT'98.

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# Introduction

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From June 2–5, 1997, selected technical representatives of the USGS and State geological surveys participated in the "AASG/USGS Digital Mapping Techniques" workshop in Lawrence, Kansas. The workshop was initiated by the AASG/USGS Data Capture Working Group, and was hosted by the Kansas Geological Survey (KGS). With a focus on methods for data capture and digital map production, the goal was to help move the state surveys and the USGS toward development of more cost-effective, flexible, and useful systems for digital mapping and GIS analysis. In this Introduction, I describe the workshop content and the context in which the workshop arose.

## BACKGROUND

More than three decades ago, computer technology began to be adapted to cartography and mapping sciences, with the vision of capturing thematic map information in digital form to use for spatial analysis and the production of maps. Since then, many agencies that conduct geologic mapping have begun to evaluate the potential uses of computers and software for assisting with the process of mapping and publishing. For example, in 1988 the USGS held informal discussions about digital mapping methods currently under development by Geologic Division projects, and published in a special issue of their internal publication "The Cross Section" a summary of those projects. I participated in that forum, and was concerned about the general lack of available guidance for newcomers to the field of digital mapping (which here includes digital map data capture, data management, and the publishing or on-line release of digital maps). Lack of guidance or standards was to be expected, as the field was evolving rapidly. Interesting and useful work was already underway at that time by various investigators, and I was impressed by the value of forums that summarized the level of knowledge at the time. In response, I coauthored a users manual on the methods we developed (Soller and others, 1990). I also looked forward with anticipation to a time when a forum of wider scope could be organized.

Within just the past few years, the evalution and adoption of digital mapping methods has accelerated markedly. As documented by the papers in this volume, many agencies now rely on digital mapping to support their scientific studies and the delivery of information to the public. This recent rapid adoption of digital mapping techniques is due in part to the increased functionality and decreasing costs for geographic information system (GIS) and map production software, and for computers that are capable of supporting these software.

More importantly, however, digital mapping is a logical response to the public's evolving demand for the rapid delivery of information, especially in forms that are amenable to spatial and statistical analysis. In the past, when information was available only in paper form, the public's expectation for information delivery was tempered by the time-consuming process of conventional printing and distribution. Further, when the information became available, its analytic utility was generally somewhat limited because a high level of expertise and/or resources was needed to extract its full value. In contrast, information in digital form, available quickly and in many cases without cost across the Internet, has changed the public's expectations for information delivery—they have learned to expect access to information soon after it is gathered.

Access across the Internet to rapidly-produced information is a new paradigm for industry and government. It has spawned in industry a rapid evolution in software designed to exploit the Internet, from the home as well as the office. Government is responding to this new paradigm by encouraging the public's electronic access to information. Perhaps the most visible response has been the establishment of the National Spatial Data Infrastructure, or NSDI (in 1994, by Executive Order 12906). The NSDI is designed to promote access to spatial data produced by government, and to encourage efficiency by minimizing the gathering of redundant digital data. These goals are addressed through the National Geospatial Data Clearinghouse, which is a network of computers each containing a library of descriptive information, or metadata, about spatial data holdings. Because the computers are linked and supported by a standard seach/query software protocol, the user can perform a national search for information. Clearinghouse "nodes," or entities participating in the NSDI, are being developed by various agencies at the State and National level. More information about the Clearinghouse and NSDI can be found on the Web at the FGDC's home page "http://www.fgdc.gov".

In the geoscience community, there is another, more specific response to the public's need for information. The National Geologic Mapping Act of 1992 mandates the construction of a National Geologic Map Database (NGMDB), to contain the following map themes: geology, geophysics, geochemistry, geochronology, and paleontology. The NGMDB is designed to be a distributed system of computers and State and Federal agency holdings of both digital and paper maps that is accessed through the search and query of metadata at a central site. Planning for the NGMDB began in mid-1995, through discussions between the USGS and the State geological surveys—in this venture, I represent the USGS, and Tom Berg (Ohio State Geologist) coordinates the state's involvement as Chair of the Association of American State Geologists' (AASG) Digital Geologic Mapping Committee. The general plan for the Database was written by Soller and Berg (1995). This plan developed into the National Geologic Map Database project, which is funded under the USGS/AASG National Cooperative Geologic Mapping Program. The NGMDB project Web site (http://ncgmp.usgs.gov/ngmdbproject) contains project plans and other pertinent information. The Database's central site is "http://ngmdb.usgs.gov".

Standards and guidelines are essential to the success of large, cooperatively-built databases such as the NSDI and NGMDB. For example, without standards for metadata content and format, a user's query of the Clearinghouse or the NGMDB would yield little useful information because the database query software would not be able to identify the appropriate metadata records. Without a standard data model for geologic maps, users would need to interpret the content of each map and, if feasible, translate it into the form they need; they also might need to reformat a collection of adjoining maps of disparate data structure so they could perform spatial analysis and produce derivative maps. The geoscience community recognizes the importance of standards. The difficulty has been the lack of organizational structure and committment needed to develop those standards. Functioning at a broad National level, the Federal Geographic Data Committee (FGDC) was formed to support functions like the NSDI by coordinating the development of both the Clearinghouse and various standards among the participating Federal agencies. Within the FGDC, each spatial theme is represented by a Subcommittee responsible for coordinating NSDI implementation at the Federal level within that theme (e.g., the Geologic Data Subcommittee). Especially because mapping within the geologic community is distributed among many State and Federal agencies, standards should first be developed through close State/Federal cooperation, before they are proposed as Federal standards.

The coordinating role of the National Geologic Map Database is critical to development of needed standards. After preliminary meetings including USGS, AASG, the Geological Society of America, and the Geological Survey of Canada, the NGMDB project and the AASG convened a meeting in St. Louis, Missouri, in August, 1996. At this meeting, various guidelines and standards were noted to be important to both the NGMDB and the development of digital mapping capabilities in the States and USGS. Six Working Groups were chartered, as follows:

1. Cartographic standards—Review and revise the USGS draft cartographic standard for geologic maps, prepare a digital version of cartographic elements, and submit to FGDC as a draft Federal standard (as Executive Secretary of FGDC Geologic Data Subcommittee, Dave Soller (USGS) is responsible for this).
2. Data Capture—Through workshops and technical evaluations, help to promote more efficient and useful methods for digital mapping through the coordination and sharing of expertise and information among the State geological surveys, the USGS, and others (Chair—Dave Soller, USGS).
3. Metadata—Evaluate the FGDC metadata content standard for applicability to geologic map information, and develop tools and guidance that lead to greater expertise in writing metadata (Chair—Peter Schweitzer, USGS).
4. Data Information Exchange (also referred to as "Guidelines for digital geologic map publications")—Produce a guideline stipulating the types of files (e.g., Readme file, FGDC-compliant metadata, graphics file) that need to be contained in digital geologic map publications, to enhance their utility (Chair—Todd Fitzgibbon, USGS).
5. Spatial Accuracy—Produce a general-interest publication that explains the accuracy of geologic maps, and investigate methods for evaluating the spatial accuracy of maps (Chair—Richard Berg, Illinois State Geological Survey).
6. Geologic Data Model—Develop a standard data model that represents in computer files the spatial relations among geologic map elements and fully captures the complex information contained in the map legend, to

permit standard queries and creation of derivative maps, from source maps produced by various agencies (Chair—Gary Raines, USGS).

The deliberations and results of each Working Group are posted for public inspection at the NGMDB project Web site. This Proceedings volume is an outcome of the Data Capture Working Group.

## THE WORKSHOP

Despite a relatively short period of announcement before the workshop, it was very well attended. In fact, the level of interest exceeded our expectations: 70 persons attended, from 30 state geological surveys, the USGS, and the Geological Survey of Canada (see Appendix A). As befitting a technical meeting of this type, the KGS provided a Web site for attendees and interested parties (Appendix B and, for a limited duration, http://www.kgs.ukans.edu/DMT97).

### Acknowledgments

The Kansas Geological Survey has earned our gratitude for hosting a productive and enjoyable meeting. I especially thank Jorgina Ross, who coordinated the meeting for the KGS and who provided all attendees with excellent support. Gina was vital to the meeting's success. Other KGS personnel who helped with the workshop were: Dana Adkins-Hieljeson, Nick Callaghan, John Charlton, LingYuan Cao, David Collins, Elizabeth Crouse, John Davis, Jim Deputy, Winston Heng, Scott Highby, Pat Moore, Jennifer Mouser, Joel Rotert, Robert Sampson, Lynn Watney, and David Williams. Gina also provided the attendees with an overview ("Digital geologic map production using the GIMMAP (Geodata Interactive Management Map Analysis and Production) system") and informal tour of the KGS digital mapping capabilities. I also note with gratitude the contributions of the following individuals: Tom Berg (Chair, AASG Digital Geologic Mapping Committee) for his help in conducting the meeting and for his continued support of AASG/USGS efforts to collaborate on the NGMDB; the members of the Data Capture Working Group (Warren Anderson, Kentucky Geological Survey; Rick Berquist and Elizabeth Campbell, Virginia Division of Mines and Geology; Rob Krumm and Barb Stiff, Illinois State Geological Survey; Scott McCulloch, West Virginia Geological and Economic Survey; Gina Ross, Kansas Geological Survey; Dave Wagner, California Division of Mines and Geology; and Tom Whitfield, Pennsylvania Geological Survey) for advice in planning the workshop's content and the suggestions to authors; John Davis (KGS) for an entertaining and enlightening keynote address; Connie Schafer (USGS) for typesetting the manuscripts; and Patricia Packard (USGS) for help with Appendix C.

### Presentations

The workshop began with the keynote address delivered by John Davis (KGS). His remarks provided an interesting perspective on early development of digital mapping, and especially at the KGS beginning in the early 1970's, that lent perspective to the specific issues addressed during the workshop. His address was followed by 23 oral presentations, and various additional posters and computer demonstrations of software and digital mapping techniques. Each presentation was supported by a short paper contained in these Proceedings. These papers represent approaches that currently meet some or all needs for digital mapping at the respective agency. There is not a single "solution" or approach to digital mapping that will work for each agency or for each program or group within an agency —personnel and funding levels, and the schedule, data format, and manner in which information is delivered to the public requires that each agency design its own approach. However, the value of this workshop, and other forums like it, is through their role in helping to design or refine these agency-specific approaches to digital mapping, and to find approaches used by other agencies that are applicable. In other words, communication helps us to avoid "reinventing the wheel." Further, workshops such as this also contribute to the evolution of GIS technolgoy and its convergence towards accepted methods and standards.

Most presentations ranged across a number of issues, so I make little attempt to organize the papers by topic. With my apologies to authors whose work I may not adequately describe, I provide here a brief description of each paper. For the sake of brevity, the presenting author only is listed. Further information about the software and hardware referred to below and elsewhere in these Proceedings is provided in Appendix C.

1. Robert Krumm (Illinois State Geological Survey)—overview of their GIS facilities, with an emphasis on digital map publication and print-on-demand.
2. Warren Anderson (Kentucky Geological Survey)—method for converting 1:24,000-scale published maps to digital format, and compilation of a 1:100,000-scale map from those files.
3. David Viljoen (Geological Survey of Canada)—advantages of structuring or organizing map data, beginning with data capture, to increase efficiency for storage, revision, and query.
4. Barbara Stiff (Illinois State Geological Survey)—specific techniques in Arc/Info for incorporating raster imagery into a geologic mapping project, to assist in the preparation of vector geologic maps.

5. Susan Tingley (Nevada Bureau of Mines and Geology)—cartographic preparation of printed geologic maps using Arc/Info and Adobe Illustrator.
6. Loudon Stanford (Idaho Geological Survey)—overview of digital map production, from author copy to plotting.
7. David Wagner (California Division of Mines and Geology)—methods and costs of developing 1:24,000-scale geologic map data in complex terranes, and of compiling it into 1:100,000-scale maps.
8. Ronald Pristas (New Jersey Geological Survey)—overview of methods, including data capture, incorporation of tabular data on rock structure, and metadata.
9. Gary Raines (U.S. Geological Survey)—progress report of the AASG/USGS Data Model Working Group.
10. David Collins (Kansas Geological Survey)—general concepts in a KGS methodology for adapting the outcrop and contact information on older geologic maps to modern topographic bases, to create new geologic maps.
11. Jorgina Ross (Kansas Geological Survey)—specifics of the KGS methodology introduced by Collins.
12. Jonathan Arthur (Florida Geological Survey)—methods used in the preparation of a Statewide map, and preparation of a three-dimensional database to support mapping in southwest Florida.
13. Berry Tew (Geological Survey of Alabama)—overview of methods, including preparatory steps for data capture and database development.
14. Paul Staub (Oregon Department of Geology and Mineral Industries)—overview of methods, with discussion of conversion of 1:100,000-scale maps to digital format.
15. Richard Lively (Minnesota Geological Survey)—overview of methods for data capture and release of map data.
16. Jim Giglierano (Iowa Geological Survey)—details of digital mapping techniques for a 1:24,000-scale, a county, and a 1:100,000-scale mapping project, using ArcView software.
17. Rick Berquist (Virginia Division of Mineral Resources)—description of an integrated system for field data collection and map preparation, using Abicas software.
18. Neil Rogers, speaking on behalf of Boyan Brodaric (Geological Survey of Canada)—description of an integrated system for field data collection and map production, and of a geologic data model, using Fieldlog software.
19. Van Williams (U.S. Geological Survey)—description of field data capture and preparation of GIS coverages using GSMCAD software.
20. Tim Cowman (South Dakota Geological Survey)—overview of methods, with discussion of a state lithologic log database and production of aquifer maps at different scales.
21. Ron Wahl (U.S. Geological Survey)—data capture by scanning and photogrammetric methods.
22. Grant Willis (Utah Geological Survey)—data capture using soft-copy photogrammetry.
23. Eric Schuster (Washington Division of Geology and Earth Resources)—database design and progress toward a Statewide 1:100,000-scale geologic map (this paper was submitted, but the author was unable to attend the workshop).

Resources, both people and money, are required to create digital map data from either field sheets or printed maps. Generally, agency personnel perform this activity. In some cases, sufficient personnel are not available to complete the job quickly enough. A workshop poster described the use of contracting services to perform the needed work. That information is summarized in Appendix D, which also includes the contract specifications used many times by the author to obtain fully attributed and geographically registered digital data from existing maps.

### Conclusions

The workshop ended with a general discussion and suggestions for topics of future workshops. Attendees noted that the workshop had provided them with valuable information, personal contacts, and insight into the general problems facing all of us. It was the consensus that a similar workshop should be held again next year. Further, certain aspects of digital mapping were raised, and it was suggested that these topics could be the focus of separate workshops. The two topics receiving the most discussion were: 1) print-on-demand technology, including problems with available topographic map digital raster graphic (DRG) files and development of methods for plotting color geologic maps on DRG base maps that produce a graphic similar to a conventionally-printed map; and 2) automated methods for line generalization to assist, for example, in converting 1:24,000-scale maps to 1:100,000-scale.

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# Review of Digital Mapping Techniques: The Illinois Experience

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## INTRODUCTION

This paper presents an overview of how the Illinois State Geological Survey (ISGS) is using Geographic Information System (GIS) technology to generate map and database products. In this paper we summarize our experience with GIS-based map products and describe our GIS operation, the existing system configuration and map production techniques. In addition, we provide specific information about costs and other resources that are required to maintain and support the GIS map production environment.

## OVERVIEW OF CURRENT GIS OPERATION AT THE ISGS

The Illinois State Geological Survey has a long history of using computer technology to build databases in support of its research and service mission. During the 1960s and 1970s, a number of methods were developed to convert map and tabular information into digital files, including ILLIMAP (Swann et al., 1970), an automated system used to produce base maps of the Public Land Survey (township and section lines) for the state. At about that time a project was started to build a keypunch computer database of selected information from records for wells and borings drilled in Illinois. The ILLIMAP system, and the well database was begun almost 30 years ago and is still used and maintained by ISGS staff.

The establishment of the Illinois Geographic Information System (Illinois GIS) in 1983 marked the beginning of the most recent era for ISGS computer mapping applications. The Illinois GIS began as a multi-agency effort to compile information about coal resources and the impacts of coal mining in Illinois. As part of this effort, a common hardware/software solution was implemented in five state agencies to support data compilation and analysis needs. Arc/Info software was selected as the primary GIS software for the system and it continues to be used for most applications and projects. The Illinois GIS now consists of a distributed network of Unix workstations. Software and databases are shared among many divisions of the Illinois Department of Natural Resources including the ISGS, Illinois State Water Survey, Illinois Natural History Survey, and the Waste Management and Research Center, in Champaign, Office of Mines and Minerals, Illinois State Museum, in Springfield and some other units of the DNR elsewhere in the state. Development of the Illinois GIS is documented in several publications (e.g., Krumm, Erdmann, and Joselyn, 1991).

The Illinois GIS database includes information input from published maps, commercial data sets, digital data provided by the U.S. Geological Survey, geologic data from well logs on file at the ISGS, and data from many other sources. Of the many map layers or data sets that provide statewide coverage (Greene, 1990), most were digitized from maps published at scales of 1:500,000 or 1:250,000. The statewide database includes base map information (the public Land Survey grid of ILLIMAP), infrastructure, bedrock geology, soil associations, Quaternary deposits, aquifers, surface water bodies, wetlands, coal resources, structural features, and many others. In addition to these geologic and hydrologic data sets, digital map data are available for many cultural features including municipal boundaries and census information. Many gigabytes of data are maintained by the participating agencies and many Illinois statewide GIS databases (Arc/Info export files, documentation and GIF images) are available on the Internet at http://www.inhs.uiuc.edu/gis/igishome.html. The statewide databases are also available on a set of two compact disks (CDs).

## HARDWARE AT THE ISGS

Within the Illinois State Geological Survey, the current computing environment includes networked workstations and personal computers. A network of 34 SUN workstations is primarily used for GIS analysis, cartographic processing, and database management. Arc/Info is used on the Sun network, and ArcView is used on both the Sun systems and on PCs running WindowsNT to access the GIS database across the network. Five workstations from Silicon Graphics, Inc. are primarily used for surface modeling, subsurface and three-dimensional geological modeling and analysis, and for groundwater and oil reservoir modeling. Our workstation environment also incorporate VAX workstations that act as a database server and clients for the ISGS Oracle well database and for subsurface modeling and mapping. The ISGS maintains its database on nearly 60 gigabytes of on-line disk storage and on optical disks and CDs. Data input devices include a number of digitizing boards and small-format scanners. Output devices include large-format color plotters, small-format color printers, laser printers, film recorders, and a CD mastering device.

The GIS expertise at the ISGS is primarily provided by the Geospatial Analysis and Modeling Section, a group of ten full-time geologists and GIS specialists and several interns and students. The role of this section is to maintain the GIS databases, provide digital data coordination, provide GIS expertise for internal projects and external requests, provide training, develop applications, and produce maps. Some ISGS staff members in other sections (Coal, Quaternary Geology, and Groundwater) are also skilled GIS practitioners involved in a number of projects.

We are using GIS and other software to support projects that include detailed (1:24,000 scale) geologic mapping, county mapping (1:100,000 scale), and statewide mapping and screening efforts. In addition to basic geologic mapping of USGS 7.5-minute quadrangles, we are also using the GIS to map shallow aquifers, assess aquifer contamination potential, compile information on man-made and geologic hazards (i.e., underground coal mines and landslides), screen counties for geologically capable sites for municipal landfill siting, evaluate mineral resources and reserves, model land surface and bedrock surface topography, analyze land cover analyses, map the extent of floods, and compile maps of regional seismic history and potential earthquake hazards.

## EARLY GIS MAP PRODUCTION TECHNIQUES AND PRODUCTS

Many ISGS projects generate maps for general distribution and as final project deliverables. Maps are also required for presentations (e.g., poster sessions) and for other in-house needs, such as quality control review during the GIS database compilation process. Our map production approach has evolved over the years to take advantage of available technology. Initially, our map production techniques were dependent on available Arcplot routines and pen plotters. Early versions of the Arc/Info software (e.g., revs. 2.4, 3.2) provided a basic suite of cartographic plotting tools, however, pen plotters limited the ability to produce maps with solid color fill and high quality text. Although we made heavy use of the pen plotters to produce maps and graphics for poster presentations, few of these maps were published or released for general distribution.

The sophistication and quality of our map products improved markedly with the purchase of an electrostatic plotter and later releases of the Arc/Info software. The electrostatic plotter technology, and enhanced Arcplot capabilities, provided many options for map production, including solid color fill, improved text quality, an abundance of standard point symbols and line types, and the ability to combine and display vector and raster data. This combination of hardware and software provided our staff with the tools needed to create higher quality map products that could be plotted on an as-needed or on-demand basis.

The ISGS Open File map series provides staff members with a mechanism to publish and distribute computer-generated maps. This series includes of maps showing aquifers with potential for development of public water supplies in Kane County (Vaiden and Curry, 1990), near-surface geologic units for a region of southern Illinois (Greenpool and Berg, 1992), features associated with one of the major coal seams in the Illinois Basin (Treworgy and Bargh, 1993), wells and borings for the entire state (McKay and Denhart, 1993), and the thickness and lithology of geologic units in Will County (Abert et al., 1993). These and many other maps were produced using Arcplot routines and a Calcomp electrostatic plotter. Because of the cost of plotter maintenance (about $12,000/year) and supplies, these maps sold for about $20 each. This per unit cost was significantly higher than that for printed maps (typically $5/map). However, the higher cost was balanced by the ability to update maps as new information became available. In addition, maps could be printed to meet demand so that the organization was not burdened with the costs and storage requirements for a large stock of printed maps.

Although the quality of the maps was good, the electrostatic plotter presented a number of disadvantages, including the necessity of a climate-controlled room (for temperature and humidity), the special handling and disposal of the toner (classified as a toxic substance), and frequent, and sometimes lengthy, interruptions caused by mechanical failure that required the services of a factory trained technician.

## CURRENT PLOTTING HARDWARE AND COST INFORMATION

After several years of use, we started to experience considerable downtime with the electrostatic plotter. In 1995 we investigated options to retool the plotter operation and decided to purchase a Hewlett-Packard 750c inkjet plotter. When compared to electrostatic plotters, the inkjet technology offers a number of advantages, particularly high overall reliability and low cost of maintenance. While there has been heavy demand on the inkjet plotter, we have had only one service call in 16 months. Other plotters now being used at the ISGS include one large-format pen plotter (HP DraftMaster) and one small-format color inkjet printer (HP PaintJet XL300) The HP 750c meets about 95% of our daily plotting demands. The HP DraftMaster is used to generate relatively simple line plots that are predominantly used to check map digitizing efforts.

Three staff members (one system administrator and two staff) provide plotter support. We estimate that their combined effort is equivalent to one half-time staff member. The duties involve plot queue management, loading ink and paper, maintaining adequate supplies, plotter accounting, and system trouble-shooting. During the last year, we have purchased approximately $6,000 worth of plotter supplies including several types of paper and ink cartridges. Maintenance for the inkjet plotter is about $400 per year. The overall plotting operation costs about $26,400 per year, including staff salaries and benefits, supplies, and maintenance.

During an average one-month time period, the inkjet plotter will generate about 260 plots. With an average plot length of 2.65 feet, monthly paper usage is about 690 linear feet, or about seven rolls of paper (100 feet per roll).

## DIGITAL MAP PRODUCTION METHODS

Most of the recent digital map products are plotted on demand and are available as open-file maps. Others have been printed from having four color separates made from the digital files. Although our current map production techniques involve using Arcplot, we also use CorelDraw, ImageMagick, Larson, Ghostscript, xv, and Microsoft Word. For most maps, Arcplot is used to produce the overall cartographic framework consisting of thematic maps, images, legends, text, scale bars, north arrows, and neatlines. Other software packages are used to take advantage of select capabilities or functions. For example, Coreldraw may be used to add text blocks, tables, or graphics to maps. The maps, *Karst Terrains and Carbonate Bedrock of Illinois* (Weibel and Panno, in press) and *Coal Industry of Illinois* (Damberger, Stiff, and Hines, 1997) both were produced using a combination of Arcplot and CorelDraw.

We view all of the available software as a tool chest containing many cartographic design and graphic file processing tools to improve the overall quality of map products and/or to make the map production process more efficient. For example, images can be incorporated onto maps using image conversion tools such as xv and ImageMagick. These tools, which are shareware, allow images downloaded from the Internet or from a digital camera to be converted into other image formats (e.g., tiff or others) and used with many software packages. These conversion tools can also be used to convert Arc/Info graphics files (.gra files) into images that can be displayed on the Internet or imported into a package such as CorelDraw. The graphics files can be converted to Postscript files, and then to any image format, usually GIF. The GIFs can be easily imported into CorelDraw for compilation to produce poster displays or smaller fliers or brochures.

Several maps initially compiled and released in the ISGS Open File Series were later printed because of increased demand. One example is the *Shaded Relief Map of Illinois* (Abert, 1996). The publication and printing process involved the creation of a "final" Arc/Info graphics file version of the map. The graphics file was then converted to a Postscript file, written to tape, and transferred to a company that created the negatives. The negatives were provided to a printing company for production. To help keep printing costs low, it was decided to create only a black and white map. The cost of the map for consumers dropped from $20.00 for the print-on-demand electrostatic plotter version to $4.25 for the printed version.

Many of our clients have indicated that paper maps remain important to their work, but other people have started to request digital data. These requests are usually from government agencies, consultants, or other companies with in-house GIS capabilities. We expect that the number of these businesses and agencies will continue to increase as the overall GIS market expands. In addition, GIS databases are being identified as one of the deliverables for some of our contracts with other agencies including the USGS and the National Forest Service.

When we provide GIS databases in Arc/Info format, part of the project deliverable will be project files that can be used with the ArcView software. Creating useful ArcView project files involves a number of cartography and database design skills. By employing efficient database design and basic cartographic principles, we believe that the ArcView project files and GIS databases will be more useful and meaningful, especially to non-technical users. The project files can contain a number of themes that all reference the same coverage yet show different interpretations of that basic information. For example, one theme can be used to display all information on a geologic map and another theme can be used to display all units ranked by their relative capability for a particular land use (e.g., relative capability for a landfill) or a concern (e.g., groundwater protection).

## SUMMARY

The Illinois State Geological Survey has been using the Arc/Info GIS software since 1983 to support a variety of projects, and many of these projects have resulted in computer-generated maps. Many maps have been released through the ISGS Open-File publication series and plotted on-demand. Our map production techniques have evolved with subsequent releases of the Arc/Info software and the availability of new plotter technology. Our current map production environment features a combination of software, including Arcplot, CorelDraw, ImageMagick, xv, and others, we use whatever capabilities of these software packages will best support the map production process. We expect that our map production techniques will continue to evolve to take advantage of new software or enhancements to existing packages. We will continue to use large format inkjet plotters to produce maps, and recently ordered another HP 750C plotter to incorporate into the in-house plotter operation. This additional plotter was purchased to make it easier to plot multiple copies of map products, and to serve as a backup to the existing plotter. We are particularly interested in new technology that will allow us to print a variety of high quality maps on-demand. Printing maps on-demand with existing inkjet plotter technology is relatively slow and more expensive than traditional printing. We will also continue to make digital data available via the Internet and on CD. For future publications, we have also discussed the possibility of providing a CD that contains GIS data, scanned graphics (e.g., cross sections, figures and other diagrams), and information from databases or spreadsheets.

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# Semi-Automated Data Capture For Vectorizing Geologic Quadrangle Maps In Kentucky

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## ABSTRACT

The Kentucky Geological Survey is using a semi-automated data capture technique to vectorize data from existing hard-copy geologic maps. A multi-step procedure is being developed to collect accurate vector data. The vector data will facilitate the use of geologic information in geographic information systems (GIS). The primary objectives of this program are to collect accurate vectorized geologic data at a scale of 1:24,000, create electronic 7.5-minute geologic quadrangle maps, and compile electronic 1:100,000-scale maps from the 1:24,000-scale maps.

Conventional geologic mapping of Kentucky at a scale of 1:24,000 was completed in 1978. In 1996, as part of the STATEMAP component of the U.S. Geological Survey's National Cooperative Geologic Mapping program, the Kentucky Geological Survey initiated a project to convert published 1:24,000-scale geologic quadrangle maps to digital format. Some published geologic quadrangle maps are out of print, and there are no plans to reprint them. The demand for digital information and the utility of digital data focused our attention toward converting these published maps to digital format. A total of 24 geologic quadrangle maps in the Hazard 30-minute by 1-degree 1:100,000-scale quadrangle in the Kentucky River Basin was chosen to begin the digitizing process.

Vectorizing existing geologic maps will create digital geologic data that can be used in computer applications and GIS. In a GIS, vectorized geologic contacts make it possible to manipulate data to obtain area and volume measurements, answer spatial queries, locate wells, and perform other geologic and mineral resource manipulations and searches.

## BACKGROUND

The STATEMAP component of the USGS National Cooperative Geologic Mapping program mandates five types of data for inclusion in electronic form: geological, geochemical, geophysical, geochronological, and paleontological. As part of this program, the Kentucky Geological Survey (KGS) is currently collecting the following information in digital form: geologic contacts, major coal beds, structural contours, faults, paleontological sites, and point data (outcrops or other features).

Under the STATEMAP program for 1996, KGS will complete the vectorization of 24 1:24,000-scale, 7.5 minute geologic quadrangle maps, and will compile them into a 1:100,000-scale geologic map by edgematching each boundary. In the process, a database of appropriate metadata will be created. The Barcreek geologic quadrangle map was the first to be vectorized using the semi-automated data capture techniques (fig. 1).

## KENTUCKY GEOLOGY AS IT RELATES TO DIGITAL MAPPING

The geology in Kentucky consists predominantly of flat-lying sedimentary rocks. The Cincinnati Arch, a large north-trending anticlinal structure in central Kentucky, divides the State into two basins: the Appalachian Basin in the east and the Illinois Basin in the west. Faulting is extensive in parts of Kentucky, but igneous intrusions are rare. Coal, limestone, sand, gravel, clay, oil, and natural gas are important mineral resources in Kentucky. Industries that extract these resources require resource assessments and

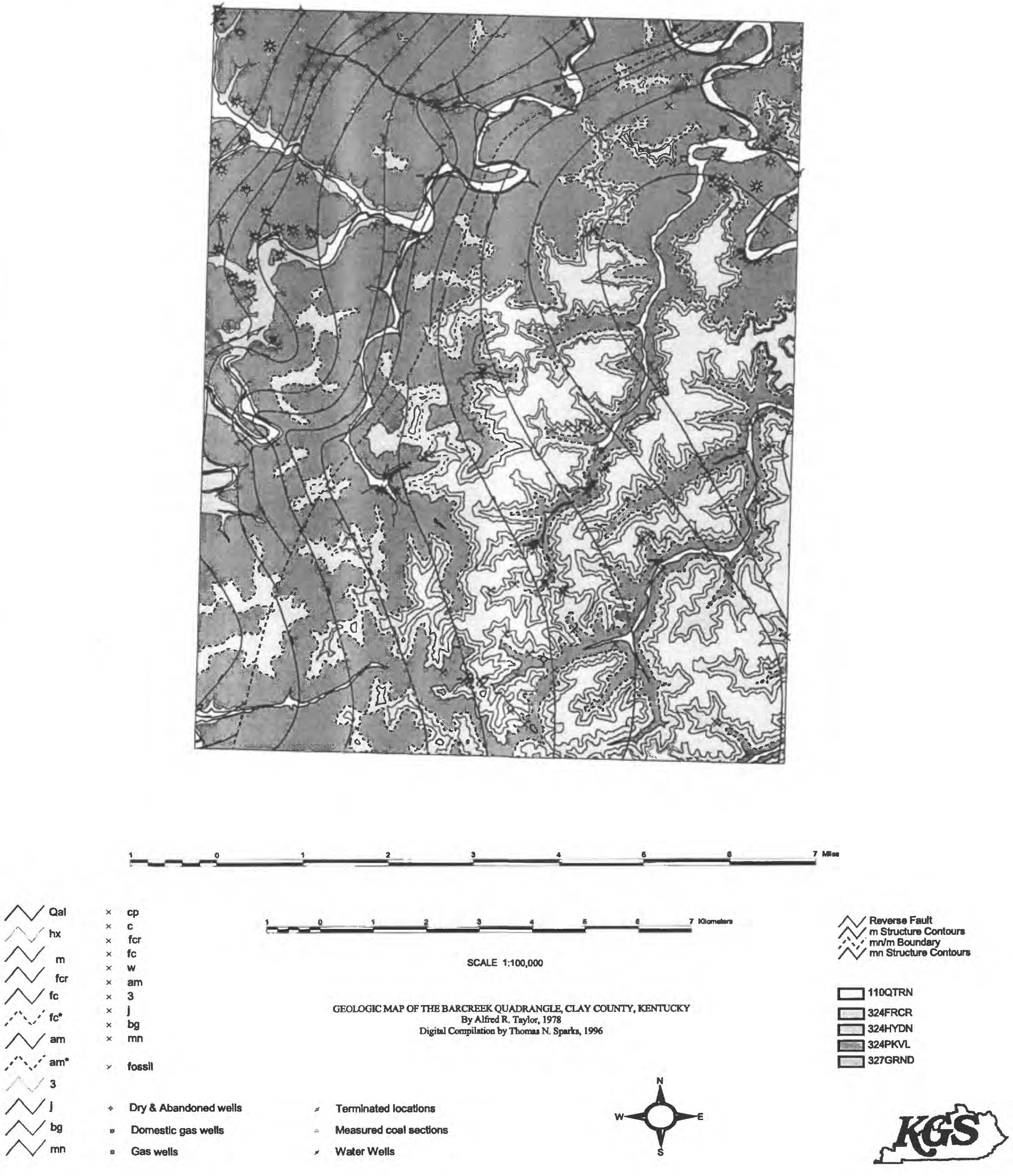



**Figure 1.** Draft geologic map of the Barcreek Quadrangle, Clay County, Kentucky

geologic analyses. Converting paper maps to digital products will provide needed digital geologic information to mineral industries, planning agencies, and other public and private interests.

## COMPUTER SYSTEMS, SOFTWARE, AND PERSONNEL

The Kentucky Geological Survey is using two 160-megahertz Pentium PC's, one Digital Equipment Corporation Alpha workstation, a Hewlett Packard 650-C color plotter, and an Eagle black and white scanner for the project. One Pentium PC is used to drive the scanner and capture the raster image, and the Alpha workstation is used for vectorization and map compilation.

Arc/Info (ArcScan) software is used to capture vector files from raster images. Experience with Arc/Info has shown that a period of 2 to 4 months is required to obtain minimum proficiency. Once proficient in the software, a geologist can complete the digital conversion of a 1:24,000-scale geologic quadrangle map in approximately 2 to 3 weeks.

Personnel for the KGS digital geologic mapping project includes a principal investigator, two individuals with expertise in both GIS and geology, and two technicians. In addition, the project receives significant support from the KGS Computer Services Section. This project will also enlist the aid of the Survey's GIS coordinator, who will provide assistance for the organization of metadata files. The KGS Database Manager will incorporate the digital geologic mapping files from this project into the KGS database. Several members of other KGS sections (Coal and Minerals, and Geologic Mapping and Hydrocarbon Resources) will also be available to help in their areas of expertise.

## PROCEDURES AND METHODS

A multi-step process for digital conversion of geologic maps has been developed for this project to obtain accurate and reliable data (fig. 2).

### Mylar Preparation

To convert published geologic maps into digital vector data, a stable-base Mylar composite of the geologic data is used. Paper maps are not stable and should not be used unless no Mylar copies are available. The composite is created by photo-enhancing the original geologic map to create a film positive that contains all geologic data but none of the topographic contours. The topographic contours cause significant problems during auto-vectorization because of the frequent line intersections encountered during the digitizing process. Later, a DEM and/or a DRG will be used to add topography to the map.

## SCAN PARAMETERS

Scanner accuracy has been an issue during our conversion process. Potential problems included stretching of the Mylar during scanning, the scanner's roller control, and the scanner's camera alignment and calibration. These three problems can be controlled by calibrating the equipment according to the manufacturer's specifications. Each scan is checked to ensure that roller slippage or medium stretching (particularly with paper) has not changed the dimensions of the map. We have resolved these issues by calibrating and recalibrating as necessary to maintain high standards of accuracy.

The scanner software permits scanning parameters to be adjusted for each scan to obtain best results. Contrast control is adjusted for each quadrangle to obtain high-contrast raster images. Speckle removal is not used because it removes some important data. Experience has shown that a resolution of 400 to 600 dots per inch gives the best results; this resolution avoids line coalescence while still resolving very thin lines that might not be totally captured at lower resolutions.

## REGISTRATION AND RECTIFICATION

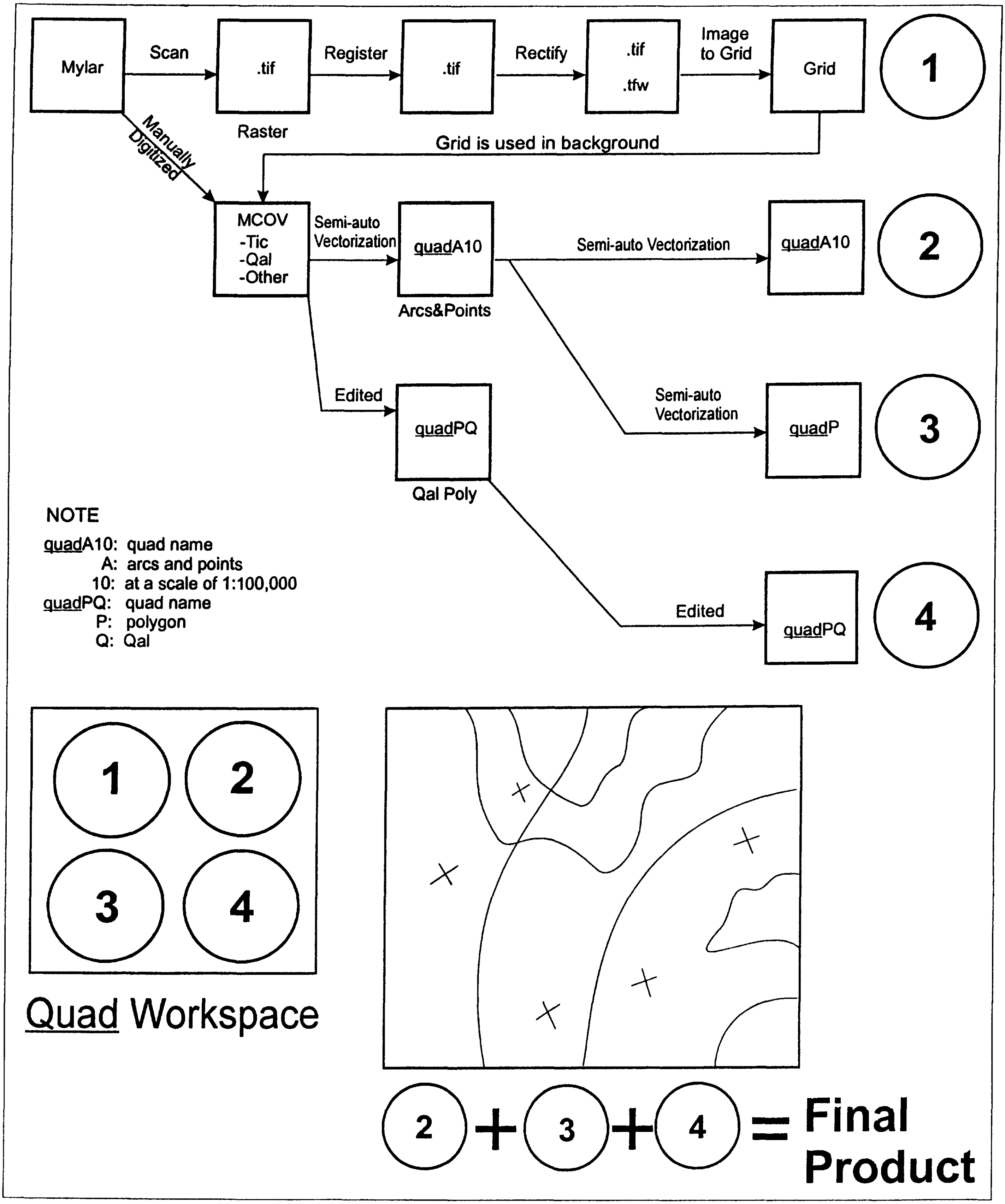
Once a mylar has been scanned and saved as a raster image (in TIFF format), the image is registered to a blank vector coverage based on the four known corner coordinates of the original Mylar. These four points can be expressed in either digitizer inches or real-world coordinates. The registered corner points serve as the georeferenced links between the original raster image and the vector coverage. Rectification corrects any skewness for a particular quadrangle.

## IMAGE TO GRID

A new rectified TIFF image is then converted into an Arc/Info grid that precisely overlies the blank vector coverage. This grid is used as a raster background during vectorization. Some Quaternary deposits are manually digitized in AutoCAD because of problems scanning the Quaternary contacts. Corner coordinates are also created as tic marks in AutoCAD, then converted to DXF format and imported into Arc/Info. This method was chosen to maintain procedural consistency in registration because of the operator's familiarity with Autocad. Future tic marks will be selected from the USGS master tic files.

# Digital Mapping Project

## Flow Chart and Synopsis



← **Figure 2.** A process for digital conversion of geologic maps.

## SEMI-AUTOMATED VECTORIZATION

Once the registered and rectified raster image is ready, it is entered into ArcScan. This software package is a semi-automated, operator-assisted, controlled method for rapid vectorization of raster data. The vector arrow traces the raster image line until it intersects another line, whereupon the operator is prompted for directions on which way to proceed. The operator directs the vectorization process, making this the slowest part of the process. The process to vectorize a complete 1:24,000-scale quadrangle took two weeks for an experienced operator.

Once vectorization of the quadrangle is completed, the resulting polygons, arcs, and points are built in Arc/Info to create topology. This establishes the coverage and attribute tables, which can later be used for analysis. The information in these coverages is made up of three Arc/Info feature classes: arcs, points, and polygons. Arcs and polygons define geologic contacts, coal outcrops, formations, structural contours, and faults. Points define selected outcrops, well locations, and fossil locations.

Attributes for arcs and points are stored in subfiles with .aat and .pat file extensions, using the following fields: Formation Name (FMNAME), Formation Code (FMCODE), Geologic Quadrangle Number (GQNUM), and Hazard 1:100,000 Code (HZ_FMCODE). Coding examples are shown in the table below.

| FMNAME | FMCODE | GQNUM | HZ_FMCODE |
|---|---|---|---|
| fc | 324FRCL | 1488 | 324FRCL |
| am | 324AMBG | 1488 | 324AMBG |

### Matching and Joining Map Boundaries

Once several quadrangles have been vectorized, their boundaries must be matched and joined. This involves establishing a "snap environment" where geologic features are connected and a seamless boundary is created. This process is important for maintaining geologic integrity and cartographic smoothness, because most boundaries are not perfectly aligned. Once the quadrangles are joined, they are imported into ArcView, where the final map is produced.

## FINAL MAP PRODUCT

A preliminary draft of a 1:24,000-scale map is shown in Figure 1. The legend, scale, and titles are added in the layout windows of ArcView. In the future, we plan to include a raster image of the original geologic quadrangle map as a part of the digital product, perhaps in the metadata file.

The 1:100,000-scale digital geologic map of the Hazard quadrangle will include a stratigraphic column, topographic base, and legend. The map is being created as follows:

1. Map data were Arc/Info coverages compiled in ArcView, where the layout, title, authors, scale, corner labels, and legend were established.
2. The stratigraphic column was created in Autocad, converted to DXF format and imported into ArcView. The cross section was partly created in a Terrastation computer plot of subsurface data, which was supplemented with near-surface data. It was compiled in Autocad, converted into DXF format and imported into ArcView.
3. The text for the stratigraphic column lithologic descriptions, economic geology, and references sections were compiled in Microsoft Word, imported into ArcView, and converted into a "text with line breaks" format. These data were manipulated in the Text Layout window of ArcView to achieve the final map product.

## DATABASE DESIGN

An integral part of digital mapping is establishing a mapping database that links the graphic information with its geologic components. Of the five major types of data being captured in the STATEMAP program, geology has the most subcategories. It is important to be able to search digital files for geologic subcategories such as quadrangle, lithology, formation, faults, fossils, minerals, engineering properties, environmental properties, imagery, and drill holes.

In addition to the new mapping database, we are working toward establishing dynamic links to the principal KGS databases on petroleum, coal, water, and minerals. This will allow us to produce custom digital geologic maps, on which options such as locations of oil and gas wells, coal data, water data, and mineral data can be plotted. The ultimate goal is to integrate the digital geologic mapping spatial database with the point locations and attributes in the KGS relational database.

## TECHNOLOGY ADVANCES

Several new software products on the market combine a true automatic vectorization with optical character recognition to vectorize all the data for a quadrangle. Programs with the ability to recognize text and labels and the ability to distinguish between the various line widths are a major advance in automatic vectorization. These programs still require operator control and cleanup after vectorization, but the future is promising.

# Topological and Thematic Layering of Geological Map Information: Improving Efficiency of Digital Data Capture and Management

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## ABSTRACT

Geological maps are typically complicated documents containing a variety of information that is both spatial and descriptive, such as lithology, structure, mineralogy, topography, and hydrography. This information can be digitally captured, stored, manipulated, and analyzed in a Geographic Information System (GIS). It can be input and stored as points for features at a specific location (e.g. structural observations), lines (chains) for linear features (e.g. faults), and polygons for areal features (e.g. lithological units).

One of the keys to efficient capture and management of geological map data is understanding how polygons are stored in a GIS. Topological and thematic layering are powerful methods that can be utilized to dramatically decrease the amount of time spent capturing, manipulating, analyzing, and managing geological map information. Topological layering involves separating the lines and polygon labels (area points) required to "build" polygons in a GIS from other line and point features. Thematic layering entails separating spatial information by theme (e.g. topography and geology). It is very useful to separate polygon layers thematically. The most dramatic example of this is separating geological (e.g. lithological units) and hydrographic (e.g. lakes) polygons.

There are presently two dominant pathways for digital data capture: digitizing tablet and scan/vectorize. The layering concepts introduced in this paper can be utilized regardless of the data capture pathway and will improve the efficiency of data capture.

This paper will review how polygons are created and stored in a GIS and compare the "single-layer" map oriented approach and "multi-layer" GIS approach to digitally capturing and managing geological map information. It will highlight the advantages of the "multi-layer" approach in terms of data management, analysis, and visualization.

## INTRODUCTION

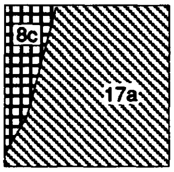
There are many references that describe how GIS store information (Aronoff, 1993; Burrough, 1986), how GIS has been used for addressing geological problems (Van Driel, 1989), and issues related to digital data capture (Wright et al, 1990) but few discuss how to manage geological map information with a GIS. The goal of this paper is to propose a methodology for digitally capturing and managing geological map information more efficiently and effectively.

Geoscientific information can be represented by utilizing four spatial data models: points, lines, polygons, and rasters. A spatial data model is a conceptual model of real-world features and has a graphical representation on maps and a digital representation in a CAD or GIS. Map features are defined by two types of information:

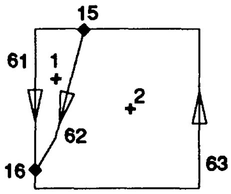
1. Spatial information defining locations of point features, shapes of linear or polygonal features, and reference coordinate and pixel size for raster (image) information
2. Descriptive information describing what the point, line, and polygonal features or pixel values represent.

For example, a capital city on a small scale map may be graphically represented by a point positioned somewhere on a map (spatial information) and a red star might be used to differentiate capital cities from others on the map. In a GIS, this red star would be special symbolization associated with the descriptive information for that point.

**Map View**




**GIS View**




KEY:
+ area point
◆ node
Δ digitization direction

**Digital File Representation**

**Spatial Information**

Area Point Spatial Data

| POLY-ID | X | Y |
|---|---|---|
| 1 | 440189 | 6092334 |
| 2 | 451632 | 6091495 |

Chain Spatial Data

| CHAIN-ID | COORDS |
|---|---|
| 61 | $X_1,Y_1;..X_n,Y_n$ |
| 62 | ... |
| 63 | ... |

Area Point Topological Data

| POLY-ID | CHAINS |
|---|---|
| 1 | 61, -62 |
| 2 | -62, -63 |

Chain Topological Data

| CHAIN-ID | LPOLY | RPOLY | SNODE | ENODE |
|---|---|---|---|---|
| 61 | 1 | 0 | 15 | 16 |
| 62 | 1 | 2 | 16 | 15 |
| 63 | 2 | 0 | 16 | 15 |

**Descriptive Information**

Polygon Attribute Data

| POLY-ID | LITHO-CODE |
|---|---|
| 1 | 8c |
| 2 | 17a |

**Figure 1.** Representation of areal (polygonal) features in a GIS.

This paper will review how areal features (polygons) such as lithological units are created and stored in a GIS. It will then demonstrate how effective layering of information can dramatically improve the efficiency of geological map data capture, management, analysis, and visualization.

## POLYGON TOPOLOGY RE-VISITED

From a GIS point of view, topology defines the relationships between spatial objects (e.g. an area point/polygon label and its enclosing lines as shown in Figure 1) that are unaltered through common geometric transformations. The encoding of topological relationships is essential for capturing and managing polygons in a GIS.

Figure 1 shows the map and GIS view of two adjacent polygons with different lithologies as well as the data required to store these polygons in a GIS. There are three types of data required to store polygons in a GIS: spatial, topological, and attribute. The spatial data describes the shapes of the lines (chains) that are used to define the outline of the polygon and the location of the polygon labels (area points). The topological data describe the relationships between the chains, nodes, and area points. The area point topological data describes the connectivity of arcs used to define the polygons. The chain topological data describe the left/right polygon relationships between the chains and the polygons. The attribute data describe which lithology the polygons represent.

## SINGLE-LAYER APPROACH TO DATA CAPTURE AND MANAGEMENT

Given a simple geological map, as in Figure 2, there might be an inclination to digitize with a map oriented, single-layer approach. That is, digitize the lines and attribute the polygons such that the map view can be easily generated by drawing and symbolizing one data layer. While this may seem to be the simplest and most efficient method, there are many negative implications that will be reviewed later in the Multi-layer vs. Single-layer Approach section that clearly demonstrate that this is not the case.

## MULTI-LAYER APPROACH TO DATA CAPTURE AND MANAGEMENT

Figure 3 shows a multi-layer approach to capturing and managing the same map described in the previous section. In this case the data has been layered topologically and thematically. Initially, this method may seem to be more com-

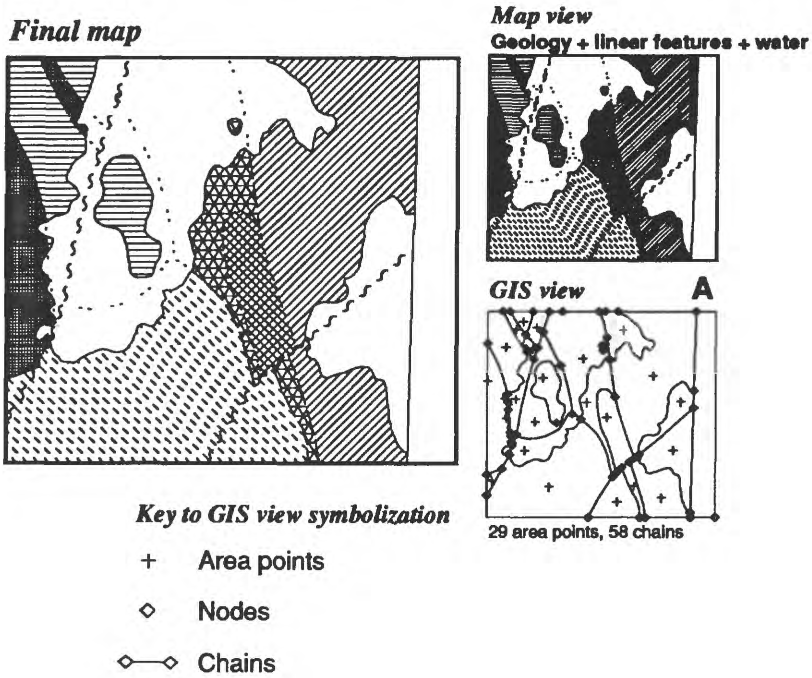



**Figure 2.** Single-layer approach to capturing and storing geological map information

plicated to implement and requires geological interpretations where there is no outcrop (e.g. under water). However, there are significant advantages to this methodology that will be reviewed in Multi-layer vs. Single-layer Approach section.

### Topological Layering

Topological layering involves separating the lines and polygon labels (area points) required to build polygons in a GIS from other line and point features. In this example, the lines representing lithological contacts and fault-contacts are separated from the faults. There are portions of faults that are duplicated in both the geology and fault layer. This does not necessarily have to be the case but it does simplify using the fault layer separately for other applications such as a fault overlay on a satellite image. Data management can be dramatically simplified by separating faults and lithological contacts as shown in Figure 4. In addition, a dangling chain (i.e. a line with one or both nodes not shared with another line or lines) is perceived to be a topological error by GIS. This means that including all faults in a lithological contact layer will display many dangling chains that are not necessarily topological errors. This can dramatically slow the process of finding "true" dangling chains and building polygon topology.

In general, it is desirable to minimize the number of points, lines, and polygons required to digitally capture and manage a geological map. Topological layering is a major step in this direction.

### Thematic Layering

Thematic layering entails separating spatial information by theme (e.g. topography and geology). In the example shown in Figure 3, it was wise of the GIS specialist to recognize that there were two polygon themes in this map: one geological (i.e. lithological units) and the other hydrographic (i.e. lakes). Separating these two themes into individual data sets has several advantages that will be outlined in Multi-layer vs. Single-layer Approach section.

## MULTI-LAYER VS. SINGLE-LAYER APPROACH

The multi-layer approach which entails topological and thematic layering of geological map information reduces the number of features (points, lines, polygons) that the GIS specialist needs to manage, simplifies updating themes, and enhances the potential for map generalization, analysis, and visualization.

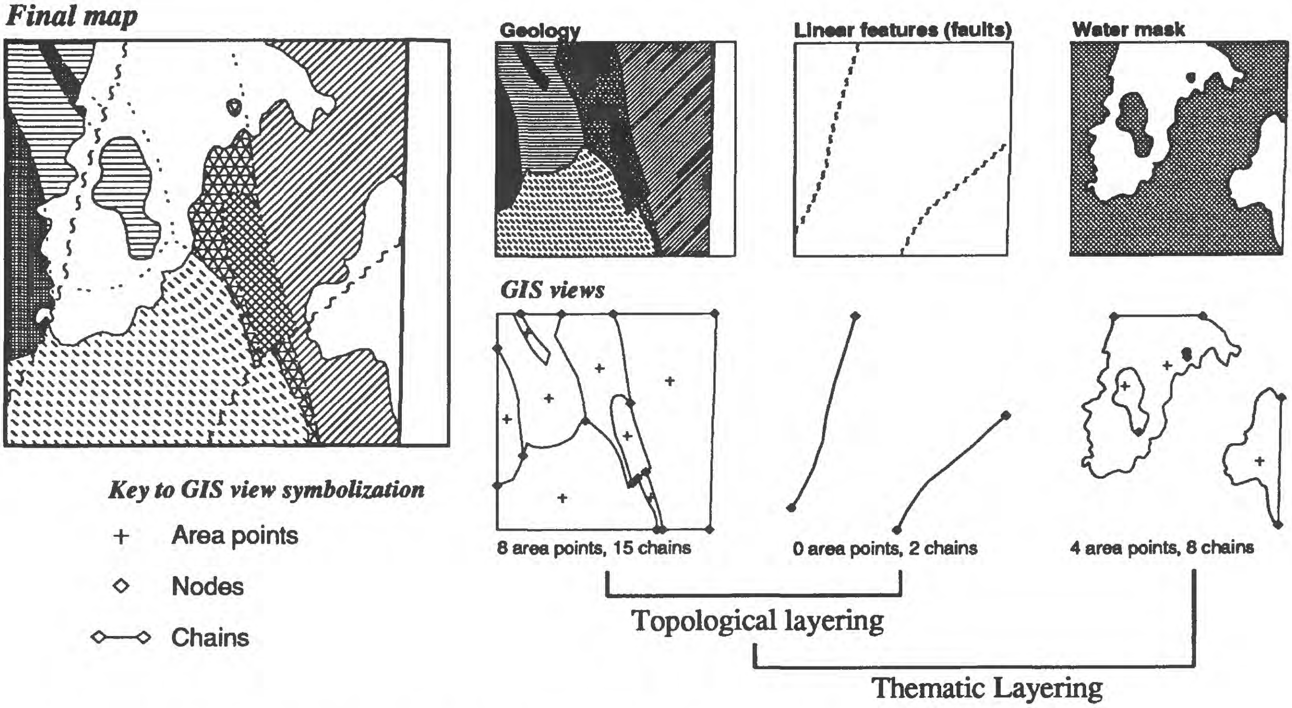



**Figure 3.** Multi-layer approach to capturing and storing geological map information

### Data Management Efficiency

Table 1 clearly demonstrates how the multi-layer approach, highlighted in Figure 3, results in significantly fewer features to manage than the single-layer approach shown in Figure 2. In this example, there are approximately 60% fewer features to manage. This can translate into much more than a 60% savings in terms of capturing and managing this particular map.

**Table 1.** Comparison of the number of features to manage with the single-layer and multi-layer approaches.

| Feature | Single-layer (All) | Multi-layer (geology+faults+lakes) | % fewer features |
|---|---|---|---|
| Area points | 29 | 8 + 0 + 4 = 12 | 59% |
| Chains | 58 | 15 + 2 + 8 = 25 | 57% |

### Layer Updates Simplified

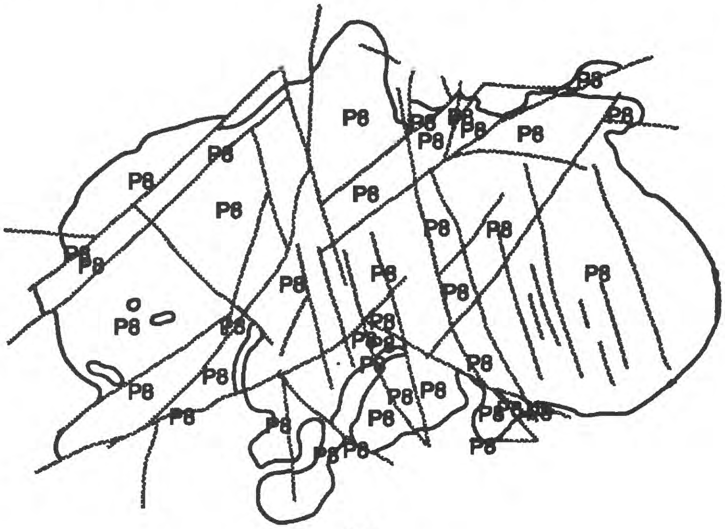
It is quite common for a digital geological map to be used as a starting point for a smaller scale, more generalized geology map. This often requires a change in the hydrographic layer used as shown in Figure 5. Table 2 compares the editing and polygon topology building operations that are required to achieve the integration of a smaller scale hydrographic layer. With the single-layer approach, the change in hydrology involves removal of all shoreline chains and extraneous area points, adding new shoreline chains and area points, and re-building polygon topology. With the multi-layered approach, the change is simply accomplished by plotting the new hydrology layer over the existing geology.

**Table 2.** Summary of changes to a single-layer vs. multi-layer data set required by a change to a smaller scale, more generalized hydrographic layer

| Spatial feature | Operation | Number of operations | |
|---|---|---|---|
| | | Single-layer | Multi-layer |
| Area points | Delete | 5 | 0 |
| | Add | 1 | 0 |
| Chains | Delete | 14 | 0 |
| | Add | 6 | 0 |
| Polygons | Rebuild topology | Yes | No |

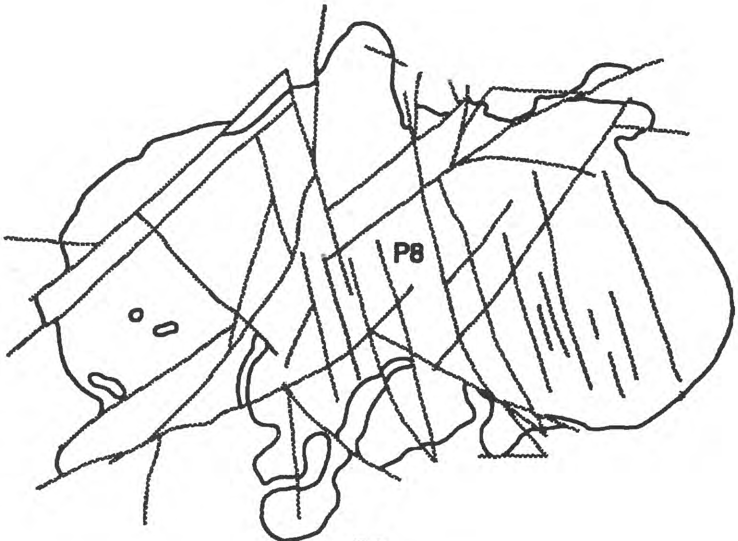
### Impacts on analysis

The multi-layered approach can also have dramatic effects on the efficiency of spatial data analysis. For example, in Figure 6, the user may wish to know the total area of lithological unit V1a. If the data were managed using a single-layer approach, with hydrology and geology on one layer, then the total area of unit V1a will be underestimated




**(a)**

Single-layer approach - all faults and contacts on lithological polygon layer. Each P8 label represents a polyon label. There are many more polygons to manage than the single polygon shown in (b).




**(b)**

Multi-layer approach - contacts and fault-contacts on lithological polygon layer. This is a single polygon extracted from a digital geological map. All of the faults shown are managed as a separate dataset.

**Figure 4.** Example of additional complexity caused by including all faults in same data set as lithological contacts

since the location of the underwater fault is not used to bound polygon. It is virtually impossible to accurately determine the area of geological units from a single-layered data set. Using the multi-layer approach, however, a much better estimation of area can be achieved. If the geology is not well known under lakes, then the lithology can be coded in the descriptive information to reflect this (e.g. N/A). With the multi-layer approach, it will be possible to compute statistics on the basis of known geology. Other types of analysis could be impacted negatively using the single layer approach such as a point-in-polygon analysis (e.g. lithology for a gravity measurement on a lake) or a polygon-

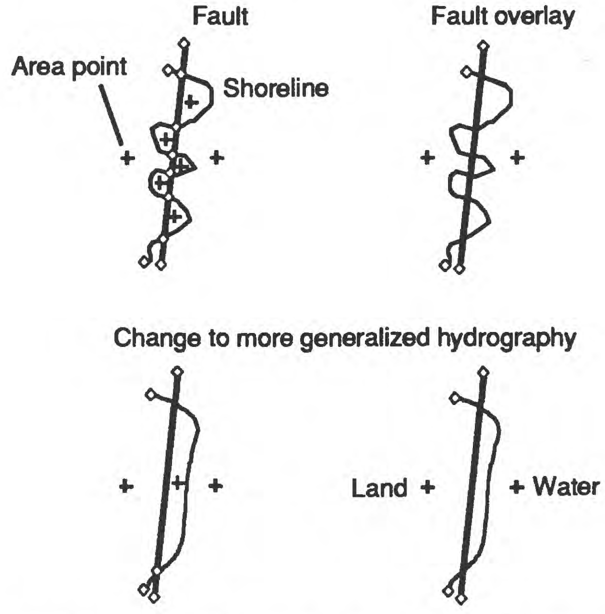



Figure 5. Updating a hydrographic layer in a geological map using single-layer vs. multi-layer approach.

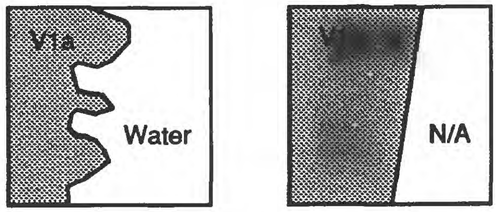



Figure 6. Area estimation or overlay analysis using single-layer vs. multi-layer approach

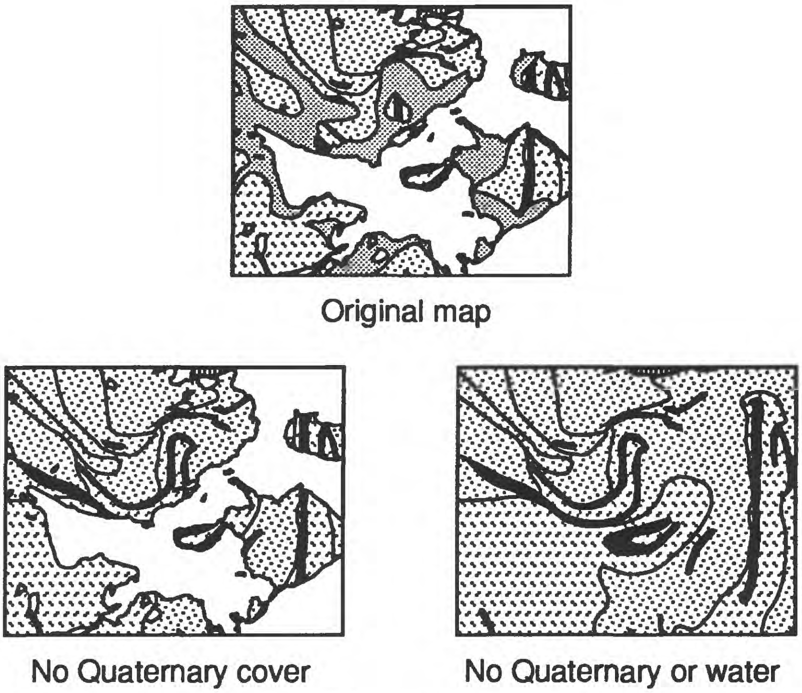



Figure 7. The multi-layer approach provides for more flexible visualization of geological map information. (a) geology as portrayed in original map; (b) same as (a) with Quaternary geology layer removed; (c) same as (b) with lakes removed; (d) geology with patterned fills for Quaternary and lake layers

on-raster analysis (e.g. average total field value for a particular lithology).

### Impacts on Visualization

The multi-layer approach provides for more flexible visualization of geological map information as shown in Figure 7. In this example, there are three polygonal themes: bedrock geology, Quaternary cover, and lakes. This provides the option of displaying any one of the three polygonal themes separately or the opportunity of overlaying the lakes and Quaternary layers with patterned fills such that the underlying bedrock geology is still visible. With patterned fill overlays, a level of confidence in the geological interpretation can be inferred by whether the geology is overlain by Quaternary sediments or water. With a single layer approach, none of these visualizations would be possible.

Digital geological maps are now often integrated with other data (e.g. shaded relief topography or total field magnetics) to highlight interrelationships. In the case of integration with total field magnetics, water and many sediments are magnetically transparent. This means that an integration of geology with magnetics would be best visualized if the bedrock geology was interpreted with the geologist treating lakes and Quaternary sediments as overlays that might be removed for analysis or visualization.

## THE MULTI-LAYER APPROACH: A FEW SIMPLE GUIDELINES

The steps to follow to implement the multi-layer approach are:

1. Identify the polygon layers in your map (topological layering). For example, lakes, lithological units, Quaternary units, metamorphic zones would be *independent* polygon layers.
2. Identify only the layers of lines required to define the polygon layers in step 1. Shorelines for lakes and islands would only be incorporated to define lake polygons. Lithological contacts should not, for example, terminate at a lake shore line creating a dependency between one polygon layer and another. The attribution of the lines would enable the user to distinguish the various "layers" used to define the polygons. Lithological polygons, for example, might be bounded by approximate, defined, assumed, and fault contacts.
3. Digitize and manage each polygon layer separately from each other and especially from other "non-topological" data (lines and points that are not required for creating polygons). For example, if a fault is not a boundary between two different lithologies, then it should not included with lithological contacts.

The goal is to minimize the number of objects the GIS user has to capture and manage which also simplifies updating themes, and enhances the potential for map generalization, analysis, and visualization.

## CONCLUSIONS

An understanding of how polygons are created and stored in a GIS is important in appreciating the benefits of proper data capture and management. The benefits of multi- versus single-layer approach to data management are evident from the smaller number of spatial objects that are required in the multi-layer design, the ease with which changes to individual themes can be made, and positive impacts on analysis and visualization. To implement the multi-layer approach, map features should be layered topologically and thematically. For example, thematic layering ensures that hydrographic features are not on the same layer as geological features. Topological layering ensures that only those features required to define polygons are stored together.

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# Use of Raster Imagery and Vector Data in Support of a Geologic Mapping Project


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## INTRODUCTION

The Illinois State Geological Survey is expanding its geologic mapping program for 7.5-minute quadrangles in the state. The Vincennes quadrangle, started this fiscal year, is one of two study areas chosen to test and/or determine new mapping procedures. One of these new procedures is incorporating multidisciplinary data exchange and GIS methods at the initiation of the mapping process, beginning with the field scientist. This paper discusses the procedures used to produce 1:24,000-scale working maps that combine U.S. Geological Survey (USGS) Digital Raster Graphic (DRG) and Digital Orthophotoquadrangle (DOQ) base data with vector format overlays using Arc/Info software.

At the ISGS, digital data have been utilized in geologic mapping and map production for some time. We maintain an extensive database that includes geologic information from water wells, oil and gas wells and coal, structural and engineering test borings. Logs of water well drillers provide descriptions of unconsolidated materials above bedrock. Logs of borings described by geologists and/or engineers provide quality control. The well data are housed on a VAX 3800 running Oracle RDBMS. Other geologic and cultural vector-based data (such as bedrock geology, bedrock aquifers, Quaternary geology, coal resources, the public land survey grid, municipal boundaries, etc.) are housed in a distributed computing environment consisting of Sun workstations running Solaris and OpenWindows. This computing system supports advanced earth science and mapping applications such as Arc/Info, PCI, and Earthvision, as well as common business applications including WordPerfect, CorelDraw, e-mail, and Netscape Navigator. Most of the data were automated as state-wide coverages at scales of 1:500,000 or 1:250,000 (Greene, 1990).

The ISGS quadrangle mapping project databases are being compiled at 1:24,000, a much larger scale than 1:250,000. Because 1:24,000 is a standard mapping format, geologists are accustomed to using the base map data available on USGS 7.5-minute quadrangle maps. DRG and DOQ raster format data/imagery now provide *digital*, spatially referenced data at the 1:24,000 scale that can be used "as is," or for extraction of base map and derivative data.

The usual method for developing working/field maps has been manual transfer of historical data to USGS 7.5-minute quadrangle maps. Because of scale differences among the many resources (National Resources Conservation Service (NRCS) soil maps, archived field notes of previous research, figures from publications, driller's records, etc.) map compilation has been a time consuming, frequently repetitive process. For the Vincennes geologic mapping project, USGS DRG, DOQ and other raster format data were used: (1) to create a map base by adding points, lines and/or text, on top of the raster image, (2) to plot image and areal data (such as soil associations) in transparent format, (3) to plot vector data with raster data (such as water bodies) extracted from an image after it had been converted to Arc/Info GRID format, (4) to interactively convert selected data to vector format, and (5) to serve as a reference base to which user-scanned data (*e.g.*, NRCS soil association maps) were registered using ground control points identifiable both on the DRG and on the image.

## METHODS

To produce 7.5-minute quadrangle sheets for field verification maps, plotting raster data with point, line, text overlays was a straight-forward incorporation of the Arcplot *image* command in the Arc Macro Language (AML) file that generates the map. For example:

```
/* ..... map parameters
mapextent <pathname>/<filename>        /* map area
mapunits meters                        /* unit of measure
mapposition ll .38 .73                 /* location on the page
mapscale 24000                         /* scale
/*..... map data
image <pathname>/<filename>.tif        /* imagery
arclines <pathname/<filename>          /* lines
pointmarkers <pathname>/<filename> 208/* points
pointtext <pathname>/<filename> <field> /* text
/*..... end
```

In addition to plotting well points and identification codes or soil association groups on the DRGs, these text, point and line data were plotted on DOQ and National Aerial Photography Program (NAPP) raster format imagery. After the map extent and scale are set, the *image* command is issued followed by commands for appropriate vector data. Sequence is important. It is more efficient to write an AML assuming an opaque plotting format because the same file may be produced many ways—on a plotter (opaque or transparent), as a slide (opaque), or on screen (opaque). If text, points, lines, and area fills are plotted first, followed by imagery (or other area fills), the initial data will be overwritten by subsequent data as it plots (note that, in an image, white paper areas are also composed of value coded cells).

An image may be converted to Arc/Info GRID format depending upon the expertise or intentions of the user (*e.g.*, to use analytical tools, to remap colors, or to create a plot) of the user. The standard color map for DRG data is:

| | Color | R | G | B | |
|---|---|---|---|---|---|
| 0 | Black | 0 | 0 | 0 | text, miscellaneous lines |
| 1 | White | 255 | 255 | 255 | background |
| 2 | Blue | 0 | 151 | 164 | water bodies fill |
| 3 | Red | 203 | 0 | 23 | highways, land survey data |
| 4 | Brown | 131 | 66 | 37 | topographic lines |
| 5 | Green | 201 | 234 | 157 | wooded areas |
| 6 | Purple | 137 | 51 | 128 | overprint for disturbed ground |
| 7 | Yellow | 255 | 234 | 0 | non-standard (woodlands, reservations, etc.) |
| 8 | Light Blue | 167 | 226 | 226 | water boundaries, lines or text |
| 9 | Light Red | 255 | 184 | 184 | municipal areas w/landmarks |
| 10 | Light Purple | 218 | 179 | 214 | extension of urban area |
| 11 | Light Grey | 209 | 209 | 209 | provisional urban |
| 12 | Light Brown | 207 | 164 | 142 | complex surface area |

Note that rather than coding the background color (white) as 0, it is 1 and foreground text (black) is zero. This can be inconvenient when plotting a GRID format image. It is a three-step process to interchange the values for black and white cells in the GRID format image use the *con* command. The input grid (in-grid) is grid1. Step 1 opens an output grid (grid2) in which all in-grid cells with a value equal to 1 are set to 999; all other cells retain their original values. In step 2, grid2 becomes the in-grid. All in-grid cells with a value equal to 0 are set to 1 in the output grid (grid3); all other cells retain their input values. Step 3 opens an output grid (grid4) in which all grid3 cells with a value of 999 are set to 0; all other cells retain their in-grid values.

```
out-grid          in-grid values
step 1: grid2 = con ( grid1 == 1, 999, grid1)
step 2: grid3 = con ( grid2 == 0, 1, grid2)
step 3: grid4 = con ( grid3 == 1, 999, grid3)
```

Although a plot that contains solid area fills and imagery must be sent in transparent mode, a transparent effect can be achieved on the monitor for slides or demonstrations by using the Arcplot *image* command:

```
image <pathname>/<filename> TRANSPARENT 0
```

One way to remap colors, in Arc/Info, is to copy the value attribute table (*.vat) to a lookup table (*.lup) using:

```
copyinfo <gridfile>.vat <gridfile>.lup
additem <gridfile>.lup <gridfile>.lup symbol 3 3 i
```

Add the field "symbol" to the *.lup and set all values to zero except for the selected feature (*i.e.*, topographic lines (4) in the following example):

| gridname.vat | | | gridname.lup | | | |
|---|---|---|---|---|---|---|
| Rec# | Value | Count | Rec# | Value | Count | Symbol |
| 1 | 0 | 807783 | 1 | 0 | 807783 | 0 |
| 2 | 1 | 30723108 | 2 | 1 | 30723108 | 0 |
| 3 | 2 | 140292 | 3 | 2 | 140292 | 0 |
| 4 | 3 | 312763 | 4 | 3 | 312763 | 0 |
| 5 | 4 | 379627 | 5 | 4 | 379627 | 10 |
| 6 | 5 | 1401261 | 6 | 5 | 1401261 | 0 |
| 7 | 6 | 326482 | 7 | 6 | 326482 | 0 |
| 8 | 8 | 690254 | 8 | 8 | 690254 | 0 |
| 9 | 9 | 779983 | 9 | 9 | 779983 | 0 |
| 10 | 12 | 753567 | 10 | 12 | 753567 | 0 |

As an alternative, a new colormap file may be created and called when the command to print the grid is issued. For example:

```
gridpaint<pathname>/<filename> # # # <pathname>/<colormap file>
```

Sample Colormap File

| Original file | | | Selected-features file | | | |
|---|---|---|---|---|---|---|
| R | G | B | Value | R | G | B |
| 255 | 255 | 255 | 0 | 255 | 255 | 255 |
| 0 | 0 | 0 | 1 | 255 | 255 | 255 |
| 0 | 151 | 164 | 2 | 255 | 255 | 255 |
| 203 | 0 | 23 | 3 | 255 | 255 | 255 |
| 131 | 66 | 37 | 4 | 0 | 0 | 0 |
| 20 | 234 | 157 | 5 | 255 | 255 | 255 |
| 137 | 51 | 128 | 6 | 255 | 255 | 255 |
| 255 | 2234 | 0 | 7 | 255 | 255 | 255 |
| 167 | 226 | 226 | 8 | 255 | 255 | 255 |
| 255 | 184 | 184 | 9 | 255 | 255 | 255 |
| 218 | 179 | 214 | 10 | 255 | 255 | 255 |
| 209 | 209 | 209 | 11 | 255 | 255 | 255 |
| 207 | 164 | 142 | 12 | 255 | 255 | 255 |

Conversion of lines from raster to vector format may be accomplished either interactively using Arcedit or semi-automatically using Arcscan. It is up to the user and the demands of a specific project to select the most appropriate method. In choosing between ArcScan and Arcedit extraction, the following factors should be considered:

1. the quality of the raster data (there will be varying amounts of hand digitizing even with automatic generation),
2. user experience with the software (Arcscan presents new users with a steep learning curve because its tools are complex and somewhat cryptic),
3. time limitations (Arcscan may be faster than Arcedit).
4. acceptable cartographic quality of both lines and polygons,
5. accuracy (some generalization may occur with Arcscan),
6. the scale at which the data will be used,

Interactive Arcedit extraction requires the usual Arcedit commands plus the *image* command (*i.e.*, image <filename>.tif) which displays the DRG or DOQ. Initially, it may take a little time for the system to format the data, then the *draw* command causes the image to reappear each time the edit screen is refreshed/rescaled. The Arcedit session proceeds with the image as a background. The command *image < off | on >* may be used to turn the image off in order to speed the drawing time during editing, coding, etc. Since USGS DRG (<filename>.tif) files are associated with a world (<filename>.tifw) file, the lines, points, and/or polygons generated are added in "real space" because the image is georeferenced. If using an unreferenced image, ground control points in the image, such as road intersections, can be associated with "known" reference points in the DRG to transform data extracted from scanned imagery.

To start the Arcscan process, the raster image is converted to grid format (in Arc or Arctools). From the Arctools window select *edit tools, file* and *open grid.* The image will draw in false-color. To correct this, or to color only the cells from which vectors are to be generated, select *display, draw env grid,* and then choose an appropriate color format (gray scale, colormap.file, etc.). Select *draw* and the altered image will appear as a screen display that facilitates vectorization of the selected cells. Now select *file coverage new,* enter a name for the file, select *arcs* and then *OK* because a coverage must exist to hold the generated lines.

Vectorization parameters may be established in order to tailor the generation process to suit the particular job requirements. The *tracing environment* menu provides access to all properties that determine line and edit environment characteristics, mouse control, graphics, session termination, etc. Once a set of parameters has been entered, they may be stored in a file (*.vtp) for future use. A few basic metric settings (in the UTM projection) and their definitions might be:

| Parameter | Unit | Definition |
|---|---|---|
| width | 6.5 | maximum size of connected cells that constitute a raster line |
| value | 1 | value ( from the *.vat ) of the line being traced |
| gap | 15 | maximum distance between raster line segments |
| dash | 25 | acceptable spacing of dashes in the raster line to follow |
| hole | 1.5 | ignores gaps in the raster line |
| fan angle | 35 | primary search angle for continuing a vector across a gap |
| second angle | 100 | secondary search angle for continuing a vector across a gap |
| variance | 100 | response to line width variations |

To trace a line, select a starting point on a raster cell by positioning the crosshairs in the edit window and press the *left* mouse button. The arrow that appears does not point along the "line" but simply indicates a general direction that the trace will follow. To change the direction of the arrow press the *middle* mouse button, press the *right* mouse button to proceed with tracing.

## PROCESSES USED AND PRELIMINARY RESULTS

Color-averaging during the rasterization of the Vincennes quadrangle map resulted in a considerable loss of brown cells—the topographic lines. In addition, there are a large number of supplemental contours on the floodplain of the Wabash River. As a result, topographic lines from the DRG were vectorized "on-the-fly" in Arcedit using the color image as a background. Vectorizing, editing, and coding of the lines were accomplished in a single step.

Soils boundaries were extracted from scanned Lawrence County, Illinois, and Knox County, Indiana map sheets using a density slice procedure in PCI. These raster data were converted to vector format using Arcscan and registered using GCPs recognizable on both the DRG and scanned soils imagery. After the data are coded, updated by NRCS personnel, and field verified, they will be incorporated in the national soils inventory being compiled by NRCS.

The Vincennes DRG data were converted to grid format and remapped to produce four base grids that contain various combinations of original color cells whose use depends on the requirements of the final map product. The black and white areas were interchanged so that land survey information could be included to screen dump slides. Wooded areas were removed because they interfered with other colored data included on the soils and parent materials maps. The Wabash river boundary was updated using 1994 imagery. Considerable alteration had occurred in channel contours since the quadrangle map was last updated.

Three sets of 1:12,000-scale quarter-quadrangles were produced for initial field reconnaissance. The base data for the map sets were: 1988 NAPP-1 data, 1994 NAPP-2, and classified color Infrared (CIR). These maps cost $6.90 each to plot on a Hewlett Packard 750C ink jet plotter. Images produced at the 1:24,000-scale by a commercial vendor cost approximately $300.00 per print. The detail and quality of the plots and the "bird's-eye view" of the landscape with topographic and land survey data superimposed have been very helpful to geologists working in the field.

The imagery, plus various combinations of wells, soil groups, parent materials, and other base data have been plotted for presentation maps, field maps, slides, etc. At the completion of the Vincennes mapping project some of these maps and coverages will be written to CD for archiving and future data transfer.

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# Adobe Illustrator for Macintosh—A Cartographic Solution at the Nevada Bureau of Mines and Geology

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The Nevada Bureau of Mines and Geology (NBMG) is a research and public service unit of the University of Nevada and is the state geological survey. Our scientists conduct research and publish reports on mineral resources, engineering geology, environmental geology, hydrogeology, and geologic mapping. Our public service responsibilities include earth science education projects, geologic and geographic information collection and dissemination, development of statewide geographic information systems, maintenance of core and cuttings facilities, rock and mineral collections, aerial photographic imagery, and extensive files on Nevada geoiogy.

## HOW WE USED TO MAKE MAPS

Before 1986, we were scribing all the line work, using wax-backed custom-ordered typography, peeling windows for color separation, and printing several thousand copies of every publication with Williams & Heintz in Washington D.C. In October of 1986, the cartography section of NBMG acquired an IBM AT for our first attempt at digital cartography. Those first years saw our efforts limited to page-size figures. We experimented with GS Draw, Generic Cadd, and finally AutoCad. Our output device was a small format HP pen plotter.

With these first attempts at digital cartography we initiated the struggle that we are still coping with today. Geologists and other authors want their published maps looking as published geologic maps have looked for the last 50 years. Our Director felt our role as a support group within a state survey was to keep our authors happy while at the same time adhering to the highest possible cartographic standards. So we began what has become an ongoing challenge to produce published digital cartography that looks like traditional cartography.

With our first attempts came the immediate recognition that our authors were not pleased with the coarse line patterns available on pen plotters. The stick-like fonts and crude symbols also left them less than impressed. For a few years we used computer-generated linework but supplemented it with stick-on type generated on IBM Composers and Zip-a-Tone type patterns. The fonts available on IBM Composers were proportionally spaced and available in either serif or sans serif faces, regular, bold or italic. The Zip-a-Tone type patterns allowed use of fine screens and detailed patterns. Using this combination of techniques allowed us to produce maps that were as acceptable to our authors as traditionally drafted maps.

## THE FIRST MACINTOSH

In October of 1989, we ordered out first Apple Macintosh and laser printer. From what we had heard, the Macintosh and laser printer would solve many of our problems. We could have fine patterns and nice fonts and eliminate the time-consuming tasks of modifying the computer line work with traditional hand drafting. For graphic software we chose to go with Adobe Illustrator because Adobe had the foresight to provide packages of patterns that included standard US Geologic Survey's topographic and geologic patterns. We now had a functioning system that allowed computer generation of page-size illustrations which had the appearance of traditional published geologic maps.

Our next assignment was to design a process to produce large-format geologic maps that would maintain the author-pleasing traditional appearance. In 1991, we met with Joe Vigil (USGS). He had developed many custom patterns and fonts specifically for geologic applications for the Macintosh, which he shared with us. His opinion was that Arc/Info was a great analytical tool but was weak in cartographic presentation.

ESRI (Environmental Systems Research Institute) also recommended output from Arc/Info to Adobe Illustrator for final cartographic presentation. Another factor that contributed to the Macintosh solution was our final product. At that time we published all of our geologic maps as commercially printed maps. The printers we dealt with had never heard of Arc/Info and were not able to suggest any way to get color separation negatives from Arc/Info. The conclusion at this point was that if we wanted the highest quality graphic output we needed to be communicating in Adobe PostScript, the printing industry standard.

## OUR INITIAL PROCEDURES—DIGITIZING

Our first large-format, full-color printed maps were digitized in Arc/Info. While still in ARC, the line work was cleaned and edited; polygons were built and filled. This file was then exported into Adobe Illustrator. We quickly learned some tricks that made the process easier. Lines should never be exported with a wide line symbol, nor with decorations, because these import as multiple lines in Illustrator. However, if lines are exported with attributes shown as color only, they can be easily separated into layers and formatted in Illustrator. For example, solid contacts could be red, dashed contacts blue, dotted contacts green, etc. When opened in Illustrator a layer for each symbol is created. Select all red lines, drag to the "solid contact" layer, and format all at one time by designating format specifications.

The cartographic finishing was all done in Illustrator. Marginal type, large text blocks, cross sections, index maps, scales, correlation charts, lists of symbols, etc. are all easily prepared in Illustrator with the click-and-drag ease of a graphics design program. The final output was color separation negatives generated by a service bureau directly from the Illustrator files. The printer used these negatives to print the final maps.

The shortcoming with this procedure was the digitizing. At NBMG, digitizing is done by student employees. Student employees by their very nature are temporary and lack a depth of experience. Since our primary task is turning author's field sketches into printed maps, a degree of geologic and cartographic experience is required to make the decisions that are necessary to interpret these sketches. We tried explaining to the students about the cartographic representation of geologic contacts and faults. Often the students did not have the background or interest to incorporate this theory into their digitizing. When one student would grasp the implications and start producing acceptable geologic line work, he would graduate and leave. Because the students do not work full time, digitizing is also exceedingly slow. Many repetitions of author proofing and revision were necessary. Budget constraints eliminated the possibility of hiring permanent digitizing employees.

## OUR SECOND ATTEMPT—VECTORIZING

Next we tried scanning the author's field maps and having them vectorized. We published several geologic maps using this procedure. This approach eliminated the use of low-priced, inexperienced employees to perform the labor-intensive job of digitizing. The vectorized files were cleaned and edited in Illustrator by experienced geologic cartographers. However, the process is time-consuming and as is true everywhere, there was always pressure to produce the maps with the same quality but faster. Being a relatively small state survey with an extremely limited budget, owning our own large-format scanner and vectorization software was not a viable option. That meant that we were at the mercy of the scheduling of the vendor providing the vectorized files. At times, weeks were wasted waiting for delivery of files.

## OUR CURRENT PROCEDURES—THE MACINTOSH SOLUTION

We worked to develop a procedure that did not depend upon circumstances beyond our control. We are currently dividing each map into small segments and scanning them in-house on a page-sized scanner. We place 2.5′ quad tics on our 7.5′ quads and 7.5′ quad tics on our 30′×60′ quads. We generate a grid of these tics in Arc/Info and export it to Illustrator. The tic grid from Arc/Info gives us a scale-true grid with which to register the small segments. The small segments also allow us to use high resolution scans and yet keep each file to a manageable size. Illustrator has the capability of rectifying any distortion in the scan to match the true tic grid from Arc/Info. We generate transparent scans so that they can be overlapped as they are placed in Illustrator This insures smooth transitions from one small segment scan to the adjacent scan.

Once a small segment scan is placed in Illustrator, the geologic linework is drawn. Illustrator provides great flexibility in its curve drawing capabilities. On tight, curvy contacts, you can use the freehand tool. This produces lines very much like a scriber or a technical pen. On gentle, flowing curves, the pen tool is recommended. This produces smooth, generalized curves, similar to those drawn with a flexible curve or French curve. This type of line (e.g., long, regional dashed faults) was always very difficult to digitize smoothly enough to please our authors. To make tracing these curves even easier, we have a pencil-like stylus that feels and handles like a traditional drafting instrument.

Since we began capturing lines in Illustrator with the curve tools, we have received many favorable comments from geologists. Since the tracing of the scan can be done at any level of magnification, it is also much easier to exactly duplicate the author's positioning and conformation of lines. This technique is also extremely quick. When we used student digitizers, most 7.5′ quads took an average of two months to generate acceptable line work. The current procedure of capturing lines from a 7.5′ quad takes 8 to 12 hours. Our authors also spend significantly fewer hours of their time with repetitive proofing and fine tuning of digitized lines.

After the lines are generated, they are output to a HP DesignJet 755CM and proofed by both a cartographer and the author. Lines are then separated, by type, into different layers in Illustrator. These lines are then exported to Arc/Info for creation of polygons. Currently we use Deneba's Canvas as a translation bridge between Illustrator and DXF. The resulting file can then be imported into Arc/Info. Each layer plus the border is exported separately. As they are translated into Arc/Info a "select all" can help to attribute all lines of a particular type very easily and quickly. As the layers are converted into coverages and globally attributed, they are appended together. After some minor editing, polygons are then built. Printing colors are selected following USGS suggestions for geologic units by age. A shadeset is created using these selected colors. The filled polygons are then exported back to Illustrator. In the current version of Arc/Info (ver. 7.0.4), we use EPS export rather than Illustrator export. This change has eliminated the earlier problem of "tie-lines" within the polygons that had to be mitigated in Illustrator.

In Illustrator, each layer is then formatted, basically following the USGS "Cartographic and Digital Standard for Geologic Map Information" (Open-File Report 95–525). After all formatting is finished, filled polygons from Arc/Info are merged with the file and marginal information is added. After author's modifications are addressed, the file is ready for our vendor to create color separation printing negatives. If modifications have been made by the author and if the geologic map is to be released as a digital product, then the Illustrator layers are again exported to Arc/Info. Again the layers are globally attributed and appended together into a single coverage with attributes.

## FUTURE PROCEDURES

These techniques evolve quickly. We have many aspects that need improvement and we are currently working on better solutions to most of the problems. With developing computer technology and opportunities for sharing such as the AASG-USGS Workshop on Digital Mapping Techniques, we can continue to progress toward the better-faster-cheaper, while maintaining high quality geologic maps. One avenue we are currently investigating is Avenza's MAPublisher, a bridge between Arc/Info and Illustrator. As a plug-in that allows Illustrator to retain GIS functionality, MAPublisher should make the transition from geologist's sketch to published map even more efficient.

## NBMG PRODUCTS

Last year it was decided that Nevada needed to print more geologic maps than our budget could support . We have adopted a couple of responses to this situation. Most of our geologic maps are still traditionally printed in full color. Some, especially those of more limited interest, are printed in black and white. These black and white printed maps go through all the same steps for production as the full-color maps. After printing in black and white, custom plotted full-color copies are available as a "on-demand" publication. Some, especially those with a very limited audience, are released only as "on-demand" publications. Nearly all of our geologic maps published in the last year are available as digital files. These are released as Arc/Info coverages, as Arc/Info .e00 export files, and as Portable Document Format (PDF) files. Currently our digital Arc/Info releases do not carry marginal information, topographic base information, nor point symbol notation. The PDF files contain all components of the published map with the exception of the topographic base, which at NBMG is still composited photographically by the printer.

## NBMG SERVICES

During the last few years, we have been contacted by individuals and organizations desiring a high quality, traditional, cartographic publication. They have line work in Arc/Info and are not satisfied with the quality of hardcopy output from that software. Because of our experience in this aspect of geologic cartography, we have assisted others by taking their Arc/Info coverages and reformatting them in Illustrator, replacing type and symbols, designing layouts and creating geologic publications of traditional appearance. Our most ambitious undertaking to date has been the formatting of the Rhode Island State Geologic Map. We are also currently working on two projects of reformatting Arc/Info files as Illustrator publications for the USGS. We are still fulfilling that instruction from our Director of many years ago, "...make those geologists happy."

## APPENDIX A

### Cartographic Section's Hardware and Software

Computer, Purchase Date, Hard Drive (in mb)/Memory (in mb):

- Macintosh
  - Quadra 900 (with PowerPro Accelerator), 11–91, 160/54
  - Quadra 800 (with PowerPro Accelerator), 2–93, 1430/40 (used mostly for desktop publishing)
  - Centris 650 (with PowerPro Accelerator), 8–93, 230/90
  - PowerMac 7100, 7–95, 680/80
  - PowerMac 7500, 10–95, 518/114
- Sun
  - Sun SPARC Station, 9–92. 1000/32

Output devices:

- HP DesignJet 755CM large format ink jet plotter
- Tektronix Phaser III phase-change tabloid printer
- PrePRESS VT1200, tabloid, 1200 dpi laser printer
- LaserWriter Pro 630, page-size 600 dpi laser printer
- LaserWriter II NT, page-size 300 dpi laser printer

Input devices:

- GTCO 24x36 digitizing tablet
- Agfa Argus II color page-size scanner
- Canon page-size scanner
- Datacopy 730 GS page-size scanner
- Wacom ArtZ II Tablet with Stylus

# Digital Map Production at the Idaho Geological Survey

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## ABSTRACT

The Idaho Geological Survey collects and publishes new geologic mapping data digitally. The survey's Digital Mapping and Information Lab digitizes geologic maps using large format digitizing tablets and Pentium PCs loaded with AutoCAD r12 and CADmappr, a third party geologic mapping utility. The digitizing process is controlled and semi-automated by CADmappr. Digitizing proceeds in a systematic manner starting with the contacts, then the dangling faults, then the geologic symbols, and finally the map units are labeled including label points for GIS export. When complete, a copy of this database version of the map is reduced to publication scale from the Idaho State Plane Coordinates in which it was digitized. Legend items such as the correlation chart, any cross sections, and the unit descriptions are then imported for layout. Once layout is complete the map is plotted for author and mapping lab review. Revisions to the map are made after author, technical, and editor reviews. Changes in the geology are made in the database. Postscript files are generated from the final map and used to produce press-ready negatives on an image setter. Metadata is collected during the map-making process. Geologic map themes digitized in CADmappr/ AutoCAD can be exported as Arc/Info E00 files.

## INTRODUCTION

The Idaho Geological Survey (IGS) at the University of Idaho serves the state of Idaho through geologic research, and is also charged with collecting and distributing geologic data. The survey's Digital Mapping and Information Lab (DMI) produces all new geologic mapping digitally. Mapping can be released as paper maps and in a Geographic Information System (GIS) format. The purpose of this paper is to show how geologic mapping data at IGS is captured, published, and released for GIS.

## PRODUCTS

IGS publishes two categories of geologic map products: Technical Reports (95%) and Geologic Map Series full-color press-run maps (5%). Technical Report maps include new 1:24,000 scale mapping and compilations of existing geology. Most new mapping is released as black and white maps reproduced xerographically. Future compilations will be published at a scale of 1:100,000 as plot-on-demand color maps. All published geology is available in digital format as GIS (Arc/Info) coverages or Computer Aided Drafting (CAD) drawings.

## SOFTWARE

IGS began using CAD software in 1989 to draft geologic mapping. Generic CADD, a low-end CAD package, was originally used. Experience gained with this software proved that geologic maps could be produced and published digitally. But it also showed that a more robust software was needed to improve publication quality and GIS output.

Map data capture is now done entirely in AutoCAD r12, a popular and powerful CAD software. CADmappr, a third party AutoCAD geologic mapping utility, permits IGS to capture geologic map data, publish, and export to GIS. By taking advantage of AutoCAD's editing and programming features, CADmappr, with its customized additions, permits the followings mapping functions:

- Multi-point transformation using latitude and longitude points
- Storing each contact with its topologic information

- Digitizing contacts only once
- Digitizing, labeling, and editing are semi-automated with map unit list (lookup table)
- Digitizing in State Plain coordinate system or UTM
- Projecting between coordinate systems
- Rubber Sheeting
- Importing or exporting point data in latitude/longitude or projected coordinates
- Attaching map identifiers to any and all map entities (used to link to metadata)
- Postscript level 2 output (color fills, line work)
- Exporting Arc/Info E00 files
- Menu driven symbols placement, legend layout tools, labeling, map compilation tools

## HARDWARE

The Idaho Geological Survey's mapping lab is primarily PC based. AutoCAD is run in DOS on Pentium machines with 48-64 megs of RAM. Files are served locally to the digitizing stations with a Windows NT server. Digitizing is done on two large format CalComp tablets. The survey has an eight year old Hewlett-Packard Draft-Master pen plotter which is used to plot line work for visual inspection. HP InkJet plotters are available through the campus network and are used for color plots and plot-on-demand publications. Unix based Arc/Info is accessed at one of the university labs or via x-terminal emulation software on one of the lab's PCs. The long-term direction of the lab is to move gradually over to Windows NT-based systems.

## DIGITAL MAP PRODUCTION

### Author Responsibilities

The map author is required to submit the following with every new map:

- Geologic map neatly drafted in fine pencil or ink on Mylar, keyed to stable base map
- A hand colored copy of the geologic maps (preferably colored by the author)
- A description of map units, credits, title, authors, field dates, references in WordPerfect
- A sketch of the correlation of map units chart
- Cross section(s)
- The name(s) of technical reviewer(s)

The mapping lab is responsible for digitizing the geology, adding the necessary map components, performing layout tasks, and finally seeing the map through to publication. The lab collects and maintains metadata for each geology data set. The lab also maintains all generated geologic map data.

### Digitizing

Geology is either digitized by hand on a high-accuracy digitizing tablet or scanned by high-resolution scanner with subsequent data conversion and extraction. IGS digitizes by tablet most new maps because this process can be accomplished entirely in-house. CADmappr semi-automates the digitizing process through a series of dialog box-driven routines. Digitizing proceeds unit-by-unit. Only one copy of each contacts or fault-contact is digitized. Remaining dangling faults are then added. After that, geologic attitudes (strike and dip, foliation, etc..) and the other geologic symbols are digitized. Finally map unit labels are added including label points (points necessary for topology in a GIS.) Once digitizing is complete, a unit-by-unit visual on-screen check is done. The map is plotted on Mylar for further line work inspection. Lines should look drawn, not digitized. Necessary additions and changes are then made. The digitizing of this database version of the map, takes place in Idaho State Plane Coordinates. Key metadata information is noted for each work session. The IGS map publication process is outlined in Figure 1.

### Map Layout

A copy of the database map is reduced to final publication size. Legend building proceeds in this scaled, publication copy. This step prevents the database from being corrupted during layout and allows the cartographer to work in the more familiar units of points and inches. Much of the layout process is accomplished via menu driven utilities. Importing text, laying out unit boxes, and designing correlation charts are all semi-automated procedures. Currently, unit descriptions, references, and other text are edited in WordPerfect and then imported into AutoCAD in columns as ASCII text. Parts of the legend can be imported from a catalog of template drawings compiled over the years.

Each section of the legend is placed in a different CAD layer making the map more editable. Postscript configuration output is based on these layer names. Final publication line widths, line grey scales, and line join types are also assigned by layer. When the legend is complete the map is plotted again on Mylar, temporarily overlaid on a film-positive base map, and Xeroxed for review by the mapping lab and the author.

### Publication

The author is allowed one chance at this stage of production to make minor content changes to the map. This is

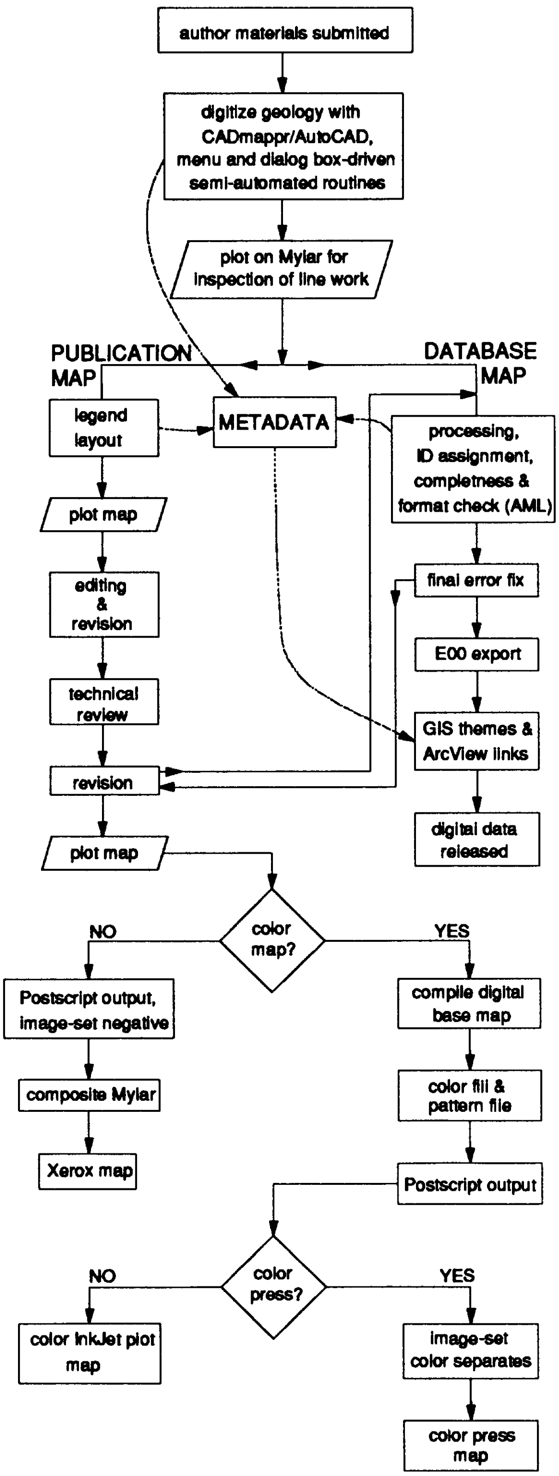


**Figure 1.** Flowchart showing geologic map production.

followed by a technical review and an IGS editor review. Changes to the geology must be made to the database version of the map. The revised geology is then re-inserted into the publication map. Changes to the legend text are done in either CAD or WordPerfect, depending on the amount of revision. When the changes are completed the map is ready to be configured for publication.

Postscript is a programming language used to make publication-ready output files. CADmappr includes a Postscript output utility which takes advantage of three configuration files: line work, fill colors, and patterns. A default Postscript configuration file for line work is generated by CADmappr and modified in an ASCII editor. Then a Postscript version of the map is plotted on an InkJet device. This map provides a pre-publication test for line widths, fonts and font sizes, and omissions. When ready for press, a full black Postscript file of the map is sent to a contractor with an image setter and a direct negative is made. The final IGS product is a frosted Mylar composite of the image-set geologic map and the screened USGS base map.

Although Technical Reports are currently released in Xeroxed black and white, they can also be done as one-off color plots. A RGB look-up table of geologic unit colors (polygons) is created using, as a guide, the *Colors and Patterns Commonly Used in U.S. Geological Survey Publications* found in *Cartographic and Digital Standard for Geologic Map Information* (U.S. Geological Survey, 1995). USGS Digital Line Graph data (DLG) is added and a full-color InkJet version of each Technical Report is plotted.

#### The Future of Technical Reports

Digital Raster Graphics (DRG), a scanned base map product, are now available for the entire state of Idaho. IGS hopes to combine these DRG maps with full-color Postscript to publish new Technical Reports as on-demand plotted maps. Currently with new utility software IGS can export the CAD-finished geology as Encapsulated Postscript files (EPS). The EPS files can then be placed in publication layout programs like FreeHand or Adobe Illustrator. These softwares offer improved text and bitmap layout tools and "speak in the language" of publication.

### Color Publication

Because of its limited budget, IGS sends few maps to a color press. Except for the base map, color press maps follow most of the production steps discussed above.

IGS is currently working on a map that will go to a color press in the fall of 1997 which serves as an example of how we compile the base map for publication. The base map for this product is constructed from tiled 1:100,000 scale DLGs (transportation, streams, hypsography), a clipped section of the Idaho Public Land Survey System

(PLSS) file, and the Idaho Geographic Names Information System (GNIS) file.

DLG data is run through an Arc/Info AML (Arc Macro Language) routine to convert the vector data to AutoCAD Drawing Interchange File (DXF) format and separate it into CAD layers. These DLG tiles are projected, edge-matched, and checked for completeness in AutoCAD. PLSS data is handled much the same way. The GNIS is a listing of place names and their attribute data including a latitude/longitude location. A specially written AutoCAD routine uses a subset of the GNIS and semi-automates the placement, layering, color assignment, font assignment, and rotation of each geographic label.

To add color to the map, a RGB table is created as with Technical Reports. Using this RGB table and the Postscript configuration file, EPS file(s) are created and brought into FreeHand where final text layout is done. When the map is ready for publication, 5 press-ready negatives (cyan, magenta, yellow, black, and a Pantone base map color) are generated from Postscript file(s) on a large format image setter.

### GIS Export

All geologic map data digitized in CADmappr can be exported to an Arc/Info E00 file. Many sub-themes can be generated from one CAD geologic database. The usual coverages exported include rocks (lines and polygons of the geology), faults, dikes, fold axis, and three categories of symbols (point data).

A menu-driven series of AMLs facilitates the processing of the geologic data in Arc. Imported data is checked for dangle errors, tables are joined, extra label points are eliminated, and coverages are built.

Data sets also include an ArcView project file which displays all themes and links other relevant databases, including metadata, to the geology.

Data sets are officially released when the map is complete, all metadata is entered, and the data is listed in the IGS *List of Publications*. Data is delivered on CD ROM.

### Metadata

IGS collects metadata (i.e., data about the data,) on new geospatial products using the *Content Standards for Digital Geospatial Metadata* (Federal Geographic Data Committee, 1994) as a guide. Each contact, fault, dike, and symbol receives a metadata id tag. This identifier relates the source of the geology to each of its map entities. For example, in a geologic map compilation there may be several sources of geologic data. All the spatial geologic data related to one source will receive the same tag. This tag exports to a "reference _id" field within Arc/Info and can easily be linked to the relevant metadata for that source: scale, digitizing techniques used, author, title, etc.. Geologic map unit descriptions are also included as a database. With the help of geologists, descriptions are summarized and sorted into key fields and linked to the spatial data via the polygon label point.

Currently all metadata is collected in dBASE files to make linking and sorting possible. Metadata "***source***" fields double as an inventory of IGS digital geologic maps thus serving an in-house data tracking function.

Geologic mapping metadata for several data sets has already been submitted to the Idaho GIS Metadata Server.

## CONCLUSION Q & A

*Why does IGS use CAD and not GIS software?*

The answer is part history and part practicality. IGS uses both types of software and is using more of ArcView to test completed coverages and display linked metadata. But the bulk of the work day is spent in AutoCAD. Digitizing, editing, and layout are all more efficiently done in CAD when compared to many GIS packages. CAD also runs very fast on less expensive PC machines.

*What are some of the drawbacks to the IGS approach to digital map capture and publication?*

By necessity many routines have been written to digitize, edit, publish, and export to GIS. Many different softwares must be learned to make it all work. This makes the system both flexible and cumbersome. The learning curve for training is long. CADmappr has no documentation outside of what the IGS mapping lab has developed internally.

*How long does it take to train someone at IGS to use this system?*

This depends on the background and interests of the trainee. On average it take 3 weeks to train someone to digitize well, and another 3 months of supervision before they are ready to complete an entire map for publication.

*How long does a geologic map take to digitize and layout for publication?*

For a skilled digital cartographer a complex 7.5 minute (1:24,000 scale) map of 300-400 polygons takes 4-6 days to digitize and another day to build the complete legend.

# Digital Mapping Techniques Employed by the California Division of Mines and Geology

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## ABSTRACT

The California Department of Conservation's Division of Mines and Geology (DMG) uses three Geographic Information Systems (GIS) platforms for a variety of applications. Arc/Info is used for digitizing basic data such as geologic, landslide, and fault maps. MAPINFO is used for planimetric map applications and INTERGRAPH is used for generation of seismic hazards zones maps that integrate surficial and subsurface data . DMG map digitization activities have evolved from a close cooperation with the U.S. Geological Survey (USGS). DMG uses Sun workstations running Arc/Info software. The ALACARTE interface developed by the USGS is used to simplify digitization. DMG employs students to do geologic map digitization under the supervision of staff geologists. A typical 7.5-minute quadrangle takes about 100±40 hours of student operator time and about 40 hours of geologist time for supervision and review. The labor cost for a typical 7.5-minute quadrangle is about $2300±600. Digitizing a 1:100,000 quadrangle is accomplished by using the largest available source data, preferably 1:24,000 at a total cost of about $143,000. DMG digitizes geologic maps at a scale of 1:24,000 and publishes regional maps at 1:100,000 scale. The reasons for this are: 1) hazards maps prepared by DMG for regulatory and planning purposes are 1:24,000 scale and require basic geologic map data at the same scale; 2) 1:24,000 is the most commonly requested map scale by geologic map users in California; 3) most of the densely populated urban areas in California are geologically complex that require 1:24,000 scale to portray the necessary detail. In the absence of geologic data at appropriately large scale, small scale maps are enlarged for application for which they were never intended. DMG has not released digital geologic maps for general distribution pending development of polices and procedures for release of digital products. Although most of our users still need paper geologic maps, DMG recognizes the future is in digital geologic maps.

## INTRODUCTION

The California Department of Conservation's Division of Mines and Geology (DMG) is employing three Geographic Information Systems (GIS) to produce digital maps for a variety of applications. Digital maps include geologic, landslide, fault, geologic hazards, mineral resource evaluation and probabilistic ground response maps. Geologic, fault, and landslide maps provide basic data used in the preparation of regulatory maps (Earthquake Fault Zone Maps; Seismic Hazards Zone Maps) and for probabilistic analysis to produce site response maps that serve as a basis for amendments to building codes and establishing earthquake insurance rates. Some of these maps can be accessed on the Department of Conservation's website (http://www.consrv.ca.gov/dmg/) and more will be added in the near future. The GIS platforms employed by DMG are:

**ARC/INFO** used for digitization of geologic maps, fault maps, and landslide maps;

**MAPINFO** used for planimetric map applications such as map indexes, some probabilistic site response maps, mine location maps, mineral commodity maps, and fault maps;

**INTERGRAPH** used for preparation of online Seismic Hazards Zones Maps that integrate and analyze geologic map data converted from Arc/Info, subsurface data, and digital elevation models to show areas prone to ground failure during earthquakes.

This paper discusses the digital mapping techniques used by DMG's Regional Geologic Mapping Project to prepare digital geologic maps using Arc/Info. The objective of digital geologic mapping by DMG is to produce a digital database of geologic mapping in California that will be readily available to earth scientists, engineers, planners, decision-makers, and the public. The Regional Geologic Mapping group is in the process of converting from the production of analog geologic maps to digital maps. Geologic maps presently sold by DMG are analog produced by conventional techniques. Although digital geologic maps have been prepared and have been used internally and released informally, the policies and procedures for distribution of digital geologic maps have not been established.

## OVERVIEW OF THE EVOLUTION OF DMG DIGITIZATION ACTIVITIES AND FACILITIES

The first use of digital technology in geologic mapping by DMG was in 1984. It was used to contract for the scanning of a 1:250,000 scale geologic map to prepare printing plates instead of conventional scribing techniques. This attempt failed because the contractor did not have any knowledge of geologic maps and DMG staff did not know how to prepare the map for scanning. After a year delay, the map was scribed and published using traditional techniques.

DMG geologic map digitization activities have evolved as a result of close cooperation with the U.S. Geological Survey (USGS). In 1990, DMG began a cooperative geologic mapping project in southern California with the USGS, the Southern California Areal Mapping Project (SCAMP) of the USGS. A GIS laboratory supported by both agencies was established at the University of California campus at Riverside. In 1993 a workstation was set up in DMG offices in Sacramento. Since 1995, DMG geologists have been digitizing geologic maps in USGS offices in Menlo Park, California on a part time basis. DMG and the USGS are establishing a cooperative geologic mapping program in the San Francisco Bay area (BAYMAP) similar to the southern California project. DMG is now setting up additional workstations in Sacramento and in its San Francisco Regional office.

Preliminary digital versions of the Geologic Map of California (Jennings, 1977) and the Fault Activity Map of California (Jennings, 1994), both at 1:750,000 scale have been produced by the USGS in cooperation with CDMG. In 1991 Gary Raines of the USGS proposed digitizing the Geologic Map of California for use in the mineral resource analysis of the western United States. He was provided with stable base materials with the understanding that the digital map would be for internal USGS use and the ownership and distribution rights for the map would remain with DMG. The digitization was done by a private contractor. DMG is now revising and editing the map. DMG has been providing the files to users who have an immediate need for them provided they agree not to distribute the files. Michael Machette of USGS digitized Quaternary faults from a preliminary version of the Fault Activity Map of California for use in preparation of a Quaternary fault map of the United States. DMG staff updated the files after the final version of the Fault Activity Map of California and Adjacent areas was published in 1994. A digital database of Quaternary faults in California will be released soon.

DMG uses Sun workstations running UNIX-based Arc/Info software to digitize geologic maps. DMG uses the ALACARTE interface developed by the USGS (Fitzgibbon and Wentworth, 1991). ALACARTE, a program specific to digitizing geologic maps running on top of Arc/Info, enables an operator without an extensive knowledge of UNIX or Arc/Info to digitize geologic maps. ALACARTE provides line types and symbol sets commonly used for geologic maps and greatly simplifies the placement and orientation of geologic symbols.

Although some digitization is done by staff geologists, most of it is done by students under the direct supervision by staff geologists. We have had success employing students majoring in geology who have training in GIS. Geology students who have training in GIS (usually taught in geography classes) are hard to find but they are becoming more common. We have had success with students without GIS training but they require more supervision, thus raising the costs because of increased staff time on the project. DMG has initiated interagency agreements with both the California State University and the University of California systems to provide students to do digitization. This has proved to be cost effective for DMG as well as providing employment opportunities and on-the-job training for students.

## METHODOLOGY

The goal of DMG is to assemble a statewide database of geologic mapping at a scale of 1:24,000. Of the 2,832 7.5-minute quadrangles in California, an estimated 2,257 have not been mapped. Obviously, this long-term goal is a formidable challenge. A rationale for this approach is discussed in the Data Capture Standards section of the paper. Historically, the publication scale for regional geologic maps in California has been 1:250,000. The complexity of the geology in many areas and the availability of the base maps at 1:100,000 scale prompted the switch to a larger scale.

In the past, DMG compiled an analog version of a 1:100,000 scale geologic map prior to digitizing. This can take one to three years depending on how much original mapping is conducted and the geologic complexity of the map area. As our digitizing capability has improved, we are beginning to move away from this approach. A major task that still must be completed, however, is the preparation of a stratigraphic framework for each 1:100,000 quadrangle. The complex geology of California poses special problems for regional syntheses. A typical 1:100,000 scale quadrangle in California has 80 to 120 geologic units and some may have even more. The state has been divided into 11 provinces based on geology and physiography. Most 1:000,000 scale quadrangles cover more than one province, so parallel stratigraphic frameworks must be established. Some map units are common among adjacent provinces but many are not. In particular, stratigraphic columns on either side of major strike slip faults are different. For example, our compilation of the Monterey 100K quadrangle has two explanations, describing units on either side of the San Andreas fault. A stratigraphic framework for a 1:100,000 quadrangle is prepared, reviewed, and accepted before digitization of the 1:24,000 quadrangles that make up the regional map. The preparation of the framework is critical to producing a seamless 1:100,000 geologic map mosaicked from thirty-two 7.5′ quadrangles.

The DMG procedure in digitizing a 1:24,000-scale geologic map is as follows:

1. Select the geologic maps at the largest scale available, preferably at 1:24,000 scale and on stable base material. Assuming the map is a suitable scale, quality and ready for digitization, a geologist prepares an explanation for the map units that is consistent with the previously prepared stratigraphic framework for the 1:100,000 quadrangle. The 1:24,000-scale maps often must be generalized before digitization as part of a 1:100,000-scale quadrangle. The geologist prepares a guide showing lines to be digitized. If major changes are made, it may be necessary to compile a new version of the map.
2. Digitize the line work. We use both hand digitizing and scanning techniques depending on the nature of the original maps. The advantage of hand digitizing is that the operator has control over the data entry. The disadvantage of hand digitizing is that data entry is time consuming and labor-intensive. Scanning of a typical geologic map takes only minutes but the resulting raster image must be georeferenced and vectorized. A disadvantage is that a scanned image must be edited which can be as time-consuming as hand digitizing. Since our access to scanners is limited and our operators seem to prefer hand digitizing, we rely mainly on hand digitizing of 1:24,000 scale geologic maps. We digitize faults and geologic contacts on the same layer in the GIS. Digitizing the linework on a moderately complex 7.5-minute quadrangle takes 16 to 32 working hours.
3. Attribute. Attributing consists of tagging each polygon with a geologic map symbol usually requires 8 to 16 working hours.
4. Structure layer. Structural symbols (strike and dip; foliations etc.) and attributing faults (e.g., thrusts). This usually requires 16 to 32 hours.
5. Edgematch. The map is matched with the adjacent quadrangles and mismatches are corrected. If an analog version of the 1:100,000 quadrangle covering the larger scale map was prepared, it is used as a guide to fix mismatches. If there is no analog map, a geologist usually has to rectify the problem. The time required for this step is highly variable.
6. Review and edit. A check plot of the map is prepared for review and reviewed by a geologist. This step requires 8 to 24 hours. The resulting edits are usually made in a matter of hours.

The times above are approximate. Operator's time for a typical 7.5-minute quadrangle is about 100 ±40 hours. Geologist's time for supervision and review is about 40 hours.

## COSTS FOR THIS METHODOLOGY

A Sun workstation ranges from about $12,000 to over $30,000 and the Arc/Info license costs about $17,000. Scanners cost about $ 30,000 to $40,000 and a 48 × 60 inch digitizing tablet costs about $9,500. A plotter suitable for plotting geologic maps ranges from about $7,000 to over $10,000. Supplies cost about $1,000 to $3,000 per year.

Compilation of an analog version of the 1:100,000 scale geologic map is about $100,000 per year. At one to three years, such a compilation is often not affordable despite its usefulness. If an analog version of the map is not prepared, a geologist still must prepare a stratigraphic framework (i.e., map explanation) that will require three months or about $25,000. Operators (students) cost an average of $10 per hour and staff geologists average about $32 per hour. Therefore, an average cost for this method is $1,000 for the operator and $1,280 for the geologist. For planning purposes the labor cost for digitizing a 7.5-minute quadrangle is $2,300±$600. Using the estimate of $2,300, the cost of digitizing a 1:100,000 quadrangle (32 7.5-minute quadrangles) is $73,600±$19,200. This does not include equipment cost, support staff, and overhead which will substantially increase the ultimate cost.

Summary of labor costs for digitizing a 7.5-minute quadrangle:

| | | |
|---|---|---|
| Operator (student; 100 hours @ $10/hour) | | $1,000 |
| Geologist (40 hours @ $32/hour) | | $1,280 |
| | Total | $2,280 |

Costs of digitizing a 1:100,000 quadrangle:

| | | |
|---|---|---|
| Preparation of stratigraphic framework | | $25,000 |
| Digitization of 32 7.5′ quads @ $2,280 each | | $72,960 |
| Support staff | | $12,000 |
| | Subtotal | $109,960 |
| Overhead (30%) | | $32,988 |
| | Total | $142,948 |

## DATA CAPTURE STANDARDS

DMG digitizes geologic maps at a scale of 1:24,000 and publishes regional maps at 1:100,000 scale. The reasons for this are: 1) hazards maps prepared by DMG for regulatory and planning purposes are 1:24,000 scale and require basic geologic map data at the same scale; 2) 1:24,000 is the most commonly requested map scale by geologic map users in California; 3) most of the densely populated urban areas in California are geologically so complex they require 1:24,000 scale to portray the necessary detail.

DMG has been criticized for high costs of digitizing geologic maps in its USGS National Cooperative Geologic Mapping Program STATEMAP proposals. Digitizing 32 1:24,000 scale maps and assembling them into a seamless 1:100,000 geologic map is a far more time consuming, expensive proposition than scanning a map at 1:100,000 scale. Many uses for geologic maps in California require 1:24,000 scale. Where such maps are unavailable, the smaller scale maps are used improperly. There are many instances of maps being enlarged to unreasonable extents because larger scale maps do not exist. This is not a new problem; small scale regional geologic maps have been enlarged and misused before, but digital maps can be abused far more easily than conventionally printed maps.

## PRODUCTS

DMG has prepared digital geologic maps in fulfillment of contracts for STATEMAP and for the DMG Seismic Hazards Zoning Program. DMG has not released digital geologic maps for general distribution pending development of polices and procedures for release of these products. Although most of our users still need paper geologic maps, DMG recognizes the future is in digital geologic maps. DMG derives revenue from the sale of its publications; cost recovery is an important consideration. It is uncertain how or if costs of digitizing maps can be recovered. An evaluation of on-demand printing of maps versus large press runs of maps is underway.

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# Overview of New Jersey Geological Survey Digital Data Methods

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## INTRODUCTION

This paper explains some of the methods used by the New Jersey Geological Survey (NJGS) for generating, managing, analyzing, displaying, and distributing digital geologic data. These methods include a geographic information system (GIS) running on Sun microcomputers to produce digital maps and geo-referenced data and the use of personal computer (PC) software for managing outcrop and remotely-sensed structural geology data. The geological data layers (coverages) are documented according to federal standards, archived as electronic data, and distributed to the public through a publication sales office and the Internet.

## BACKGROUND

For a State/USGS cooperative mapping project, the NJGS began designing a digital geologic database using Arc/Info geographic information system (GIS) software. The Survey also modernized the GIS laboratory with Sun SPARCstation microcomputers (workstations) connected to desktop PCs using an ethernet local-area network. This effort included adding an E-format (34 inch-wide media) optical scanner, raster-to-vector conversion software, and an electrostatic plotter. By 1994 the NJGS had a modern GIS laboratory for creating and maintaining digital geological databases and publishing geological maps using digital cartography. More recent efforts include the development of an electronic information archive with a distribution outlet on the Internet's World-Wide Web at http://www.state.nj.us/dep/njgs/.

The Survey started building geology coverages in 1987. In 1992, mylar sheets were produced of machine-drafted lines representing geologic contacts and oriented map symbols in lieu of scribing lines on peel coats as part of the standard cartographic process for producing geologic maps. ARC Macro Language (AML) scripts were written for use in ARCPLOT for automatically plotting oriented geologic-map symbols. This work formed the basis for other digital-cartographic tools that the NJGS later developed to produce full-color, bedrock geologic maps. The advance of these digital-cartographic methods also spurred the development of other PC-DOS geologic data input/output (I/O) programs.

## DATA CAPTURE OF GEOLOGIC COVERAGES

Most geologic coverages produced by the NJGS are initially generated in NAD27 State Plane Coordinate (SPC) feet because United States Geological Survey (USGS) 7½′ topographic maps are based on this datum and because the New Jersey Department of Environmental Protection (NJDEP) uses SPC feet as the default geographic projection. Each map is geo-referenced (registered) to the NAD27 projection grid using at least four corresponding reference points (tics) for each map. The tics usually correspond to the corners of 1:24,000-scale 7½′ quadrangles, or 2½′ graticules corresponding to the corners of 1:12,000-scale quarter quadrangles. The NJDEP Bureau of Geographic Information Analysis maintains a reference set of tics.

All archived data sets at the NJGS are projected into NAD83 SPC feet upon completion. This projection typically results in map rotations of about ±0.5 percent, and translation shifts of about .015″ (+120 SPC feet) for 1:100,000-scale coverages scanned and traced from NAD27 base maps

The NJGS normally maintains a maximum root-mean-square (RMS) error of .006 (about 12 ft. at the 1:24,000 scale) for coverage development. An estimated 85 percent of the archived geologic and hydrogeologic coverages are accurate to within .003 RMS deviation. Quality assurance is maintained by comparing a proof plot of each coverage to the original base map. Any line that deviates from the original position by more than .012 inch (about 1 to 1.5 line widths) is redigitized, replotted, and corrected until it is acceptable.

Geology coverages are digitized using either a digitizing tablet and/or an optical scanner in conjunction with raster-to-vector (R-to-V) conversion software. Point themes are typically generated using a digitizing tablet. The NJGS uses CalComp 9100 and 9500 digitizers with a reported accuracy of ±0.005 in. (±0.127 mm). A set of at least four points (tics) is used for registering map sheets on a digitizing tablet at the beginning of each editing session.

Line and polygon themes are commonly built by optically scanning a map as a raster image, and then tracing linear arrays of image cells (pixels) with R-to-V conversion software. The NJGS uses a CalComp ScanPlus II roll-feed, E-format, two-camera scanner for maps larger than legal-sized documents. Most maps are scanned using 400 dots-per-inch (dpi) image resolution. The scanned image accuracy is reported as ±.25 percent. The NJGS has obtained the best imaging results from scanning either translucent or clear mylar separates with drafted neatlines of black rapidigraph ink. Acceptable results have been obtained from using soft-lead pencils (at least a No. 2, or HB pencil lead) on white paper or mylar.

R-to-V coverage development usually requires more time preparing media for reproduction than normally spent when using a digitizing tablet, but an estimated 50 percent of the time developing a coverage is recouped using the R-to-V approach if the coverage is physically large or detailed. The R-to-V approach allows a uniform coverage to be developed without having to worry about errors stemming from repeatedly registering maps on a digitizing tablet at the start of consecutive digitizing sessions. This concern frequently arises when digitizing large maps drafted at intermediate (1:100,000) and small (1:250,000 or less) scales. The R-to-V method works best with maps having continuous lines requiring no ornamentation. Separate mylar sheets should be prepared for each set of points, lines, and polygons to be individually generated from a pre-existing map.

The NJGS uses CADCore, Version 2.0 R-to-V software and Arc/Info GRID. Original maps or mylar separates are scanned and saved using a TIFF-5.0 image format. The TIFF image is imported to CADCore where it is converted into a CADCore image format (*.hrf) used for image display, processing, and line tracing. The raster image is centerline or outline traced with vector-line segments measured in inches. The vectors are saved as a CADCore drawing file (*.drw) and exported as an input file for use with Arc/Info generate command. The output files are generated as lines in Arc/Info and built into an arc coverage having inch units. GRID can perform a centerline trace without intervention from the digital compiler. The TIFF file is converted to a GRID and then processed by the GRID module into an arc coverage. The map is then transformed from inch units into NAD27 or NAD83 coordinates using the standard reference tics or other sets of links in the map-transformation process. Coverages are subsequently edited using Arc/Info ARCEDIT. Quality assurance is maintained by comparing a proof plot of each coverage to the original base map. Any line that deviates from the original position by more than .012 inch (about 1 to 1.5 line widths) is digitized, replotted, and corrected until it is acceptable.

## FIELD DATA MANAGEMENT SYSTEM

The Field data Management System (FMS v. 2.1) is computer software designed for managing, analyzing, and plotting structural geology data. The FMS is composed of two sets of files: one for managing structural geology data on the DOS-PC platform, and another for displaying and generating structural geology themes within the Arc/Info GIS environment. The latter set of programs was developed for use on Sun SPARCstations running Arc/Info (v. 7.0) and has not been tested on other platforms.

The FMS is used by the NJGS for managing and analyzing outcrop-based and remotely-sensed structural data and for integrating these data into full-color, quadrangle-scale geologic maps with oriented and annotated structural symbols. The FMS uses geological data that are organized into ASCII data files, usually through keyboard entry. Structural data can then be sorted based on location, stratigraphic unit, and structural variables and graphically plotted in either the map or profile view using a variety of PC-analysis tools. Most of these tools use standard or circular histograms for analyzing the frequency of structural bearing. Statistics are also available for the structural inclination and the quantity of structural data within a sorted data set. Other DOS-PC utilities include data import and export filters that format structural data for use with other commercial geologic analysis software. The FMS does not build GIS coverages of structural symbols on its own. It provides tools for automatically plotting oriented structural geology symbols on maps. It also can be used for generating GIS themes for the structural bearing or apparent inclination of structures such as fracture traces, in conjunction with Arc/Info.

## GEOLOGY COVERAGES

NJGS geology coverages are geo-referenced sets of points, lines, and polygons stored as electronic data in computers running GIS software. Coverages are developed for both map-based and cross-sectional views. Point coverages are built for sets of geologic features unable to be displayed as a line or polygon (field stations, wells). Line coverages represent features too narrow to be displayed as a polygon (structural contacts, contours). Polygon coverages denote an area (geologic unit, aquifer).

Cross sections represent a special case for GIS coverage development because they depict subsurface geologic information based on the vertical (z) dimension relative to the map (x and y) dimensions. Cross-section coverages are currently unable to be geo-referenced in Arc/Info because they are built using the standard GIS programs and contain x and y coordinates. They are built at the scale in which they are drafted, digitized or scanned.

## BEDROCK COVERAGE ATTRIBUTES

The Survey has developed a standardized set of coverage items (database fields) and item variables for assigning attributes to features in bedrock line and polygon coverages. The line attribute list is called GEOITEM. It contains coverage items and variables, and variable descriptions. GEOABB is the polygon attribute list. It holds coverage items and variables as well as geologic unit names for bedrock and surficial geology. Cross section coverages use the same item fields and attributes as the map-based bedrock coverages. A line attribute list is under development for surficial geology.

## METADATA AND DIGITAL DATA DISTRIBUTION

Metadata is defined by the Federal Geographic Data Committee (FGDC) as data that describe the content, quality, condition, and other characteristics of data, or in other words "data about data." Metadata are required as an integral part of a complete GIS coverage in order to convey details explicating its origin and use. These details include important information such as a citation, the physical limitations, and scope.

The NJGS produces and archives geologic, hydrogeologic, geophysical, and geographic data as digital data files for electronic distribution to the public. One method of electronic-data transfer uses the Internet mail protocol from the World Wide Web (WWW) home page for the NJGS (http://www.state.nj.us/dep/njgs/). Because the Web reaches a global market, the NJGS developed a metadata file format based on the content standards for digital geospatial metadata proposed by the Federal Geographic Data Committee (FGDC). These content standards were evaluated for completeness, applicability, and content for use with geologic data produced by the NJGS. A comparison was also made to the NJDEP data dictionary file, which currently serves as the NJDEP metadata standard. An ASCII-text format was chosen as a document template due to its broad user base and because of the need to develop metadata files utilizing different computer platforms (DOS, Windows, Apple, and UNIX). A prototype NJGS metadata format was reviewed by the NJGS staff and the NJDEP Office of Information Resources Management in 1995, and the abstracted version of the FGDC standard was adopted for use by the NJGS in 1996.

This standard is applied to all electronic files intended for distribution over the Web and all GIS coverages to be archived by the NJGS. The NJGS currently archives Arc/Info coverages and related dBASE relational data files as part of its Digital Geodata Archive. Compressed data files containing less than 1.4 megabytes of information are also being made available as Digital Geodata Series (DGS) publications. The NJGS DGS products are designed for use by ESRI's ARCVIEW software. The NJGS metadata documents therefore focus on Arc/Info coverages and dBASE files. However, metadata are also being generated for other products that include ASCII-text document files and computer-software programs such as the NJGS FMS.

Digital data are also distributed through the NJDEP publication and sales office and by written request. A reproduction fee is normally charged for the data.

## CONCLUSION

NJGS uses a modern GIS lab to capture, manage, and display geologic data. Machine drafted lines and oriented map symbols are now a part of the standard cartographic process. Data capture is accomplished by digitizing or scanning separates of hard-copy maps. The FMS software is used to manage, analyze, display, and plot structural geology data. Point, line, polygon, and cross sectional coverages are built on the GIS. Bedrock line and polygon coverages employ a standard set of coverage items and variables to assign attributes to features. Electronic data intended for distribution over the Internet or archive on the GIS have metadata based on FGDC standards. Data are distributed through the World-Wide Web, a publication sales office, and by written request.

# Progress Report—
# Digital Geologic Map Data Model

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What is a digital geologic map? A digital geologic map is any geologic map whose geographic details and explanatory data are recorded in a digital format that is readable by computer. There are two fundamentally different conceptual uses for digital geologic maps, cartography and analysis. Digital systems are used by cartographers to produce geologic maps for a number of reasons. Although there are differences of opinion about whether digital methods are faster or more efficient for the initial production of geologic maps, nearly all agree that digital maps are much faster and more efficient to update. Digital geologic maps are much more likely to be re-used for purposes beyond their original goals. Digital maps can easily be re-drawn at a different scale or projection than the original, and features on the maps can be easily added, deleted, or modified. Thus, the original map does not become obsolete just because of changing needs or purposes of the cartographers. Cartographers are generally concerned with using the digital representation of the geologic map to produce one or more published geologic maps, usually on paper.

Analysts, on the other hand, are usually more interested in the representation of the geology in its digital form. Their interest is in combining the digital geology with other types of digital data in an attempt to model natural systems or to solve problems related to natural systems. The analyst needs to represent his products on paper also; so the analyst's needs include those of the cartographer. Consequently, the analyst's perspective is taken in this model development.

So we are involved with modeling because we are attempting to define for computing purposes how people think about and use geologic maps. With this understanding we can design a database that will meet the needs of both the cartographer and the analyst.

The purpose of a data model for digital geologic maps is to provide a structure for the organization, storage, and use of geologic map data in a computer. The data model formally defines the grammar of the digital geologic maps. This grammar is independent of the vocabulary of geologic maps. To be truly powerful it is necessary to address both the grammar and the vocabulary. The primary objective of this effort will be to develop a digital data model (grammar) for geologic map information. Time will tell how much of the vocabulary will be addressed.

The model is being developed in two forms: a conceptual and a relational database presentation. Because technology is rapidly evolving, we are attempting to be forward looking in developing a conceptual data model. Consequently, some aspects of this conceptual model cannot be easily implemented in common relational database GIS software. The relational presentation of the model is an attempt to translate the more general conceptual model into a more easily implemented relational database form. This relational database form is the starting point for implementing the data model in a GIS such as Arc/Info. We intend to implement this model in Arc/Info and ArcView 3 with prototype tools to facilitate data entry and analysis.

Over the last decade we have gained much experience in using various simple approaches to digital geologic map data models. Interestingly, most of these simple data models have been developed independently by separate groups, but they have been similar. The important feature lacking from most of these approaches, however, is the recognition that the text information in a map legend, explanation, or associated book report contains essential information needed to apply the geologic map to solving problems. In order to use the geologic map for spatial analysis, this text information

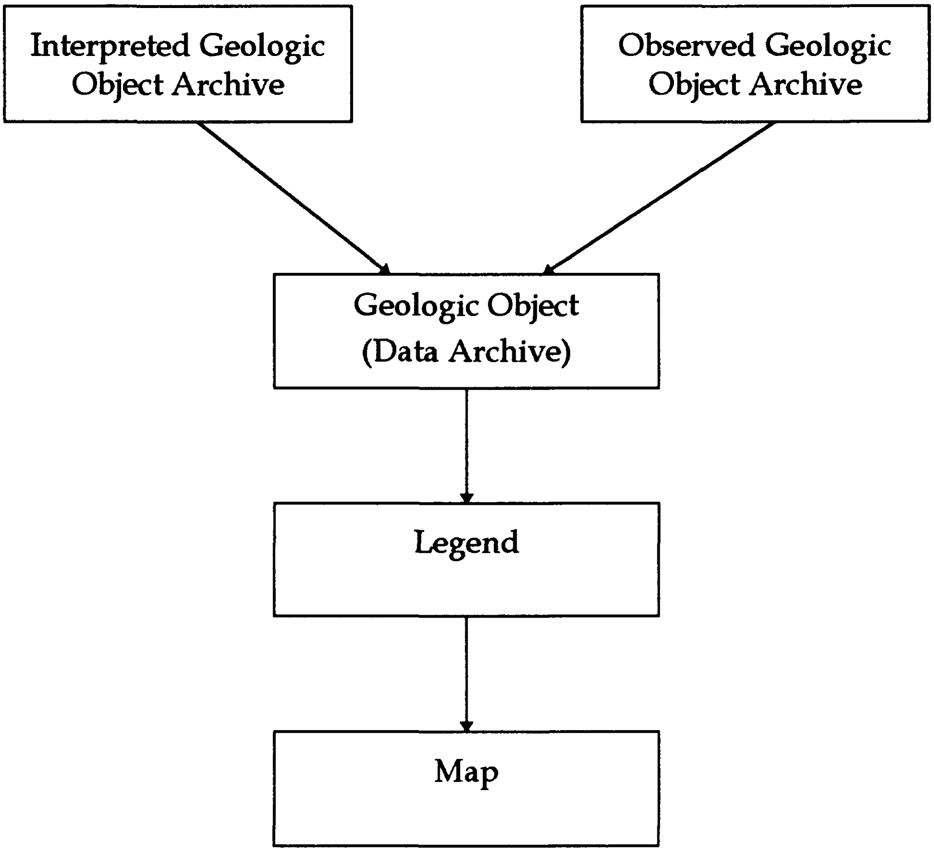


**Figure 1.** Summary diagram of the components of the data model.

needs to be organized in a form that can be analyzed by computer. Geologic maps can be extremely complex with many different types of information. Most geologic maps include a background of polygonal areas, which represent geologic units or materials that cover the geologic units such as water, ice, etc. The lines that separate the polygons also have significance; they represent differing types of contacts. Overlaying this background are usually numerous linear features such as faults, folds, dikes, veins, etc., and several different types of point features such as structural symbols and sample location symbols.

Additional complexity is introduced by the lack of symbolization standards for geologic maps. Although some general colors are often used for the same general types of rock units, there is no convention in common use for assigning a particular rock unit the same color on all maps. The same is true to a lesser degree for line patterns and point symbols. A pattern that may represent a dike on one map may be used to represent a fault or a vein on an adjacent map.

In the use of such complex information, there are cartographic and analytical considerations, each making its own demands. To deal with all of these issues is a complex task requiring a complex data model. There is also a competing need for simplicity, that is, the task of getting information from a digital geologic map into a data model must be efficient. Considering all of these diverse and complex requirements, it has been concluded by users of simple data models that they are not adequate. A long list of problems has been identified that summarizes the concerns that arise in using the simple model. A more complete data model is needed and a formal analysis of the goals of such a model is necessary. Development of this more complete model has evolved from efforts of the USGS, the GSC, and U.S. state and Canadian provincial geological surveys.

In designing this more complete model, the point of view considered is that of the user of geologic maps. Figure 1 presents the user's perspective on digital geologic maps. The real world is composed of many entities including geologic objects. Geologic objects include such things as structural measurements, faults, map units such as formations, and other geologic features commonly represented on geologic maps. These real world geologic objects are of two types, interpreted and observed. Observed geologic objects consist of things that are actually observed or measured in the field, such as structural measurements, fault traces in outcrop, or characterizations of individual samples or outcrops. Interpreted geologic objects consist of the interpretation, grouping, or classification of multiple observed geologic objects, such as map units defined by observations of outcrops or fault traces defined from evidence observed in several outcrops. Representation of both interpreted and observed geologic objects are stored in a geologic object data archive, which requires a GIS to deal with the geometric and spatial aspects. A map legend establishes an association between objects in the data archive and their geometric, spatial, semantic, and symbolic representation on a particular map. Thus, a map is a representation of selected geologic objects symbolized and described for some specific purpose. Symbolization is defined by scale and purpose. Any geologic object, from the object archive, could be represented, for example as a point, line, polygon, or volume, depending on the scale and purpose of the map. The major point of this concept is to separate symbolization from data description.

These concepts lead to a large number of tables with complex linkages. The complexity of such data structures is managed through user interface tools. With proper tools, the complexity of the data model is transparent to the user. The critical tools needed are computerized data entry forms and standardized queries that can be packaged with a geologic map visualization tool such as Arc/Info or Arcview 3. In developing the data model, such tools are currently being developed as prototypes in order to test and demonstrate the use of the model. A complete description of the data model and a demonstration data set is planned for early summer, 1997.

A number of design criteria have been identified that guide the development of the data model. Those criteria are the following:

- The data model should be easy to implement and should place minimal requirements on the person or organization creating a digital geologic map. However, there are many things that only occur on some maps, such as strike and dip symbols, that need to be considered. These are addressed as defined extensions of the core requirements.
- The data model should be easily extended to include new features. These extensions should be additional tables or objects that attach additional information to the geologic map. Examples might include amplification of the legend, engineering properties, etc. The opportunities for extensions will evolve with time and definition of new uses. The objective of extensions is to enhance the information and maintain a connection with the ultimate source of the geologic data.
- There should be a set of minimal requirements that are necessary for all geologic maps. The minimal requirements are indicated as required tables.
- The model should avoid explicit use of code dictionaries for translation of geologic vocabulary. The use of codes where needed, however, can be facilitated through software tools.
- The data model does not address standard vocabulary but provides the capability to incorporate vocabulary standards. The words used in most data fields can be selected from a defined list of terms so that the resulting digital maps can be used efficiently for computer analysis. The words in these lists are by definition broad terms. Specific finer subdivision of terminology might better be left as extensions, as discussed above. Additional memo-type fields might be used to store short free-form descriptions intended to be read by people. We are attempting to add more structure to the communication of information to minimize ambiguity.
- There needs to be a mechanism to identify individual geologic occurrences. These occurrences provide for such things as outcrop mapping, describing the lithology of a specific area within a larger map unit, or a specific segment of a fault zone.
- Geologic maps have, as a fundamental characteristic, line and polygon attributes that are interrelated. Thus, a fault may separate two polygons and continue internally into a third polygon. Such lines need to be included with the polygon data in order to do structural analyses, for example, to select individual polygons on the upper plate of a thrust. In an Arc/Info implementation, this requires that dangling lines are included in the topological definition of the polygon coverage.
- Mechanisms are needed to document the source of each individual geologic object. For example, the source would include the full bibliographic reference for the object.

## CONCEPTS OF DATA MODELING

Why define a data model? Modeling is a complex task that attempts to capture the intricacies of real-world situations, including the characteristics of real-world objects, events, and object-event interrelations. Modeling by its very nature is from a particular point of view, often a combination of the view of an expert in the system being described (the earth, wildlife, surface geology, etc.) and an expert in implementing models on computer systems (databases, forward modeling, etc.). Thus, the modeling process occurs at many levels of abstraction. In the domain of geological mapping, the real world objects modeled typically range widely from the details of individual observations, to their interconnections, and to their synthesis into explanatory structures.

When the modeling process is intended to produce a data manipulation framework, the conceptual setting in which it occurs is typically called a data model. A data model is formally defined as a set of fundamental conceptual objects and mathematical and logical rules that govern their behavior. The rules are usually expressed in terms of how and why objects may exist, and what interactions are permitted (Codd 1980).

The formal objects and operators of a data model are generally abstract in nature and form a language in which real world situations may be expressed. Generally such languages are intended to be mapped into computing constructs, easing the transition from the real world, to the abstract and finally to the computer. This process requires the identification of key concepts within a specific real-world domain (as seen through the eyes of an expert) and an expression of their interactions using the data model's conceptual objects and operators. In this sense, a data model may be seen as a tool kit composed of concepts, operators, and their rules of behavior, all used to describe some real world phenomenon for computing purposes. In its most abstract sense a data model provides the logical framework in which the real world may be described for computing.

However, there exist many possible levels of examination in this process. At one level it can be described as a rigorous, abstract notation for describing some real world domain (i.e., geologic maps). On another level, it can be seen as a way of organizing and manipulating data pertaining to the real world domain at the physical level of the computer, in terms of bytes, records and files. Both perspectives are commonly referred to as a type of data model. Hence, the term *data model* is often used to describe the product of a modeling process, usually as a database design for a particular real world domain, as well as the method and rules of abstraction used to generate such representations of reality. For instance, it is not uncommon to speak of geometric data models or geological data models—these are each abstractions containing domain-specific concepts and rules. In another sense, however, the computing paradigm in which the models are formed, be it relational, object-oriented, or some other, is also a data model (of a data model) as it describes how the domain models are created and how their architecture behaves.

In some cases the domain specific model is called a *database model* (Burrough 1992; Teory 1988), as database design is the ultimate purpose at hand. This notion of the model being directly expressed as a database design may be attributed to the seminal work of Codd on relational databases (Codd 1970), which has caused data modeling to become linked with database design. As a result, the relational data model has become the standard example of a data model.

This initial notion of a data model providing a conceptual framework as well as a logical mapping into computing constructs has been under review for some time. Computationally driven frameworks that are expressed as an algebra with mathematical operators, as in the relational model, are seen as being generally insufficient in expressing many semantic relationships between data. Because of this, conceptual models utilize semantically richer, often non-mathematical operators. However, this results in their translation to computing environments being more complex or impossible to implement with commercial systems.

The results of a modeling process must ultimately be applied in a computing environment, be it spatial (GIS—Geographical Information System), or non-spatial (RDBMS—Relational Database Systems, Object-Oriented Database Systems), or both. Before this can occur a model must first minutely and exactly describe the type and behavior of the information to be managed by the database. This process usually involves the undertaking of ***requirements analysis*** and ***database modeling,*** resulting in a particular database design for a given subject area and set of data. The needs are identified during the requirement analysis, and these in turn lead to the identification of critical concepts, their interactions, and other implementation criteria, all of which constitute the database model. It is important to design and populate the database for optimum querying, both in terms of conceptual completeness as well as performance efficiency: a bad database design can result in slow, incomplete, or incorrect responses. Database models are usually described at the three levels of conceptual, logical, and physical models (Frank 1992). Once a design is formulated it can be programmed within a database system, the resultant database can be populated with data, and finally, the database becomes useful for thematic querying.

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# Mining Information from Published Geologic Maps (An Extractive Industry)

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## INTRODUCTION

This paper addresses the development of digital geologic map databases through the extraction of information from existing published geologic maps. As in any mining operation, the objective is an efficient and cost effective method for extracting and processing the ore while (in an environmentally safe way) leaving behind the tailings. The underlying concept of this paper is that information contained in existing small-scale geologic maps can be related to a high quality, larger-scale, topographic maps in the same manner that the information is commonly related to the real world (which has the ultimate scale of 1:1). The characteristics which are most useful in this process involve the relationship which exist between geologic boundaries (separating distinct and identifiable geologic units) and nongeologic features (cultural or topographic). Although the nature of sedimentary stratigraphy without complicating unconformities makes it the easiest environment for application of these principles, the interactions between geologic boundaries and variations in topography in almost any geologic environment will create patterns and spatial relationships to which the principles of this paper may be usefully applied.

## BLOWING UP MAPS

Proverbs are generally the outcome of experience blended with wisdom. People who violate old proverbs may survive the experience, but they do so at their own risk. There is an old proverb among geologists and cartographers:

***Don't take a map drawn at a smaller scale and enlarge it for work at a larger scale.***

As stated by Robinson et al. (1984, p.427), "... the accuracy of the source data must always be a matter of primary concern for the map compiler." The fundamental concern addressed by this proverb is map accuracy; more specifically, the accuracy of feature locations on the map. Implicit in the proverb is the understanding explicitly stated by Thompson (1981, p.31) in *Maps for America*: "Generalization is used to some extent ... at any map scale ... The amount of detail omitted varies inversely with the map scale." In the drawing of geologic outcrop patterns, greater omission of detail corresponds to the introduction of greater location inaccuracies.

Addressing the current issue of map scale changes, Robinson gives his own version of our proverb:

"Progressive generalization with smaller scales is an inevitable aspect of the mapping process. For this reason compilation should always be from larger-scale sources rather than smaller. The temptation to enlarge a smaller-scale source map is bad enough. But it would be even worse to **blow up** a smaller-scale map of one feature ... to be overlaid on a compilation worksheet containing other features ... that were compiled from larger scales. (p.427–428 emphasis added)"

The first temptation is probably not so much a sin as Robinson suggests, unless the resulting enlargement is used in a way which implies location accuracy only possible from original compilation at the larger size (scale).

Robinson's warning against the second temptation suggests a more specific statement of our first proverb:

***Don't enlarge features compiled and generalized for a map at a smaller scale in order to integrate those features, on a composite map, with features compiled and generalized for a map at a larger scale.***

Violation of this proverb probably generates the worst possible results when it involves features of the same type. Newell's (1935) geologic map of Johnson County includes the outcrop pattern for the base of the Westerville Limestone (now considered a member of the Cherryvale Formation). The map is published at a scale of 1:126,720. O'Connor (1971) did not include this unit in his more recent map, compiled for publication at a scale of 1:48,000 from field work done on 1:24,000 scale topographic maps. Believing that information about the Westerville Limestone Member would improve O'Connor's map, a poorly trained cartographer might digitize the outcrop from Newell's map, enlarge the data to a scale of 1:48,000, and plot the result with data from O'Connor's map. The superimposed outcrop pattern for the base of the Westerville would cut back and forth between outcrops derived from O'Connor's map of geologic contacts above and below the Westerville Limestone, possibly crossing one or the other. Cartographic transgression could easily violate a fundamental geologic principle, inverting the order of formations within a normal stratigraphic sequence.

The location distortion of the transferred outcrop pattern for the Westerville Limestone Member in relation to surrounding units results from differences in the quality of the base maps and, more significantly, a higher degree of generalization inherent in Newell's smaller-scale map. Rather than improving the information content of the composite map, violation of the cartographic principles expressed in our first proverb (as revised) would degrade and call into question all the information presented on the composite map.

## MAKING GEOLOGIC MAPS

***Geologic maps are models of information transferred from a 3-D, topographic relief map at the scale of the real world.***

This is the first axiom of geologic mapping. With new field mapping, geologists follow Robinson's admonition against the use of smaller-scale sources in the compilation of maps. Working in the real world they use the largest available source, at the scale of 1:1, where a foot is a foot (and a rose is still a rose).

Once they identify exposed rock units, geologists search for geologic contacts; where the top of one mapped interval of rock units is in contact with the base of the next mapped interval. Using the best available methods, the geographic location and elevation of these geologic contact observation points are carefully determined. The process used in compilation of field maps from these potentially sparse observations is described by Sawin (1996, p.3):

"Geologic maps are compilations of data and inference. Because most bedrock is covered by soil and vegetation, the information gleaned from outcrops are pieced together to build a map. Because outcrops may be a mile or more apart, geologists must use their training and experience to connect the data points by extrapolating and interpreting what happens between the scattered points of information. . . The geologist's job is to visualize the bedrock near the surface without the soil cover and to make a map that reflects this image."

Accurate positioning of outcrop patterns is probably the principle concern for the field geologist and the cartographic compiler of geologic maps. However, it is the forms of those outcrop lines in relation to the forms of the landscape (or the representation of those land forms on topographic maps) and their position in relation to cultural features (such as section corners and boundaries in the Public Land Survey System) which provides the most useful information regarding the location and spatial relationship of rock units. To a large extent these information-loaded aspects of form and spatial relationships are maintained in the preparation of geologic maps over a large range of scales. In mathematics and cartographic applications, geometric properties which are invariant with scale transformations define the topology of the mappings. For a geologic map to accomplish the geologist's objective of representing the spatial relationship between rock units, maintaining the topology of geologic features is more important than the absolute position of those features. In many cases the scientist is unaware of the distinction between position and form, and the primary significance of form, to the success of the map making effort.

The interaction between geologist and cartographer, trying to achieve location accuracy despite small map publication scales, produces cartographic generalization of map features dependent on the attributes as well as the relative positions of the features represented on the map. The result is preservation of the geologic information which the geologist seeks to convey through the map.

## USING GEOLOGIC MAPS

***When a geologic map is used in the field, the information content of the smaller-scale map is related back to a 3-D, topographic relief map with the larger scale of the real world.***

This is the first axiom of map use. Significant errors between the map coordinates of points along a line representing the outcrop pattern of a geologic contact and the corresponding geographic location of the outcrop occur as the result of generalization, and increase with decreases in scale. Despite this obvious fact, geologic maps published at small scales (ranging from 1:24,000 down to 1:320,000 for county maps and 1:500,000 for the state geologic map in Kansas) maintain a high degree of usefulness in a wide variety of applications. The fundamental quality of a truly good geologic map is the fact that users derive most of the available information from map characteristics other than the precise position of outcrop lines on the map.

Consulting geologists, highway engineers, civil engineers, zoning boards and a multitude of other users of the end product of the field geologist's efforts take advantage of the topological characteristics of geologic maps. They use their training and experience to relate the forms of outcrops on geologic maps to the corresponding topographic form of the real world where knowledge of near surface geology is crucial for success in performance of their jobs.

## DEVELOPMENT OF DIGITAL DATABASES FROM PUBLISHED GEOLOGIC MAPS

High quality topographic maps, such as the 7.5 minute quadrangles published by the USGS, provide excellent models of actual land forms in the real world. When smaller-scale geologic maps are used to locate geologic features in the field, the user commonly invokes the following principal:

***The information content of all geologic maps can also be related to models of the large 1:1 scale topographic relief map.***

This is an important corollary to the first axiom of map use. With emphasis on the information content of maps, it is a concept which must be adequately conveyed to geoscientists, technicians and program managers responsible for geologic database development. For many, its acceptance requires a major paradigm shift. Without its acceptance, the typical responses from all these groups, based on a misunderstanding of the nature of the information content of geologic maps, pose roadblocks to development of high quality digital geologic databases from existing published maps.

Computer mapping technicians generally see the task of data compilation from published maps as a challenge to find the best technology for capturing the precise location of each and every relevant line as shown on the map or maps in question. They focus on resolutions of scanning equipment, repeatability of point location measurement on specific digitizing tables, the medium on which the source map is printed, possible distortions in the medium, and the quality and clarity of lines on the map. Their efforts for accurate reproduction of the lines on the map will result in accurate reproduction of the cartographic generalizations (i.e., the position errors) built into the particular scale at which the map was drafted.

Project managers for geologic map database development intuitively recognize the merits of Robinson's admonition against blowing up a small-scale geologic map and printing it as an overlay on base map data derived from larger-scale sources. Large programs such as development of state or national databases are established in relation to a "standard" scale (e.g., 1:100,000 for the National Geologic Map Database). It is commonly presumed that no maps published at a scale smaller than the "standard" can be acceptable sources of information for the program. The scales at which existing geologic maps were actually published can become a constraint on the selection of the target scale for a database development project. The goal of a national database referenced to a 1:24,000 base is rejected a priori as impractical or infeasible. This rejection is based on the assumption that maps do not generally exist at this large scale and that resulting compilation efforts would be extremely expensive. The result is an unfortunate restriction in the use of information available from many published maps.

Even among geologists who are perfectly comfortable using a small-scale map in the field, there is strong resistance to the idea of taking information from the smaller-scale map and placing it on a larger-scale map. Failing to recognize the ease with which they use the information from existing maps while working (in the field) on the largest-scale map, geologists commonly, but incorrectly, believe that map information is mostly determined by the position of the lines rather than their topology.

These typical responses result in a failure to consider the potential for capturing important information from almost any geologic maps and then relating that information in useful ways to larger-scale maps of the local topography. Once the corollary in this section is accepted, the implications for database development are immediate. Highly effective procedures for capture of geologic information from published maps have been developed and tested at the Kansas Geological Survey. The procedures require interpretation of the topologic characteristics of geologic features represented on a map with subsequent transfer of information from the published maps to a common, 1:24,000 scale, USGS topographic base. The tasks involved in this process, are described by Ross (1996) and by Ross and Collins (1997).

As Ross explains, the idea of transferring the map information to larger-scale (1:24,000) topographic maps is not a matter of "trying" to make the data more accurate than the existing maps. Nor is it a violation of Robinson's principles of map compilation. Using the topologic, stratigraphic and geologic information presented in the smaller-scale map and the more accurate representation of real world topography on the 1:24,000 base map, it is possible to develop geologic data which more accurately represent what the geologists intended to map than could be done on the existing smaller-scale maps. Rather than flagrant "cartographic license," the process represents a redrafting of available information while eliminating much (but not all) of the "cartographic license" taken when results of field mapping were prepared for publication at small scale. Cartographers are not the only ones who take this license. Many geologists, in the process of completing outcrop patterns on their field maps, will fail to follow the structure implied by their field observations (often made at sparse critical points) when interpolating between actual mapped locations of a formation.

## CONCLUSION

There is a new proverb among geocartographers:

***Don't let an old proverb keep you from using the information content of a smaller-scale map when you want to make a map at a larger scale.***

Scanned images of old maps can still be important historic resources in geologic literature. They provide an efficient, cost-effective means of preserving past geologic research and make possible electronic re-publication of the old maps, now generally out of print. Scanning is the only method recommended for this purpose because it replicates the original document in all its detail with far greater fidelity and much lower cost than any manual digitizing technique.

Digitizing or scanning geologic formation boundaries and outcrop patterns directly from existing smaller-scale maps or from bases prepared at a small scale such as 1:100,000 for the purpose of database development would simply perpetuate the errors introduced by cartographic generalization. Using these images, or elements vectorized from the images, in conjunction with databases derived from more accurate, larger-scale maps would be a return to map terrorism, violating the wisdom of old proverbs and basic principles of cartography. This a constant concern in other geographic information systems applications as well as in automated cartography.

Databases derived from published maps through transfer of map information to a common, larger-scale base provide an appropriate alternative to this violence.

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# Information Capture from Previously Published Maps

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## INTRODUCTION

This paper addresses geologic map database development. The emphasis here is on the use of previously published maps as source documents. Although the perspective is significantly different, the principles which guide our procedures correspond to those which guide database development from new field mapping.

The Kansas Geologic Mapping and Database Development Project was initiated by the Kansas Geological Survey (KGS) in 1987 to update lower quality county maps and develop geologic maps for counties with no published map. The project has focused on new field work. Funding has come primarily from cost sharing in federal programs such as the STATEMAP component of the USGS National Cooperative Geologic Mapping Program. Costs, generally funded over several years, tend to exceed $100,000 per county. Development of digital geologic map databases for use in map publication has been an essential element of the project from the beginning.

In response to the National Geologic Mapping Act of 1992, the National Geologic Map Database Project was organized. The project seeks to promote development and access to earth science map information. Products may be paper or digital. This project is supported by the U.S. Geological Survey and the Association of American State Geologists. The project is targeting efforts on nation-wide mapping at 1:100,000 or smaller.

The National Geologic Mapping Act and associated Database Project have been positive forces in support of the Kansas Mapping Project. However, with reduced federal funding for programs like STATEMAP, tight state budgets and rapidly increasing local demand for digital geologic map data, it is essential that state mapping programs maximize efficiency in digital geologic map database development.

## STATUS OF GEOLOGIC MAPPING IN KANSAS

A detailed bibliography of county geologic maps in Kansas is found at the KGS web-site (www.kgs.ukans.edu/General/Geology/geoMapIndex.html). Table 1 shows the types of published county maps available in Kansas. The counties which have no separate county-wide map available are represented on the Geologic Map of Kansas at 1:500,000. In many cases, maps listed as in print would be more accurately described as maps in stock with no plans to reprint. Maps in digital form do not go out of print. They can also be modified and updated within local study areas at low marginal cost.

**Table 1.** Summary of County Maps by Publication Format

| | |
|---|---|
| 85 | Maps from non-digital proofs |
| | 41 in print |
| | 44 out of print |
| 1 | Maps for 80% of county from non-digital proofs (out of print) |
| 12 | Maps from digital map databases |
| 7 | Counties with no published map |

These county maps actually occur in more than 25 different scales. Publication dates range from 1930 to the present. The wide range in published scales interferes with the productive use of adjacent paper maps when those maps are of different scales. It also poses a significant problem for statewide development of digital databases from the published maps. Maps published at larger scales will generally have more detail and will be appropriate for use at a wider range of scales than maps published at smaller scales. Tech-

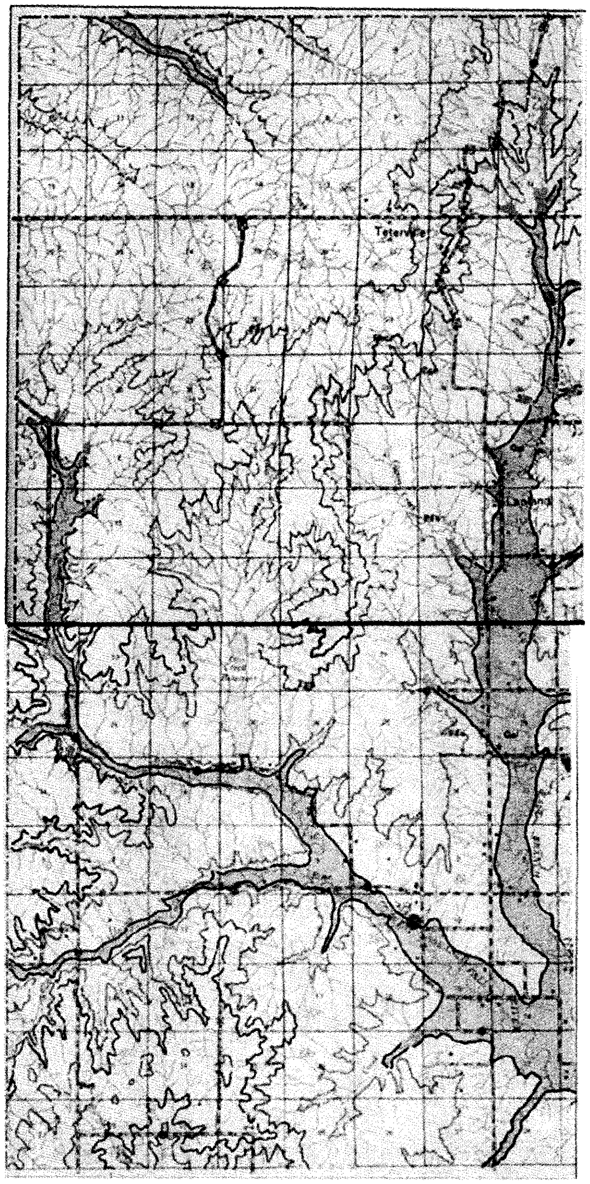

**Figure 1.** KDOT map of NW Greenwood County.

niques such as scanning or direct digitizing from the published maps maintain these differences in the resulting data.

## BACK TO THE FUTURE: AN INTEGRATED RESPONSE

In response to these problems and the increasing forces for change, the Kansas Geological Survey has implemented highly effective techniques for development of new geologic map databases from previously published maps. The testing and application of these techniques at the Kansas Geological Survey have occurred within the context of sedimentary stratigraphy typical of Kansas and the mid-continent. However, as noted by Collins (1997), there is no reason the same techniques could not be applied in any region lacking digital geologic map databases where high quality, larger scale, topographic maps are available in combination with reputable, smaller scale, geologic maps (provided the technique for database development is documented in the metadata). The basic steps involved in the process are outlined in Table 2.

**Table 2.** General Outline for Database Development from Published Maps

1. Transfer available geologic information from each source document to a common (1:24,000) topographic base
   a. Identify critical points on published map for each mapped unit, for example:
      - extremes in outcrop geometry
      - proximity of outcrop to non-geologic map features
   b. Locate these points on 1:24,000 topographic map
2. Derive 1:24,000 outcrop patterns
3. Digitize and edit outcrops and other geologic features
4. Create databases
   a. Edge match quadrangles
   b. Build and attribute polygons
5. Develop maps for publication (labels, legends, etc.)

The procedures in steps 3, 4, and 5 are identical, whether the geologic information was derived from previous publications or from new field investigations. As indicated by item 1, the process permits integration of map information from multiple sources, including different maps and field notes. When sources don't agree, an assessment must be made to determine the preferred source.

Critical points are locations in geologic outcrop patterns where the form of the outcrop or its proximity to non-geologic map features permit a reasonably accurate determination of its location. These characteristics enable us to locate the critical points on a topographic map, just as they would help to locate the formation in the field. The following examples will illustrate the concept of critical points on published maps.

Figure 1 is taken from Plate 3 (the north half of the figure) and Plate 6 (the south half) of the surface geology maps in the Kansas Department of Transportation (KDOT) "Construction Material Inventory of Greenwood Co.", published in 1982. The area represented is in the northwest corner of Greenwood County. The original plates are published at a scale of 1:64,000 with considerable generalization in the drafting of both base map features and geologic outcrops. The rock units in this area are Lower Permian and Upper Pennsylvanian.

Figure 2a is an enlarged area from the southwest part of KDOT's Plate 3. Figure 2b is the interpretation derived from 2a, using our procedures, as seen on the 1:24,000 Lapland, KS, quadrangle. Black arrows identify critical points determined by the geometry of the outcrop pattern. White

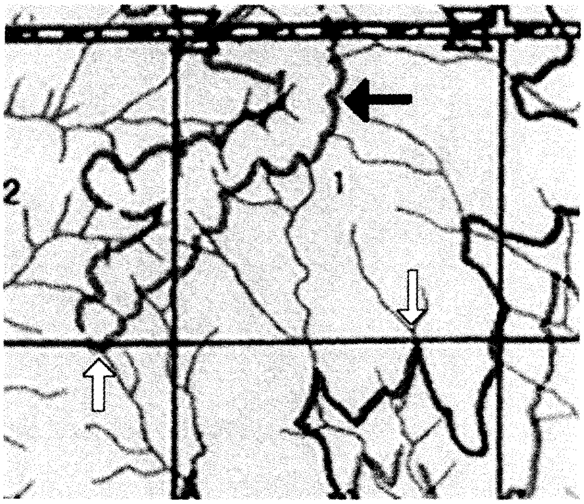


**Figure 2A.** Enlargement of ridge line from Figure 1.

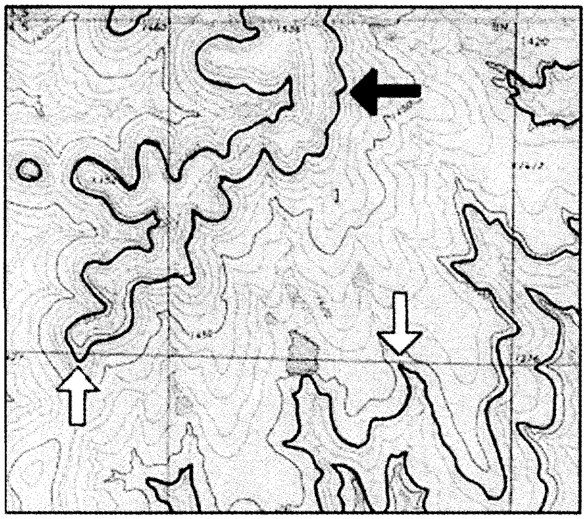

**Figure 2B.** Interpreted geology in the area of Figure 2A.

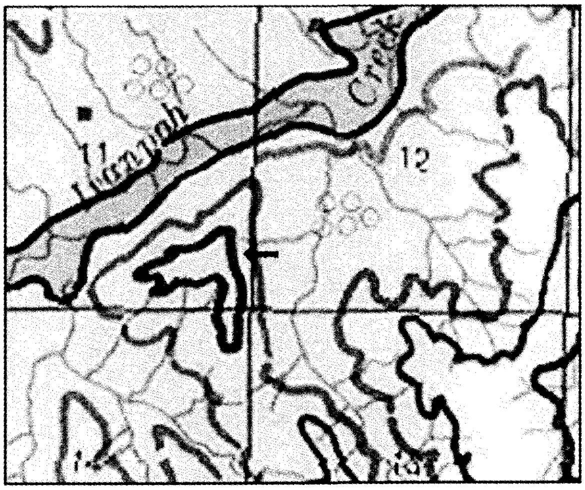


**Figure 3A.** Enlargement of isolated outcrop island from Figure 1.

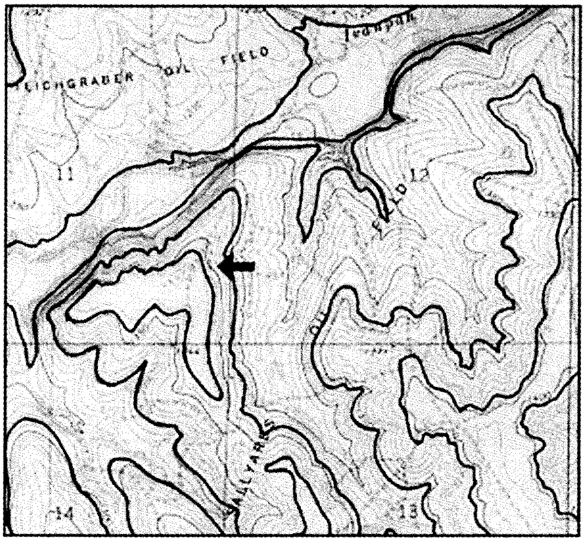

**Figure 3B.** Interpreted geology in the area of Figure 3A.

arrows identify critical points determined by the proximity of outcrops to non-geologic map features.

The black arrows at the top of these images show an area where the land form almost causes a pinchout in the outcrop of the Threemile Limestone Member at the base of the Wreford Limestone along a ridge line. The geometry of the outcrop pattern, together with the actual land form, permit accurate determination of the location and elevation of the outcrop whether using the map in the real world or in our topographic model. The white arrows to the left on each map identify the southern extension of the Threemile Limestone Member along a ridge, to its limit at the south line of Section 2. To the right on both maps, white arrows identify the limit of northward erosion of the Cottonwood Limestone Member (therefore the northern limit of its outcrop, at the base of the Beattie Limestone) extending up a stream valley, to the south line of Section 1. The proximity of these extremes, or critical points, to topographic or cultural features enables us to determine location and elevation of the outcrop.

Based on critical points identified on the KDOT map, it was determined that an isolated outcrop of the Threemile Limestone probably occurs near the top of the knoll on the west edge of the map area. Prior to confirmation by a field check, this would be flagged as 'probable' in the database and could be shown on a derived map by a different line style, to indicate the uncertain status of the outcrop, as is sometimes done on maps developed from new field mapping where outcrops are obscure.

To the south of the previous examples, black arrows in Figures 3a and 3b identify an isolated island in the outcrop of the Cottonwood Limestone. Figure 3a is enlarged from near the center of the west half of KDOT's Plate 6, while Figure 3b is the derived interpretation. Island features of this type are extremely useful for establishing limits on the possible range of elevations where the outcrop could occur in the real world, permitting accurate location on our topographic model.

The idea of identifying critical points, for use in deriving a geologic outcrop, is consistent with situations often encountered by geologists doing new field mapping. Persistent, mappable units may be clearly identifiable only at scattered locations such as road cuts.

The process for deriving outcrop patterns from critical point locations is basically a problem in solid geometry. The surface geology occurs on a land form which can be represented by contours on a topographic map. Isolated outcrops or critical points are located on the map. Three such points in space determine an inclined plane which corresponds to the local trend of the geologic formation. The line of intersection between the plane representing the geologic formation and the irregular land form corresponds to the probable outcrop pattern of the formation.

The ability of these procedures to develop results which can be merged with data from other sources is shown in the composite map of Figure 4. The work of James Aber in Butler County (on the left) is joined to our interpretation from KDOT's map of Greenwood County (on the right). While Aber mapped more geologic units than KDOT, the level of detail in outcrop patterns is comparable in Aber's map and our interpretation of KDOT's map, since both were developed from the common 1:24,000 base. Greenwood County is currently being mapped in the field by Dan Merriam, one of the Survey's top senior geologists. Preliminary comparisons of new field mapping with our interpreted maps suggest a very high quality for our results.

The superiority of this technique over direct scanning or digitizing of the source map is seen in a direct comparison. We will look at results within a typical area of Raymond C. Moore's map of Chase County, KS, published in 1951 at a scale of about 1:62,000. Figure 5a shows the area from Moore's map used for this example. Geology was digitized directly from R. C. Moore's map and registered to a topographic map. The results are shown in Figure 5b. Geology drafted according to our procedures for interpretation of Moore's map is shown on the 1:24,000 topographic map base in Figure 5c.

Errors in the precise location of outcrops in Figure 5b are the result of differences in the quality of base maps available at the time and the unavoidable process of cartographic generalization which becomes more pronounced with manual drafting at smaller scales. Direct enlargement of outcrop patterns from published maps maintains the distortions of form and location which were introduced with drafting of the original map.

As seen in Figure 5b, which is by no means a worst case example, cuts in the outcrop due to erosion are shifted to positions where they coincide with topographic highs, the outcrop pattern then drops into adjacent valleys. The improvement resulting from our method can be seen in Figure 5c, which eliminates the distortions found in the digital recreation (5b) of the original published map (5a). The result cannot eliminate mistakes in the original field mapping such as incorrect identification of a formation, but in any case it provides an improved representation of what the geologist intended to show on the map.

Once outcrop patterns are drafted on the base map, the remaining procedures for database development and map production are the same whether information was collected in the field or drawn from published maps. The outcrop patterns are digitized using point mode techniques on tables with 0.001" resolution and 0.003" repeatability. Using the Kansas Geological Survey's GIMMAP (Geodata Information Management, Mapping, and Production) system, databases are created and work proceeds to design maps for publication.

## RESOURCE REQUIREMENTS

Cost estimates and extensive testing suggest that database development from previously published maps would average less than $10,000 for a typical county in Kansas. A range of costs from $1000 to $16,000 would be expected. Time requirements to develop a finished geologic map for a single 1:24,000 quadrangle derived from a previously published, smaller scale map are summarized in Table 3. Using one staff member, it would take two and one-half to three months to complete an interpreted map from the published map of an average county.

**Table 3.** Interpretation and map production for a single 1:24,000 quadrangle.

| Task | Time (hours) |
|---|---|
| Identify and locate critical points | 5.0 |
| Derive outcrop patterns | 8.2 |
| Digitize and edit geologic features | 11.6 |
| Edge match quadrangles | 4.0 |
| Build and attribute polygons | 2.7 |
| Add labels, etc. | 3.6 |
| Total | 35.1 |

## CONCLUSION

To borrow from the poet Adrianne Rich, "What Is Found There" depends on how you look at it.

If the position of every point on every line of a published map is viewed as an absolute statement of ground truth, the results will be unsatisfactory; as seen in Figure 5b.

**Figure 4.** Composite of geology in Butler County (left) obtained from new field mapping, with geology in Greenwood County (right) interpreted from the KDOT map in Figure 1.

But, if you use the available information—contained in form and relative position of map features—published maps can yield valuable data. Use of the procedures outlined here will yield other beneficial results beyond database development. Rather than diverting resources from field mapping, this process will prove to be a valuable tool for assessing the quality of existing geologic mapping and establishing priorities to target more expensive, but sometimes essential, field mapping on true problem areas.

Digitizing or scanning outcrops from published maps perpetuates errors introduced by cartographic license. Use of resulting data at scales larger than the scale of the source document would violate basic cartographic principles. Databases derived directly from maps published at different

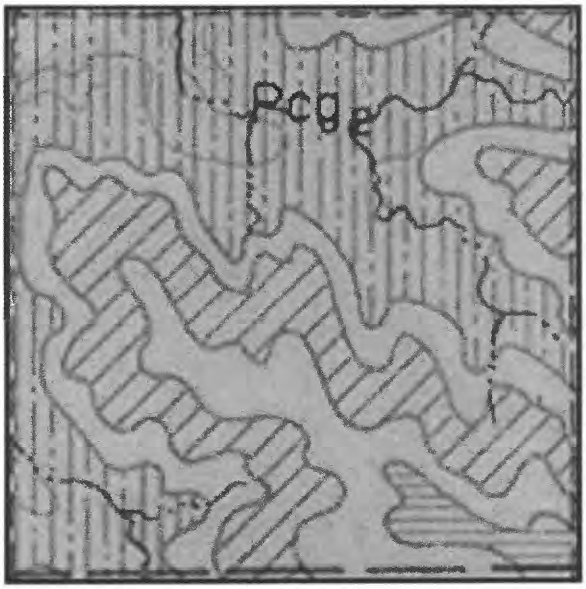

**Figure 5A.** Typical section from Geology of Chase County (R.C. Moore, 1952)

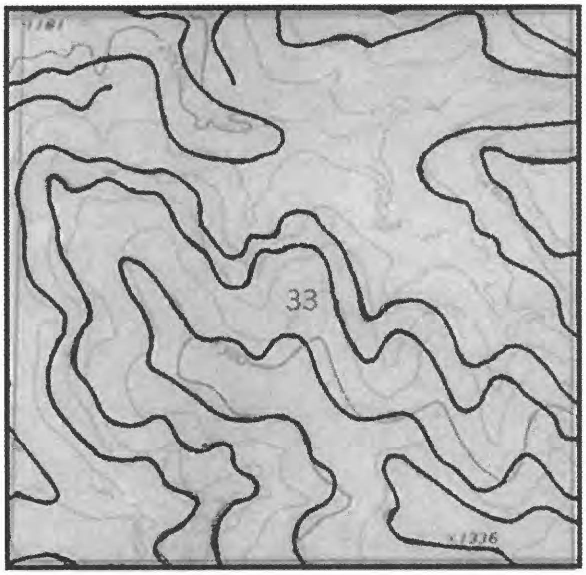


**Figure 5B.** Results of direct digitizing from Figure 5a superimposed on 1:24,000 topographic map

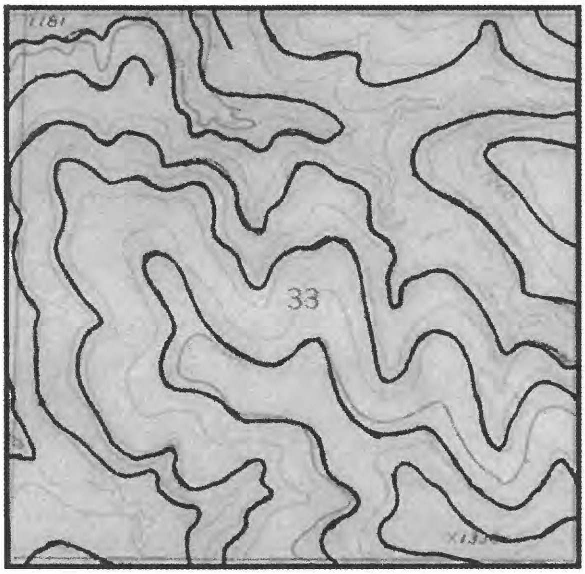


**Figure 5C.** Results, in the area of Figure 5a, from interpretation of R.C. Moore's map on a 1:24,000 topographic map

scales are likely to be unsuitable for use in combination. Rather than representing flagrant "cartographic license," the map interpretation methods recommended here in the development of geologic map databases represents a redrafting of available information while eliminating much of the cartographic license taken in the process of generalization which occurred when data from field mapping were originally prepared for publication at a small scale. Databases developed through the use of these interpretation methods would have an inherent compatibility due to the common base used for development, even though the information may be derived from adjacent source maps originally published at different scales.

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Since 1989, the Florida Geological Survey (FGS) has been engaged in digital mapping of local and regional surface and subsurface geology. The process has involved data transfer from paper maps to the computer-aided design (CAD) program, AutoCAD. In late 1996, the FGS acquired the requisite hardware, software and technical support to begin geographic information system (GIS) product development. Three digital mapping projects are in progress: 1) the statewide geological map of Florida; 2) subsurface mapping of lithostratigraphic and hydrostratigraphic units in Southwest Florida; and 3) a detailed geologic map of the Sarasota 1:100,000 quadrangle.

## STATEWIDE GEOLOGICAL MAP

Revision of the 1964 version of Florida's geologic map began in the late 1980's in response to the need for a peer-reviewed map that reflects current field data and lithostratigraphic nomenclature of surficial geology in Florida. In 1992, a grant from the Florida Department of Community Affairs (DCA) was obtained to support the project. DCA interest pertained to health concerns about radon and its relation to geological units in Florida. The grant, in the amount of $99,000, provided support for mapping Florida's 67 counties over an 18 month period. Six FGS staff geologists were involved in the mapping project. At the end of the grant period, continued financial support for this project came from FGS internal funds.

In Florida, surface sediments are comprised primarily of Holocene quartz sands with limited rock outcrops or exposures. Standard geologic mapping of outcrops was thus not a viable option for this project. As a result, mapping standards were developed to enhance geological detail: the *Geologic Map of Florida* is a sub-crop map that represents the uppermost geological unit observed within 20 feet of land surface. In areas where cover sediments are less than 20 feet thick, the underlying unit is mapped. If cover sediments exceed 20 feet in thickness, they are mapped as "Quaternary undifferentiated."

Geologic unit "contact" lines were hand drawn on base map 1:24,000 quadrangles. Contour lines on these maps were used as a guide for estimating sub-crop formation contacts according to the 20 foot mapping standard. The contact lines were then transferred by hand to Florida Department of Transportation maps (1:125,000) and then digitized using AutoCad (ver.10 through 12/DOS). Control points for the maps included the results from field mapping and lithologic descriptions of several hundred cores and cuttings sets. These samples were selected from the FGS core repository, which contains more than 17,500 sets of borehole cores and cuttings.

Base maps for this project were US Geological Survey 1:24,000 quadrangles. These maps were digitized using early versions of AutoCad and a composite basemap of the state of Florida was generated. Two FGS cartographers were assigned to this task during the DCA grant period. Hardware available during this phase of the project included two 486 IBM-compatible computers with at least 8Mb RAM, two digitizing tables (48" x 60") and a pen plotter. A Novell network was set up in 1993 in response to the increased need to share hardware devices, and to store, manage and backup large data files. In 1995, FGS network facilities were upgraded to Windows NT with full Internet access and e-mail capabilities.

Base maps and geologic map data were compiled by county and published in the FGS Open File Map Series (OFMS). This publication format was created to provide an interim source of information to the geological community until the statewide map becomes available in either digital or paper format. The OFMS maps were plotted at a scale of 1:125,000. Copies of the county geologic maps are available on the Internet in *.dxf format from *ftp://www.dep.state.fl.us/pub/geo/geomap*.

The statewide geologic map is an edge-matched compilation of the county maps. In 1997, this composite map has been exported as a .dxf file into the GIS software package, Arc/Info (ver.7.1). Map topology is presently being developed and will be followed by attribute definition. The map will be peer-reviewed in the second half of 1997 and a final paper version will be published in color at a scale of 1:750,000. The map, supporting text and metadata will be included in the Florida Department of Environmental Protection GIS Map Library. The final copy will become available on the FGS Internet web site as well. The format is yet to be determined.

## SOUTHWEST FLORIDA SUBSURFACE MAPPING PROJECT

This four-year project is a cooperative agreement between the FGS and the Southwest Florida Water Management District (SWFWMD). Research began in 1995 with the development of an extensive database containing more than 4,800 wells in the southwest Florida region. Funding for this part of the project totaled $15,000. The database contains all available information on the wells pertaining to location, construction, use, and types of geophysical and lithologic data. Once complete, this database was used to screen wells appropriate as control points for the subsurface mapping project, which will continue until 1999. The mapping phase is presently funded at $80,000 per year for three years. Each year, one third of the approximately 10,000 square mile study area will be mapped. Products to be generated include structure contour and isopach maps for Eocene and younger lithostratigraphic units and all regionally extensive aquifer systems, including permeable zones and confining units. The units for which the maps will be constructed are listed below:

| Hydrostratigraphic units | Lithostratigraphic units |
|---|---|
| Surficial aquifer system | Post-Pliocene |
| Intermediate confining unit and aquifer system | Hawthorn Group |
| | Peace River Formation |
| Floridan aquifer system | Arcadia Formation |
| Sub-Floridan confining unit | Tampa Member |
| | Nocatee Member |
| | Suwannee Limestone |
| | Ocala Limestone |
| | Avon Park Formation |

Database development utilized Paradox for Windows (ver.5). Basic well information had been entered into a spreadsheet prior to the beginning of this project. Data entry forms were designed to complement data existing in spreadsheet files. Information from drillers logs, geophysical log "header sheets," and index cards for each well were entered through use of the forms. Many of the wells were drilled prior to 1970 and a majority of the location information available was limited to Public Land Survey Coordinates (PLS). As such, the most accurate location for most wells was limited to the extent of a PLS section (i.e., somewhere within one square mile). Lack of sufficient funds and time precluded global positioning system (GPS) field confirmation of the more than 4,800 well locations.

Since any GIS-compatible database requires specific attribute coordinates (i.e., latitude-longitude or UTM) for a well location, each well was assigned a location accuracy value (meters radius), which becomes important when estimating well-head elevations for older wells. Elevation uncertainties translate to uncertainties in the mapped subsurface horizons. Locations accuracy values were determined by hand plotting all wells on 1:24,000 quadrangle maps using the most accurate, available location information, then calculating a maximum radius of uncertainty. For example, if the best available location for a well identifies only township, range, and section (TRS), the well is plotted in the center of the section and has a location accuracy value (radius) of 1138m. This value reflects the distance from the center of the section to any corner of the section. In order to determine Cartesian coordinates of wells plotted by TRS, each map was "locked down" using AutoCAD and through a script program, latitude-longitude and UTM coordinates were calculated and exported into ASCII text files. These files were then imported into the Paradox database. Typographical errors in location coordinates were almost completely avoided by utilizing this technique.

Once complete, the database was queried to provide a list of potential control point wells for the subsurface mapping project. Selection of control wells was based on sample location, quality (including sampling interval for cuttings) and total depth. Control point coverage for each horizon mapped is one well per 10 square miles. Although this is possible for the shallower units, deeper horizons, such as the sub-Floridan confining unit, will have less coverage due to a limited number of wells that penetrate the unit. Where possible, geophysical logs, primarily gamma-ray logs, will be evaluated for formation-contact estimates based on correlation of the logs to local stratigraphy.

Thirty cross sections generated from a separate FGS-SWFWMD cooperative study will be valuable correlation reference tools especially with regard to gamma-ray log response. Cores and cuttings from the SWFWMD Regional Observation and Monitoring Project (ROMP) wells were used in the cross sections. SWFWMD funding for the cross-section project, which began in 1992, has been $15,000 per year and is projected to continue into 1999. The cross sections not only depict regional lithostratigraphy and hydrostratigraphy, but also gamma-ray logs, topographic profiles and accessory minerals. An early effort to produce subsurface maps utilized formation contact boundaries from these cross sections. The data was imported into Arc/Info and the

Arc/Info Triangular Irregular Network (TIN) module was used to contour the data.

The database to be used for the *Southwest Florida Subsurface Mapping Project* will at least double the control point coverage used in the above-referenced TIN mapping effort. Contouring and map generation will apply the ArcView Spatial Analyst. Final stages of map generation will include consideration of boundary conditions, structural features and karst features. The final peer-reviewed maps will be published, added to the DEP GIS map library and will be available through the Internet.

## SARASOTA QUADRANGLE GEOLOGIC MAP

This mapping project began in 1996 and is funded equally by the FGS and the STATEMAP component of the USGS National Cooperative Geologic Mapping Program. Total project funding is $140,000. Detailed mapping of the 1:100,000 Sarasota County quadrangle is being conducted on a series of 1:24,000 base maps. In contrast to the statewide mapping project, this map will provide much more detail due to more extensive field mapping, data collection, review of local government files and drilling of six exploratory shallow cores (<50′ depth) using a Mobile auger drilling rig. County or regional agencies such as the SWFWMD, and Sarasota and Manatee County Health Departments, etc. have water-well and plugging-permit files that contain geological data from local drillers and consultants. This information, coupled with visits to mining and excavating operations will add significant detail to the map.

One challenge that exists in the development of this map is delineation of the Pliocene-Pleistocene units. Historically these units have been mapped based on biostratigraphy rather than lithostratigraphy. As such, many of these older units will be incorporated into more generalized subcrop units. Mapping criteria is the same as that of the statewide geological map—the uppermost geologic unit within 20' of land surface. The final product will be digitized in Autocad (ver.12), on a 1:100,000 Sarasota quadrangle basemap. Included on the map will be a description of the regional geology and up to four cross sections.

## SUMMARY AND FUTURE DIRECTIONS

Digital mapping at the Florida Geological Survey has come far since the first digitized products were completed as early as 1989. The first hardware configuration included an IBM-compatible 386 computer with a math co-processor, 2Mb RAM, a small digitizing pad and plotter. Present facilities include Pentium computers, a Sun Microsystems Ultra2 workstation, two x-terminals and an HP Designjet 750C plotter. Software used for digital mapping has evolved from AutoCAD version 10 to version 12, and mapping has just begun using Arc/Info and ArcView. Today, core drilling sites and surface samples are located using GPS, rather than estimating locations on 1:24,000 quadrangle sheets.

Future digital mapping projects at the FGS include a revision of the physiographic map of Florida and continued work on STATEMAP and water management district projects. Digital maps produced by the FGS are useful toward ecosystem management, environmental protection, solid-earth resource assessment and permitting, rules enforcement, conceptual frameworks for ground-water flow models, and baseline geologic and hydrogeologic research.

# Digital Geologic Mapping Program at the Geological Survey of Alabama

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## INTRODUCTION

Geology, like other scientific disciplines, has seen a rapid increase in the routine use of sophisticated computer technology in recent years. Desktop computer workstations continue to become more powerful and affordable while software packages with tremendous capabilities continue to become easier to use and more robust in functionality. Of particular importance to geology and the earth sciences has been the development of Geographic Information Systems (GIS) technology, which combines comprehensive geospatial database management and analytical capabilities with the ability to produce, on the computer screen or as printed output, highly-accurate maps that represent underlying database information or analytical derivatives thereof. Unlike traditional hardcopy maps, which are generally printed in relatively large quantities and distributed over a long period of time regardless of new information that might come available, maps derived from digital data can be produced on demand and, therefore, a map representative of the most recent data contained in the database can be generated, thereby assuring currency of the information depicted. Further, modifications to GIS databases, such as corrections or new data entries, can be easily and quickly implemented, imparting long-term usefulness to the data set through a program of routine maintenance and update.

For the past several years, the Geological Survey of Alabama (GSA) has conducted its geologic mapping program, particularly at the 1:24,000, 7.5-minute quadrangle scale, using GIS technology for data compilation, storage, analysis, and output. During this time, we have developed techniques that greatly automate and expedite the process of map production, integrally involve the geologic mapper or mappers in all phases of the process from field data collection through GIS development to map finalization, and result in comprehensive and useful digital geologic data sets for a variety of applications, as well as traditional hardcopy maps and reports. This geologic mapping program and the development of GIS techniques for geologic mapping have been greatly facilitated by support from cooperative agreements with the United States Geological Survey (USGS) under the auspices of the STATEMAP part of the National Cooperative Geologic Mapping Program, which was authorized by the National Geologic Mapping Act of 1992. To date, three 7.5-minute quadrangle maps have been completed under this program (Osborne, 1995; 1996; Osborne and others, in review), field mapping and data collection for three quadrangles are underway at present, and funding for four additional quadrangles has been approved. The majority of these mapping projects involve structurally deformed areas in the Valley and Ridge geologic province of Alabama and, thus, the completed projects have provided excellent cases for developing our methodology in geologically complex areas. Although the techniques used continue to evolve, we feel that we have addressed many of the major issues and problems associated with geologic mapping in the GIS environment and that our methodology suits our purposes quite well. The purpose of this paper is to provide an overview of the techniques used for digital geologic mapping at GSA and to present some of our plans and goals for the future. The methodology described below has been developed using ARC/INFO, a commercial GIS software package from Environmental Systems Research, Inc. of Redlands, California and Excel, a commercial spreadsheet software package from Microsoft Corporation, Redmond, Washington. The use of these software packages and their registered trademark names in no way constitutes their endorsement by the Geological Survey of Alabama or the State of Alabama.

## DIGITAL GEOLOGIC MAPPING PROGRAM

### Field Data Collection and Primary Compilation

As with any geologic mapping program, the most fundamental and important aspect of mapping using GIS technology is the collection of accurate, detailed field data. GSA has a highly qualified, experienced team of geologic mappers that form the nucleus of our mapping program. This team works under the guidance of a state-wide geologic mapping committee, composed of government, academic, and private sector geologists, that assists in the selection of quadrangles to be mapped through a prioritization process. Selected quadrangles are then formally proposed for mapping to USGS under the STATEMAP part of the National Cooperative Geologic Mapping Program and funded proposals are implemented as mapping projects by GSA. Data are collected using standard and accepted field mapping techniques incorporating traverses, measurements, observations, sampling, and detailed written and photographic documentation. Field data are initially compiled and interpreted by the mapping team on scale-stable contact prints produced from scale-stable film positives of 7.5-minute topographic quadrangle sheets acquired from USGS.

### Preparation for Digital Capture and GIS Database Development

Preparation of data for digital capture generally consists of three parts: (1) transfer of features for each map feature type onto scale-stable overlays to facilitate digitization, (2) uniquely identifying each feature of each type, and (3) entry of feature attribute data, along with unique identifiers, into a spreadsheet program. In order to minimize the possibility of introducing errors, the mapping geologist or geologists are responsible for data preparation in coordination with the GIS Specialist assigned to the project. We have found that this not only involves the geologist in the digital data capture process and encourages interaction between the mapper and the GIS Specialist, but also adds a level of quality control, in that the geologist, through familiarity with the study area and the data set, is more likely to recognize errors and mistakes than the GIS Specialist at this phase, thereby minimizing changes later in the process.

In general, we have found that the compiled and interpreted working maps discussed above tend to become very cluttered with information, leading to the possibility of confusion or error during the digitization process. This is especially true in areas of complex geology. Hand-drawn and -written information on the compilation map includes symbolized lines for geologic contacts, faults, and the axes of structural features, symbols indicating where structural orientation data were collected, geologic sections were measured, samples were taken, and contacts were exposed, and annotation, such as the names of structural features, codes for geologic units, dip values, and other notes. For digital data capture purposes, we have determined that it is desirable to separate features of different type by transferring each feature type (or subset thereof) onto a clear, scale-stable overlay that is punch-registered to the original compilation map. Georeferencing for each overlay is accomplished by transferring the corner tics from the quadrangle to the overlay. The primary feature types on a geologic map are: (1) polygon or area features (areal extent of geologic units), (2) lines (contacts, faults, etc.), (3) points (structural data points, exposed contacts, etc.), and (4) text. It is also helpful to depict each feature on an overlay in its simplest form. For example, on the compilation map, an approximately located thrust fault would appear as a dashed line with teeth on the upper plate, whereas an approximately located geologic contact is indicated by a dashed line. For the purposes of digital data capture, these features are transferred to the overlay as simple lines. Similarly, structural data points, depicted on the map as strike and dip symbols and symbols for horizontal and vertical beds, are transferred as simple points located at the center of the symbol.

After transfer to the overlays, each feature is assigned a unique number that will later be used to link attribute information to the feature. For each overlay, features are numbered consecutively, in most cases beginning with 1. We normally begin numbering in the upper left-hand corner of the quadrangle and attempt to make the numbering scheme as easy to follow as possible, particularly in areas with dense features. This facilitates using the capability of the GIS digitizing system to automatically increment the identification number for each new feature in the feature database, thereby allowing the GIS specialist to quickly capture the data without stopping to enter unique numbers.

The last step in data preparation is the entry of feature attribute and ancillary data onto spreadsheet. We use a spreadsheet software package for data entry primarily because the majority of our staff is familiar with its use for data compilation and manipulation and, thus, no special training is required. Tables are prepared for each feature overlay and, in these tables, feature data are keyed to the above unique numbers for features. Information entered into the tables include orientation data for structural measurements (strike, dip, bearing, plunge, etc.), codes for point and line symbolization, codes for colors of geologic units, descriptive names for features (e.g., "thrust fault, approximately located"), annotation for named geologic features (e.g., "Fungo Hollow deformed zone"), geologic unit names (e.g., "Newala Limestone") and codes (e.g., "On"), notes, remarks, etc. Having this information as part of the eventual GIS database facilitates automation of many of the orientation, symbolization, and annotation requirements for hardcopy output of the geologic map, as well as provides a robust geologic database for use in various applications.

Importantly, the spreadsheet tables are also used to calculate orientation angles for geologic symbols and annotation that require orientation, such as strike and dip symbols or geologic feature names that need to appear on hardcopy output at some angle to the horizontal. In the GIS system used, all point features, including text anchored to a justification point, have a "hidden" database attribute for rotation angle ($ANGLE) and the default value for this attribute is zero. Further, negative azimuth angles indicate clockwise rotation of the point about its center. Thus, a rotation angle of "–90" indicates a clockwise rotation (toward the east) of 90 degrees. As an example, we have created a geologic symbol set in which a strike and dip symbol with zero rotation corresponds to north strike with dip to the east, whereas a symbol with an angle of –90 corresponds to east strike with dip to the south. During field data collection, the mapping team records strike and dip data in the traditional quadrant notation form, such as N35E, 20SE. To facilitate the calculation of symbol orientation, these data are entered into spreadsheet columns as follows: strike quadrant (e.g., NE), degrees from north (e.g., 35), dip direction (e.g., SE), and dip amount (e.g., 20). At this point it is possible, using the sorting functions of the spreadsheet application, to segregate measurements into groups based on the eight possible combinations of orientation (i.e., N-S strike with E dip, N-S strike with W dip, E-W strike with N dip, E-W strike with S dip, NE strike with SE dip, NE strike with NW dip, NW strike with SW dip, and NW strike with NE dip). Following this grouping, the rotation angle can be either entered explicitly for the North-South and East-West strikes (0 (N with E dip), –90 (E with S dip), –180 (N with W dip), and –270 (E with N dip)) or calculated with a formula for orientations that are oblique to the cardinal points. It is important to note that only eight entries are necessary using the "Fill/Down" spreadsheet function for each group entry, regardless of the number of data points in the each group. In this example, the formula entries for the oblique orientations are as follows: NE strike with SE dip—rotation angle (RA) = (strike angle + 180 (–1)); NE strike with NW dip—RA = (strike angle (–1)); NW strike with SW dip—RA = (strike angle – 360); NW strike with NE dip—RA = (strike angle – 180). In our experience, the sorting and calculation process, including formula entry, takes less than five minutes. Though not absolutely necessary, as a clean-up step, we generally sort the data by unique number after the calculation process has been completed. The final step is to convert the spreadsheets to dBASE III database format files using the "Save As/DBF 3" command. The GIS can directly import dBASE III files into the INFO database, thus saving time and effort in linking the data to map features (using the unique ID) after data capture. At this point, preparation of data is complete.

## Digital Data Capture and GIS Database Development

At present, digital capture of geologic map features from the overlays discussed above is accomplished by manual digitization on a high-accuracy digitizing table using the GIS's digitizing system. Each overlay is attached to the table and registered to the quadrangle's corner tics extracted from GSA's master 7.5-minute Universal Transverse Mercator (UTM) coordinate system grid, which was generated in the GIS using the latitude and longitude coordinates for the corners of each 7.5-minute quadrangle with area in the State of Alabama and projecting the resulting base into the UTM coordinate system. An acceptable maximum residual mean squares (RMS) error for registration of each sheet is adopted and rigidly adhered to. If registration results in unacceptable RMS error, the overlay is re-registered until within the acceptable limit. Registration of overlays in this manner to a mathematically generated base assures highly accurate georeferencing of each. Features on each overlay are digitized consecutively by unique number. After digitization, the GIS layer for each overlay is processed to generate topology, checked for topological errors, and edited until all such errors are corrected. At this point, check plots are generated at map scale and checked against the overlays for obvious errors. After correction, additional check plots are generated at map scale on scale-stable media and checked against overlays and the original compilation map for proper registration and feature location. This process continues in an iterative fashion until all digitizing errors are corrected and the digital data exactly correspond to the overlays and original compilation map.

Upon completion of the topologically correct GIS layers for each overlay, we proceed with GIS database development. This consists of attaching the data from the spreadsheets above (saved as dBASE III files) to the GIS data sets. The dBASE III files are imported into INFO database tables and these tables are joined to the feature attribute tables using the software's table joining function on the basis of the common unique identification number for each feature. Once these tables are joined, the digital data development part of the digital geologic mapping process is essentially complete.

## Map Production

The digital data for a geologic map are compiled for printed output using interactive GIS map composition tools. The databases developed above contain all of the information necessary for automated symbolization, orientation, and location of geologic features and observations and text for annotation. The GIS specialist, through the use of commands to set certain parameters (map scale, page size, linesets, symbolsets, fonts, etc.) and database queries to call up desired overlay layers and features, can quickly assemble a cartographic-quality geologic map. At GSA, we have created line, symbol, and color-fill sets that incorporate standard and accepted geologic symbology and map features are drawn with these elements using codes that are included in the database. Cartographic elements, such as titles, legends, neatlines, arrows, pointers, leaders, scales, etc. are easily added to the map through an interactive, on-screen process. At the present time, we use pen, electrostatic, and ink-jet plotters for on-demand map output and have also produced scale-stable film output for use in preparation of plates for printing on an offset press.

### Future Plans

There are several areas that are integral to the continued development and automation of digital geological (and other) mapping in the GIS environment at GSA. Our process would be greatly accelerated (and much less labor intensive) with a migration from manual digitizing to utilization of scanning technology for data capture. We presently have the software capability for raster to vector data conversion and hope to acquire a large-format, high-resolution scanner in the near future for this purpose. We would also like to begin to incorporate Global Positioning System (GPS) and digital data logging technology into our field data collection efforts. Much of the data that is presently entered in field notebooks by hand and transferred to spreadsheet tables at a later time can be directly captured in a digital format in the field along with locational data using a GPS unit with attached data logger or laptop computer. These data can be directly imported into the GIS, thus saving considerable time and duplication of effort. Finally, we would like to continue to enhance our computer and software capabilities in terms of power, speed, functionality, and storage capacity in order to be able to take full advantage of new innovations in digital mapping and GIS technology.

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# Overview and Evolution of Digital Geologic Mapping at the Oregon Department of Geology and Mineral Industries

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## OREGON GEOLOGIC MAPPING

The Oregon Department of Geology and Mineral Industries (DOGAMI) has been publishing geologic maps of Oregon for 60 years, often in cooperative efforts with federal, state, regional, or local agencies. For many years, the agency has maintained cartographic staff for the production of geologic and mineral resource maps and related publication elements. The familiar multicolored geologic map on an accurate topographic base continues to be the preferred mode in meeting the agency's mandate for earth science information dissemination. However, evolving digital tools and user needs have changed the production and format of geologic map information.

## CONVERSION TO DIGITAL MAPPING METHODS

With the availability of digital tools for mapping, DOGAMI sought to gain efficiencies from automated methods while continuing the production of highly refined multicolored geologic maps. In 1992, a CAD system was installed that automated the majority of map production phases. MicroStation CAD on personal computers is used for: digitizing author's original greenline mylars; creating the various geologic line types, symbols, and text; organizing and manipulating these elements into standardized geologic map form; and finally culminating in the direct production of large-format high-resolution imagesetter negatives for offset printing. This major change in the production process resulted in the same high quality final printed map. This established production mode remains in practice today for areas of high demand with both the printed map sheet and CAD files made available to the public.

## EVOLVING GEOLOGIC MAP USER NEEDS

DOGAMI strives to meet the ever-widening range of needs of geologic map users. Users of geographic information systems (GIS), while able to utilize CAD files with some effort, have further requirements for digital geologic map files. GIS needs easily translatable, properly georeferenced, and attributed map files. As a result of funding from the USGS National Cooperative Geologic Mapping Program, DOGAMI is currently engaged in converting existing 1:100,000 scale hardcopy maps to digital form. Furthermore, the intent here is to begin creating a statewide digital geologic layer for Oregon. Three 100k geologic maps have been scanned by a contractor and are undergoing data editing, structuring, and attributing. The desktop GIS, MapInfo is being used for most of this project and has been installed in all DOGAMI offices. It is envisioned that the development of a statewide digital geologic layer for Oregon will meet many different user needs. These needs vary from local customized data sets and plot-on-demand products to support of derivative mapping and offset printed products released in high volume for heavily populated urban areas.

# Digital Map Production at the Minnesota Geological Survey

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In recent years, the Minnesota Geological Survey has moved steadily in the direction of creating and publishing maps and other materials using computer-generated digital files instead of traditional cartographic and offset printing methods. The transition from paper to digital-file formats has largely coincided with the availability at reduced cost of more powerful personal computers, inexpensive random access memory, and numerous improvements to graphics and publishing software. The MGS has created both maps and booklets in digital format and is currently working on several projects for which the end product will be digital. For example, the surficial geology map of Waseca County went from data capture through the making of composite, screened negatives for the printer entirely as a digital file. Other digitally created publications include open-file maps of Houston County, aerial gamma radiation maps of Minnesota, and educational pamphlets on Minnesota geology. A booklet produced for one of Minnesota's state parks was printed from a digital file and made use of text, scanned 35-mm color photographs, and computer-graphic files.

Conversion of data from analog to digital format at MGS is primarily done by scanning at a service bureau, in-house vectorization, in-house digitization of point data, and reading of existing digital data (for example, GPS points). We do not refer all data capture operations to service bureaus because we prefer to keep some control of the data as they are being entered. Geologists enter some map information into database files while in the field, and for one project outcrop locations are being entered by the geologist onto digital USGS base maps, from within Arc/Info. For the present and probably for the near future, initial geologic maps will still be created by hand before being scanned into a digital format. Following the data capture stage, the majority of the MGS map compilation and production is done on Sun workstations using Arc/Info. Ancillary graphics and text are created and compiled on Macintosh PowerPc computers using Adobe Illustrator, Adobe Photoshop and Microsoft Word. Final compilation and page layout is completed using Adobe Pagemaker. These programs generate files that are readily integrated with each other and with software used by printing companies for pre-press preparation and film making.

The evolution to digital map production at MGS began with the purchase of Arc/Info for a DOS personal computer platform, but it was greatly enhanced with the use of Sun workstations and more robust versions of the ARC software. The most recent evolutionary step has been the integration of ARC output into relatively user friendly Macintosh illustration and page layout software for final compilation and publication. Our recent use of personal computers to produce a single composite file from Arc/Info and other graphic and text sources allows us to create higher quality printed text over what is available from the ARC environment. With this integration, we are in the process of transferring the responsibilities for a final product from geographic information system (GIS) operators to editors and graphic artists who are more familiar with the personal computer software, editing, graphics, and publishing. We have also benefited by developing a good working relationship with several printing shops which have allowed us some experimentation with various digital formats and file types to identify which would produce the best product. Most printing shops are also in early stages of accepting and working from digital files and are quite willing to work with us on meeting our requirements.

The evolutionary process has not always been without problems. Static or shrinking budgets have restricted or prevented initial purchase of up-to-date computers, software and networking systems. We, possibly like other organizations, have more than one computer system in-house and certainly have more than one generation of hardware and software. With manufacturers constantly changing hardware and software, end users such as the MGS find it very difficult to keep up. We find that even though most of the computers in the organization are fine for general tasks, they often won't run the newest versions of software. Although not always a problem internally, keeping current with software is important when dealing with those outside organizations such as print shops that may use the latest versions of software. We also have the problem that MGS staff, particularly outside of the GIS area, are not formally trained in much of the software in use, but learn as they go, or as needed. Some of the increased productivity that computers are expected to provide is therefore being lost to learning the current software to do a particular job. That person may be doing an entirely different job when a new publication is ready, and someone else will learn what is needed to complete the job. In small organizations like the MGS, with limited staff, this needs to be factored into timelines for completion of projects.

Map production at MGS is tied in heavily with use of an appropriate geographic base. In the past, we have acquired negatives from the USGS, used Tiger (census) and digital-line-graph (DLG) files and most recently, have begun to use digital raster graphics (DRG) files from the USGS. In the move to digital compilation, digital-base files are useful in putting together a complete product. Although we have used non-digital base maps when printing a geologic map from a digital file, most of the new contracts specify that a final product be provided in digital form, therefore requiring the base also to be digital. The MGS is currently acquiring all topographic maps of Minnesota in DRG format as they become available and is moving away from the Tiger format as a digital base. Base files in DRG format work well because they supply topography and complete annotations and are usually more accurate than Tiger and DLG files. They also are available at standardized 1:24,000, 1:100,000 and 1:250,00 scales. Although we save time by not correcting and annotating the Tiger base files, the DRG files present some new problems that we are just beginning to solve. For example, the DRG files are TIFFs—bit-mapped images—rather than vector-line plots. Editing individual components of an image is more difficult and the line quality is poor for fine lines. DRG files are also very large and require substantially more computer memory and disk space than vector files. We are also still looking for a good method to transform DRG basemaps so they will print as screened, transparent grey lines over color.

The primary users of maps and reports from the MGS are the public, county and state officials, state departments, and environmental, mining and public relations organizations. As the availability of digital production formats has increased, so have the options for output to our product users. Within the ARC environment, maps can be sent directly to a plotter, or can be transferred by disk or network, for additional processing or to a printer for making film. Data and maps can also be prepared as ARC export files for transmittal to groups and organizations that wish to use the information for their own purposes. Additional output options include on-demand plotting of maps on a wide-format plotter, laser printing of text and photos, and network accessible electronic formats such as Adobe PDF or Sun TAR files on our FTP site. We presently have several files and reports available via an FTP connection or via links from the MGS Web homepage (http://geolab.geo.umn.edu/mgs).

Although our capabilities of creating output have increased, each type of reproduction and output process currently available, including traditional ink drafting, cartography and offset printing, involves trade-offs. Currently no file type is optimal for all types of reproduction. Transfer or printing of electronic files can present problems if networks are slow or unavailable and they may be printable only on certain types of printers or plotters. On the other hand, digital files can be updated, and changes published, without having to make obsolete hundreds of printed copies of an older version. We have recently updated our Geologic Map of Minnesota, Bedrock Geology (S-20). Easy digital updates raises the question of bibliographic tracking. For instance, when and how are the original and subsequent revisions (both major and minor) recorded for citation?

In the move to a digital publication process, the MGS as an organization has begun to re-examine the process of map preparation and production from the geologist conducting field work, to technical review, to data capture and input into the GIS system, to editing, final layout and printing. We view this as an ongoing learning process and, while not without difficulties and drawbacks, is a move in the direction of the future. Given the constraints of limited resources, mysteries of finances, infrastructure, personnel and experience, and the rapidly changing playing field of digital publishing, our results have been satisfying. We are well on our way to achieving our objectives of disseminating geologic maps and other research results in a timely, cost effective, and widely accessible manner through digital as well as non-digital means.

# Geological Mapping in Linn County, Iowa

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The Iowa Geological Survey Bureau (GSB) has been involved in a three year STATEMAP project in Linn County, Iowa to map the surficial geology of five 1:24,000 quadrangles and map county-wide bedrock geology and surficial geology at 1:100,000 scale ("STATEMAP" is a component of the USGS National Cooperative Geologic Mapping Program). The main goal of this project was to develop detailed geologic information for use by local officials, private businesses and the public in Linn County to aid them in natural resource decision making. While providing geological information for such purposes has always been a significant part of the mission of GSB, the development and construction of detailed 1:24,000 scale maps has not been a significant part of meeting it. Thus a secondary goal for this project was to develop expertise in field mapping techniques and construction of geologic databases. It was felt early on that developing traditional geologic maps alone would not meet the first goal of providing useful information to decision makers, such as county planners and engineers, solid waste authorities and county health officials, due to the lack of geological expertise found at their local level. More useful would be information in the form of interpreted "derivative maps", or geological data and other information presented in a thematic form, such as maps of aggregate resources or groundwater vulnerability. At the same time it was felt that providing the data as geographical information system (GIS) coverages could also enhance their usability in fledgling county and city GIS programs. At the start of the project, all of these ideas were major unknowns, and while subsequently have mostly proved to work, the acid test of really being used by those in the county still remains to be seen.

## MAPPING TECHNIQUES

The Linn County STATEMAP project became an experiment to develop "paperless" geologic maps, wherein most if not all of the construction of the geologic map takes place on the computer. This does not mean that a computer "black-box" does all the geologic mapping nor does it mean that some non-geologist computer operator interprets geological contacts. Geologic interpretations were all done by the mapping geologists using a GIS and detailed digital coverages as a base for mapping. Through the use of GIS techniques, their ability to bring many different data layers together for viewing, interpreting and mapping was greatly enhanced. The mappers still used traditional data sources such as soil surveys, topographic maps, and aerial photos, but in non-traditional digital format. Field notes and drill samples were collected and recorded on paper field notebooks and had to be entered into databases and spreadsheets. Some structural surfaces and isopach maps were also done on paper first, then digitized. The biggest experiment was in mapping surficial geologic contacts, which were composed on-screen rather than on a paper 1:24,000 scale topographic map and later digitized on a tablet. One advantage to on-screen mapping was the ability to view background data and draw contacts at a larger scale (usually 1:12,000), rather than the 1:24,000 target scale. This makes locating outcrops easier and drawing smoother looking lines. The main advantage to this procedure was that the geologist making the interpretations also did the digitizing, which in the past would normally have been done by someone else, usually a graduate student. This removed the potential for the digitizing person to misinterpret the location of the line work and made the final GIS coverage reflect the mapper's original interpretation much more closely. A side benefit was getting some non-computer-literate geologists directly involved in the creation of their spatial database, getting them to see other uses for the technology and getting away from having GIS staff do the "computer mapping" part of the project. The steps used to create the main geologic coverages are outlined below. Digital GIS coverages are underlined.

**Steps taken to create 100k bedrock topography coverage:**

1. extracted bedrock exposures from digitized soils data
2. modified bedrock exposure polygons using field notes and added unit designations
3. plotted subsurface bedrock elevations from well databases, including GSB water well strip logs files, DOT bridge borings, USGS core holes, and GSB core and auger holes
4. surface elevation contours using bedrock exposure polygons, and added to plot of bedrock elevations from wells
5. mapping geologist draws contours by hand on plot of bedrock elevations
6. digitized bedrock contours on tablet digitizer; 50 meter bedrock surface grid interpolated from contours
7. 50 meter surface elevation grid interpolated from 100k surface topographic contours
8. subtracted bedrock surface grid from surface elevation grid to create preliminary depth to bedrock grid; zeroed out negative depths; divided depth to bedrock grid by 50 to create integer classes of depth values to simplify conversion to vector format; converted to polygon coverage; made contours of Quaternary thickness
9. subtracted depth to bedrock grid ( without negative depths) from surface elevation grid to create new bedrock surface grid; calculated shaded relief of bedrock surface for visual depiction of bedrock surface features.

**Steps taken to create 100k bedrock geology coverage:**

1. plotted elevations of various bedrock mapping units from well database; mapping geologist draws structure contours by hand; some units done as isopachs to be added to other structural surfaces
2. digitize structure contours on tablet digitizer; 100 meter structural surface grids interpolated from contours
3. subtract bedrock structural surface grids from bedrock surface grid to create subcrop grids (areas of zero or less are areas of subsurface outcrop—ignore positive values)
4. combined subcrop grids together into one bedrock unit grid (start by stacking youngest unit first, and so on); converted combined grid into polygons of bedrock geology

**Steps taken to create 1:24,000 surficial geology coverage:**

1. assembled digital orthophotos, digital soils, surface topographic contours
2. digitized field locations: outcrops, excavations, core and auger holes
3. digitized surficial geology polygons on-screen (using orthos, soils and contours as back drop)
4. edited, checked and added unit designations to surficial geology polygons

The main disadvantage to these procedures is the amount of data (soils, orthophotos, etc.) that had to be assembled before the on-screen digitizing could begin. We were very fortunate that Linn County was a test project area for digital compilation of 1:24,000 line features for revising topographic maps, and many of the necessary layers were easily obtained. Also, Iowa has a statewide project to digitize all the existing soil surveys in the state, which is nearly complete. Digital raster graphics (DRGs) or scanned 1:24,000 topographic maps are coming into wide availability as another useful base map layer. On-screen digitizing was done with the Arcview 2 product from ESRI on an IBM-compatible desktop computer with a Pentium processor. Grid processing was done with the Arc/Info 7.0.1 GIS program on a UNIX workstation. It should be noted that both capabilities now exist in the Arcview 3 product with the Spatial Analyst extension for use on desktop PCs.

## DERIVATIVE MAPPING

The three basic geologic coverages were then used to create various derivative maps. The bedrock geology, depth to bedrock and surficial geology coverages were intersected at the 1:24,000 quad level to create one combined coverage with attributes and polygons from all three. One of the nice features of this approach is the ability to turn on and off various combinations of bedrock units, surficial units and depths in order to try out different scenarios and models.

1. An aggregate map showing sand and gravel deposits as well as suitable carbonate bedrock units less than 25 feet from the surface. One of our local STATEMAP partners is a quarry operator—they promptly made off with the preliminary copy of the map.
2. A groundwater resources map showing bedrock units reclassified as aquifers and aquitards, surficial units and drift sands that are aquifers.
3. Miscellaneous hazards map including surficial units that have slope stability and seepage problems, a karst forming bedrock unit less than 25 feet from the surface, and locations of underground storage tanks, the landfill, uncontrolled sites, hazardous waste generators, and waste water treatment plants along with municipal water supplies. These potential hazardous sites were extracted from various state Environmental Protection Division GIS coverages.
4. A groundwater vulnerability map developed from a GSB vulnerability model. Various surface units were reclassified into most vulnerable, vulnerable, and less vulnerable categories based on their permeabilities and natural occurrence of aquitards. Shallow bedrock aquifers less than 50 feet deep, karst developing bedrock and surficial aquifers were classified as most vulnerable to contamination from near-surface sources. Areas overlain by 100 feet or more of slowly permeable glacial deposits are

classified as protected from surface related contamination.

## MAPPING ISSUES AND FUTURE CONCERNS

One mapping issue that should be addressed at some time is the determination of the accuracy of the mapping. I believe the need for this is obvious, as in letting map users know what kind of confidence we geologists place in the interpretation. As to how to do this, I don't have any good ideas, only some old tests used in accuracy assessments of land cover derived from remote sensing data. This usually involves randomly selecting a number of locations from each mapping unit and physically visiting each site and determining whether it is correctly mapped. The documentation for the coverage or map might state something like "8 out of 10 test points for this unit tested correctly." There are many questions as to the practicality of this, and how test points would make a statistically valid sample. Assessing bedrock elevations and geology are even more problematic. Typically, a plot of the well data points is used to give a qualitative indication of the amount of information available to the mapper, but does nothing to test the validity of the geologic interpretation. This does not even begin to address the question of validity of derived products, which may be based on the intersection of several geologic coverages of unknown quality.

Throughout this article I have used the terms "geologic map" and "derivative map" to describe something which is really more specifically geologic databases, made up of one or more GIS files or coverages. Rooted in our past experiences and training, it is more comfortable to speak in terms of maps than digital geologic data. It will take some effort to develop concepts that more fully describe our geologic models in digital form. Maps, while familiar, are objects limited to a particular time, scale, and concept of reality. Digital geologic models (in our case in the form of GIS coverages) are somewhat more flexible because they can be modified and updated more readily (if one has the time), can be viewed at differing scales, and can be combined with other digital coverages to create totally new models and applications. Maps are still a very useful and necessary means of conveying information, but our focus in the "mapping" field must be turned to creating and developing the geologic databases necessary for solving society's natural resource problems (a main justification for the existence of the USGS National Cooperative Geologic Mapping Program and the National Geologic Map Database).

This gets into the discussion of developing standards for geologic data models, not standards for producing maps. Again, standards for the cartographic representation of geologic data are important and necessary, but the really critical universal element is the underlying data, its structure and content. Our experience has been that making geologic coverages compatible between different quads in the same project is sometimes difficult (lack of discipline and attention to detail), and between projects in the same state even more difficult (different mappers with different backgrounds), and between different state surveys under current circumstances may be next to impossible (state-line "faults"). Imagine trying to do some kind of a regional industrial site suitability assessment across a state border when one state's geologic model includes certain geologic units and the other state used a different set of attributes for slightly different mapping units, mapped at a different scale. Each mapping project or mapping geologist seems to have their own geologic model which usually isn't 100% compatible with other projects. Perhaps what is needed is some minimal standards for simple geologic data models that could be used as a starting point for new mapping projects. Developing such data models could be the focus of an EDMAP (educational equivalent of STATEMAP) project or some joint STATEMAP projects between adjacent states (Quad Cities, Iowa and Illinois for example). Elements that need to be considered in developing standard geologic data models include what geologic attributes are to be mapped (time, lithology, biostratigraphy, hydrogeological properties, engineering properties, etc.), type of mapping (bedrock, surficial, stack unit, soils, geomorphology, geophysical, etc.), resolution or minimum mapable features (minimum size of an object, which is somewhat related to eventual display scale; mainly a function of an attribute's variability) and how to represent three dimensional data (as a series of 2-D layers in polygon form, a series of 2-D grids, a 3-D grid of "voxels," or as 3-D vector type objects). The surficial geologic databases constructed for Linn County are 2-D vector GIS coverages mapping mostly time units with a few other material attributes thrown in, to a maximum depth of 5 meters. Even then they don't really do a complete job of portraying the variability within that 5 meters. Availability of data is a big controlling factor in what gets mapped, at what resolution, to what depth and areal extent.

Finally, a very important consideration (perhaps the most?) is the customer (probably a non-earth scientist) who will try to use this geologic information. Will a geologic map of chronostratigraphic units meet their needs for land use planning, locating sources of aggregates and groundwater, seismic hazard mitigation? Can anyone in their office read and interpret a geologic map? What system (CAD package, vector GIS, or none) do they have for using our data with theirs? I think this is a real challenge for geologists to deal with, particularly in our state survey. We need to figure out what information local users need, in what form, and how we assemble the resources to meet those needs. We're not there yet.

# Digital Geologic Mapping Program at Virginia Division of Mineral Resources

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## PART 1

### Background

The Virginia Division of Minerals Resources (DMR) initiated a program to convert its published geologic maps and all future geologic mapping, compilation and map publishing activities to a digital basis. This decision was driven by several factors:

- Need to reduce printing and storage costs
- Need to reduce budget
- Dramatic reduction in staff with restriction on future hiring
- Increasing demand for digital information by clients and customers

In light of the budget and staff restrictions, a computer group of digitizing specialists with expensive single-task hardware and software was not realistic. Furthermore, experience had shown that the more distant the data entry activity was from the data collection activity, the more errors occurred and went uncorrected. Therefore, a basic requirement for software was that it should be capable of operating in the field on a 486 or Pentium portable computer and that it should be mastered easily by any field geologist. Other important requirements were the capabilities to:

- draw mapped contacts directly over raster images of topographic sheets or satellite data
- plot strike and dip data and other structural information
- plot tabular data such as chemical analyses
- embed digitally and retrieve field observations such as outcrop or thin-section photos
- attach multiple attributes to lines and areas
- create and maintain up-to-date digital geologic maps that can also be printed as "maps-on-demand"
- produce digital maps in non-proprietary, simple, and ASCII file formats that can be readily translated into any other GIS format

The last requirement was important because as a state agency DMR felt that it could not show "favoritism" by requiring its clients and customers to purchase a particular brand of software in order to use the data. Furthermore, DMR is primarily concerned with map-making and providing data rather than with GIS analysis.

We examined a number of digital mapping systems a few years ago. The public domain GIV (Geologic Information Visualization) software developed by Russell Ambroziak of the USGS was simple but limited in scope. We collaborated with Innovative Technology of America (ITA) to develop ABICAS mapping software (which grew out of GIV) to meet all of the requirements of geologic mapping and printing at a state geological survey. ABICAS runs only on MS-DOS systems at the present time.

### Time Requirements

Four staff members have been involved with the technical process of software development and use over the past 2 to 3 years. No staff member has devoted a full-time effort to the digital program because of other critical on-going duties (field studies, computer network/hardware management).

We have not completed new geologic maps via the digital process in the field because field mapping is still in progress. Time requirements and costs for completion of new mapping by ABICAS are expected to be less than previously needed by conventional non-digital methods. This claim can be defended because we have over 2 years of experience in the conversion of published (paper) maps to digital.

The time required to digitize existing geologic maps varies with complexity and scale of the original map. The experience level of digitizing personnel is an additional but small variable in the total required time to complete a map. Using ABICAS, DMR has approximately 60 1:24,000-scale maps, 7 1:100,000-scale maps, and the 1:500,000-scale state geologic map in various stages of completion. Maps in the Appalachian Plateau (coalfields) require the most amount of time to complete because of the number of lines, line length (contacts near-parallel to topographic contours) and multiple attributes. For example, it required 50 person-days to complete the Virginia portion of the Pikeville 1:100,000 map, and 15 days for the Pound 1:24,000 quadrangle. Maps in the Valley and Ridge and Piedmont provinces required less than half of these times. The 1993 geologic map of Virginia is approaching completion and will likely require a total of 100 days.

The production of digital replicates of printed geologic maps involves two activities, data entry and editing. Data entry involves "heads-up" tracing lines over scanned images, creation of polygons, attributing lines and areas, and entry of point data (strike and dip, well locations, etc.). The bulk of this work has been done by undergraduate geology majors. The total time spent on instruction of an individual is less than a day, with slightly more time needed for those who have never used a computer. The subsequent activity of editing is done by senior staff of DMR. All digital maps undergo the same attitude of detailed scrutiny as used in final editing of printed maps. However, the digital process requires less time and is more complete in error detection and repair than the time and effort needed by the process used for printed maps.

### Present Capabilities

For an average cost of $2,500/unit, DMR can give each staff geologist the mapping software, a zip drive and a laptop computer with CD-ROM. The geologists are able to digitize contacts in the field using geophysical data, scanned topographic maps, satellite images, and scans of older and possibly unpublished fieldmaps of the area. Upon returning to the office, they can print an up-to-date geologic map of the area with the base map of their choice within an hour. Typically (at the present time), our geologists collect data in the traditional manner on paper maps and notebooks and transfer the field data to digital either in a vehicle or the office. The compilation map is the digital map. Other than a scanner, the same equipment is used to convert published (paper) maps to digital. Complexity of file structure increases only with the data complexity demanded by the geologic map.

Our geologists benefit from DMR's decision to convert to digital mapping because they do not have to spend hours transferring linework or adding stick-on symbols and letters. Our customers benefit because they now have access to the latest geologic information should it be needed. They have the added benefit of getting maps with the boundaries, projections and scale they choose. DMR benefits because the error prone steps of transferring data and adding stickups are eliminated and digital geologic maps are easily updated and printed on-demand as required. Another benefit is that geologic field mapping is not restricted by existing and frequently outdated topographic maps. The geologists can use satellite imagery to update, supplement and perhaps replace the topographic base maps.

In house, we have recreated color geologic maps on paper (from digital "vector" files) that replicate the original published (paper) map in all respects. Geology, in color, appears over a subdued topographic/culture base. We have used a HP650 color printer at USGS prior to purchase of our own (HP Design Jet 2500 CP). Digital files created in ABICAS have been translated to ATLAS, dxf, and MAPINFO formats.

Several problems critical to the success of DMR's digital mapping program have recently been solved. The 3M Corporation using DMR data as tests created water-resistant paper for maps that will not "bleed" in water. 3M also will have available by fall UV fade-resistant pigment inks. Lastly, AML programs (conversion programs) are being created to facilitate the import of ABICAS files directly into Arc/Info.

Problems still remain. Two of the most important are exchanging data with the USGS and exchanging data with other adjoining states. In exchanging data, the issue is format. If the USGS requires all digital geologic mapping data to be submitted to them using the SDTS format only, many states on limited budgets will not be able to comply. Additionally, the SDTS compliant files are large making them unwieldy to transfer electronically. These files are awkward to use as intermediate files since the actual working formats are usually significantly smaller. A large empty harddisk is required to either translate the working files into SDTS or translate them out of SDTS.

## PART 2

### Description of Data Capture Method and Technical Details

All of our digital mapping begins with a raster image created by scanning a printed topographic or geologic map, including pencil or inked mylars. Maps are typically scanned in color at 150 dpi in a 24-bit Targa format. Some applications (scanned 1:100,000 topographic mylars) require higher resolution (200 to 300 dpi), but the increased file size is still acceptable. The program TGA2DAT reduces the Targa image to an 8-bit color image in ABICAS format (binary); it also creates a color palette file (figure 1), and an image header file, both in ASCII. The color palette file contains an individual intensity (from 0 to 255) of red, green and blue for the 256 possible colors. File size is considerably reduced with minimal loss of the color information common to printed geologic or topographic maps.

The image is then georeferenced with the ABICAS program MAPROJ by entering control points on the image map graticules while viewing on the computer screen. Original map projection and these control points are used to define an algorithm that converts locations in screen coordinates to latitude and longitude. Average (rms) map error and error for each control point is provided. Any errors exceeding desirable limits for the digital map are therefore known; these errors may be reduced for the final algorithm by reentry of one or more control points. It is not difficult to obtain any error of less than 20 feet (or 2 pixels) for 1:24,000-scale maps scanned at 150 ppi.

Entry of lines is done in a menu-driven environment with the program MAPTRACE. Tracing or entry of geologic contacts is done with a mouse over the map image on the computer screen ("heads-up" digitizing). Each click of the mouse enters a point, and a line immediately appears on the screen and joins the previously entered point. The ability to zoom in on the image to 4-power magnification, or greater, enables the operator to consistently trace and replicate lines within 1 pixel of the original image lines. Hence, some quality assurance is achieved during data entry. Editing of lines and points is possible during and after data entry. As image lines are traced, nodes are created by ending the entry of points and beginning a new digital line by snapping (a menu command) the beginning point of the new line to the last point on the previously entered line. Adjacent polygons that are eventually created in this manner, thus share the same line (line tracing is done only once). All ASCII data files created in ABICAS are converted to an equivalent binary file to increase the rate of processing; conversion to and from binary and ASCII formats is automatically or manually invoked.

We begin to attribute lines simultaneously with line entry. Sixteen of the 256 available image colors in the color palette file are reserved for lines (color numbers 240 through 255). One must accept a default or choose a line color number at the beginning of each line entered. The physical color of each color number can be changed with any ASCII file editor in the image color pallette file, by changing the intensity value for red, green, and blue. We standardized the use of the last 16 color numbers to the kinds of lines found on a geologic map: for example, line color 246 is used for approximate contacts (dashed lines on the printed map); 247, political boundaries; 248, exposed faults; 249, shorelines; 252, exposed coal bed or other thin concordant lithosome. Additional information about the line such as the kind of fault, its formal name (if any) or name of a coal bed can be entered later by defining an additional two attributes. (figure 2). One defines, enters, edits, and queries line attributes in the program MAPLINE. Creation of sub-

```
0 36 32  34
1 42 42  59
2 41 44 111
......
 9 49 113 113
10 45 116 175
11 45 125 213
......
243 198 249 118
244 191 191 191
245 255 255 255
246 255   0   0
247 255 128   0
248 255 255   0
249   0 255   0
250   0 255 255
251   0 161 161
252  40  40 255
253 255   0 128
254 255   0 255
255  96  28  14
```

**Figure 1.** Portions of a typical image palette file where dots indicate removed data. The first column is the color number. The second, third and fourth columns are intensities of red, green and blue, respectively. An image pixel or line of number 246 would appear red on the computer screen.

```
line_color color TYPE long MSNG -1
line_class linclass TYPE string MSNG no_class STRLEN 9
formal_name linname TYPE string MSNG no_name STRLEN 32
*
248 thrust Bowens_Creek
36.7638130 -82.7319410 36.7637520 -82.7319720 36.7634120
   -82.7319950
 36.7632330 -82.7320020//
246 no_class no_name
36.7632330 -82.7320020 36.7632180 -82.7320020 36.7630080
   -82.7319950
36.7627680 -82.7319720 36.7625010 -82.7319640 36.7622450
   -82.7320020
36.7618330 -82.7321240 36.7614100 -82.7323070 36.7611350
   -82.7324910
36.7610000 -82.7326123//
```

**Figure 2.** A typical line file in ABICAS. The first three lines are definitions for three line attributes (line color, line class and a formal name). The first line is a segment of the Bowens Creek thrust fault. Color number 248 is reserved for a line representing an exposed fault (solid, thick line in print). The first line contains four points. It is snapped to the second line as the lat/long coordinates (in decimal degrees) of the last point are precisely equal to the coordinates of the first point of the second line. The second line is an approximate contact (thin dashed line in print) signaled by color number 246. The end of a line is delimited by "//".

files based on attributes is also a commonly used option in MAPLINE.

Not all lines on a geologic map make areas (polygons) that will become attributed (labeled) with a formation symbol (Qal, fill, Mb, etc.). Coal beds, dikes, faults often end without joining another line. Although these lines have been digitized, they will remain in a file for printing or query on computer at a later time. Such lines will not be used to create polygons, and will be removed by use of a series of "clean-up" programs. The program LIN2ARE creates an area file from the "cleaned-up" lines and contains linked polygons to their constituent lines (figure 3). Once an area file is created, one defines, enters, edits, and queries polygon attributes in the program MAPAREA.

The completely attributed digital map consisting of "vector" lines and table data is easily converted to a final colored raster image (of any scale and projection) with the program BAD2LBM and an ASCII raster control file that defines colors and patterns of areas. MAPLOT and an ASCII printer control file are used to plot dashed, dotted and solid lines in chosen thickness and color and structural or other symbols upon the colored raster image. A horizontal scale and graticules may also be plotted. The program MAPMIX is used to digitally overlay the geologic map on one or more base images. It is possible to combine a geologic map, topographic map, and a satellite image. The program COLLAR creates a map explanation and plots text or other images on the final raster image. This final raster image in 8-bit color may then be converted to 24-bit Targa (or TIFF, PCX) format that is compatible with many color printers or digital image editors.

```
Area_Number number TYPE long MSNG –1
Minimum_Latitude minlat TYPE double FORMAT %0.7lf UNITS deg. MSNG 999.0
Maximum_Latitude maxlat TYPE double FORMAT %0.7lf UNITS deg. MSNG –999.0
Minimum_Longitude minlon TYPE double FORMAT %0.7lf UNITS deg. MSNG 999.0
Maximum_Longitude maxlon TYPE double FORMAT %0.7lf UNITS deg. MSNG –999.0
Center_Latitude centlat TYPE double FORMAT %0.7lf UNITS deg. MSNG 999.0
Center_Longitude centlon TYPE double FORMAT %0.7lf UNITS deg. MSNG 999.0
Area_sq.km. sq.km. TYPE double FORMAT %0.6lf UNITS sq.km. MSNG –1
Area_sq.mi. sq.mi. TYPE double FORMAT %0.6lf UNITS sq.mi. MSNG –1
Area_acres acres TYPE double FORMAT %0.2lf UNITS acres MSNG –1
TBL_TEXT TBL_TEXT TYPE string STRLEN 32 MSNG NO_TXT
geologic_formation_symbol fmsymbol TYPE string STRLEN 15 MSNG No_Name
*
......
1 36.8503300 36.8750000 –82.6718670 –82.6250000 36.8626650 –82.6370167
3.584484873 1.3839809 885.75 area Mb
1 –1030 –867 –862 –384 –448 –447 414 –412 –411 –1031 –77//
3 36.8668590 36.8750000 –82.6512370 –82.6403580 36.8709295 –82.6449791
0.110031609 0.0424836 27.19 area Mht
2 1029 –868 1030//
4 36.8721310 36.8750000 –82.6455840 –82.6422040 36.8735655 –82.6440491
0.030478219 0.0117677 7.53 area Mh
3 –1028 –1029//
......
291 36.7736354 36.7740211 –82.6988150 –82.6972321 36.7738283 –82.6980142
0.004784251 0.0018472 1.18 area Cn
–1157 –1156//
END_AREA_LINE_IDENTIFICATION—BEGIN_LINES
line_number number TYPE long MSNG 0
area_to_left left TYPE long MSNG 0
area_to_right right TYPE long MSNG 0
*
1 1 –2
36.8750000 –82.6250000 36.8750000 –82.6326790 36.8750000 –82.6403580//
2 3 –2
36.8750000 –82.6403580 36.8750000 –82.6412925 36.8750000 –82.6422270//
3 4 –2
36.8750000 –82.6422270 36.8750000 –82.6429555 36.8750000 –82.6436840//
4 5 –2
36.8750000 –82.6436840 36.8750000 –82.6458264 36.8750000 –82.6479688//
......
```

**Figure 3.** Portions of a typical area file in ABICAS where dots represent removed data. The first 11 lines are the definitions of required attributes, the 12th line "geologic_formation_symbol" is the first optional attribute we assign. Area 1 encloses the "Mb" formation and is made up of line number 1, 1030, 867, etc. The second part of the area file contains the constituent lines: line number 1 has area 1 to its left and area –2 to its right, followed by the points that define line 1.

# Field Data Capture and Manipulation Using GSC Fieldlog v3.0

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## INTRODUCTION

Fieldlog is a software tool developed by the Geological Survey of Canada (GSC) to aid geologists in the digital management of geologic field data. It provides a means to digitally record, retrieve, display and analyze field observations, and to supplement cartographic map preparation and geologic interpretation. Fieldlog maintains a relational database within an AutoCAD environment and provides connection to several popular GIS systems through export formats. It is founded on a data model which consists of geological concepts common to the mapping process. Project databases, their cartographic representation, referenced coordinate systems and glossaries of geologic terms are completely configured and modifiable by the geologist. The data model defines much of the internal database and cartographic behavior, insulating the geologist from many technical details and providing enhancements to traditional database and cartographic operations. Sophisticated data entry and database query, including specialized geologic diagrams, are present to augment the map-making process. Integration with mobile computing devices, as well as with more standard methods of field note-taking such as traditional field notebooks, permits a broad range of data recording options. Fieldlog has been an integral component of the GSC's regional mapping and rapid digital map publication methodology since 1991.

## GEOLOGIC MAP CONSTRUCTION

Geologic maps depict geologic observations and interpreted geologic objects which are often inferred from the observational data. The exact representation of these objects as map entities is scale dependent and the geometry may vary between point, line, polygon, surface and volumetric objects. The identification or deduction of geologic objects is iterative: evidence is gathered and hypotheses are formulated which are supported or refuted by further evidence. This is an analytic process where data are mutable and prone to re-classification or re-interpretation over the course of the mapping (fig. 1). In this context a field system must ultimately be an aid to the thinking process as much as it must be an efficient mechanism to record and store thoughts. Effective gathering of data is the first priority in this process, soon followed by a need to dissemble and recast the data into different scenarios.

Under Fieldlog a geologic map usually begins as one or more digital topographic base maps which are originally purchased from some third party, typically a government agency. The maps may also be directly scanned and digitized. Once acquired, the base maps are registered in some coordinate system which defines their geographic position. A project database is constructed by the field geologist to

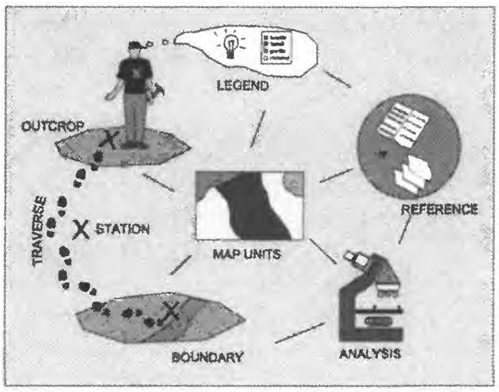


**Figure 1.** A cartoon of the field mapping process.

contain the field data and to interact with the maps. Project databases may be derived from corporate templates or may be begun anew. Once a project database is established data can be simultaneously added to the maps and to tables in the database. In this process field data may be displayed on several maps and a map may contain data from several projects. Though Fieldlog will allow several projects to be active during a session, its functions will only operate on one project at a time. For instance, query contents cannot be selected from more than one project in any one query.

Field observations typically are sites or boundaries, and these are added to the base map as points or line segments. Their attributes are entered into the database at the same time. These supporting data are manually entered into the Fieldlog database from field notebooks or forms, or are digitized from air photographs and topographic maps using small digitizing tablets. They may also be imported from mobile computing devices such as GPS (satellite-based Global Positioning Systems) and PDA (hand-held Personal Digital Assistants) or more sophisticated portable units. Some of the data are symbolized on the map—either via manual digitization or through importation and plotting via queries—and some of them reside in the database as supporting evidence. This data entry stage typically involves the entry of site information into the database and the display of select portions on the map. Boundary data may also be recorded and digitized at this time. Mesoscopic observations such as station locations, structural measurements and rock type characteristics are recorded and plotted with Fieldlog, and macroscopic observations such as contacts, folds and faults are drawn using AutoCAD's line and polygon drawing mechanisms—they may also be imported from preexisting digital geology maps or from portable field computers. Once in digital form, the evolving map is plotted at scale on a regular (i.e. daily) basis using page size printers. The plotted pages are joined, often with tape, and this growing paper mosaic represents the field map. Often interpretive features, such as geological contacts, are sketched by hand onto this mosaic, and subsequently digitized when and if confirmed. As the geological story unfolds, the various hypotheses—depicted as disconnected boundaries on the map—are joined to form polygons which eventually partition the geographic extent of the map. In this process observed supporting data are often reclassified using Fieldlog's editing capabilities which ensure that map and database equivalency is maintained. AutoCAD's standard functions are used to edit all non-Fieldlog data.

The evolution of geologic insight for a map area often involves the utilization of a myriad of tools such as stereographic plots as well as geophysical overlays. Fieldlog provides either the resources to perform these tasks or to export the data painlessly so that it can be further integrated into more sophisticated and specialized systems such as GIS or other geological plotting packages. Ultimately the results of such deliberation are returned to Fieldlog as new geologic objects on the map, or as changes to existing map entities. The end result is a geologic field map with an underlying database of field observations.

## DATA ENTRY

Fieldlog maintains field observations in a relational database which is linked to one or more digital AutoCAD maps. In a typical project most field data are stored in the relational database, and a subset of these data are displayed on the map. However, some map entities, such as geological boundaries, may exist solely as cartographic objects without being additionally described in the field database. Fieldlog permits map entities of any geometric shape (e.g. points, lines or polygons) and cartographic type (e.g. symbols, text, lines, etc.) to be described in the database. Furthermore, the data entry process allows point entities to be simultaneously added to the database and map as symbols or text. This procedure does not hold for other map entities such as lines or polygons: they must first be added to the map using AutoCAD's standard cartographic functions, and then linked to a database description during data entry. Each AutoCAD map, and thus each map entity, has positional information referenced to a previously established coordinate system taken from Fieldlog's catalog of cartographic projections. Positional information is copied from the map to the Fieldlog database only for designated points, whereas positional information for other map entities remains in the AutoCAD map.

When entering data, field observations may be typed, locations may be digitized, and either can be imported from external text or database tables. A digital topographic map is usually used as a backdrop onto which the observations are plotted. When observations are imported from external sources such as mobile data collection devices, they are retrieved from the database and plotted to the map via a user directed query process. When observations reside in paper notebooks or forms, they are manually entered by selecting a table and entering information into the columns of a new row. Column contents are verified according to various parameters configured by the geologist. If verified, the new row is inserted into the table and the values of selected columns are optionally positioned on the digital map through visual location, or via digitization from some source such as a topographic map or air photograph. When several observations occur at a site, the data may be stored in more than one table or in more than one row in a table. In this case Fieldlog will then propagate critical values between rows, or from one table to another in order to reduce data entry time and to enforce proper data connectivity between database tables (i.e. referential integrity constraints). For example site identifiers will propagate to all rows and tables until a new site is specified. Fieldlog also permits customizable dictionaries of geological terms to be created and attached

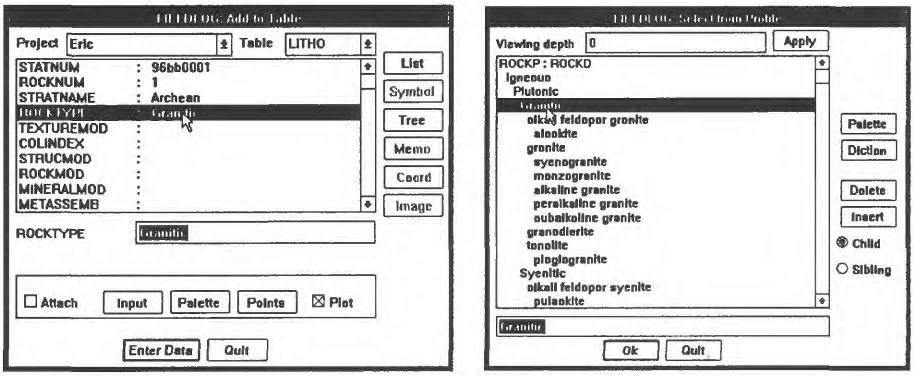


Figure 2. Data entry using a hierarchical profile.

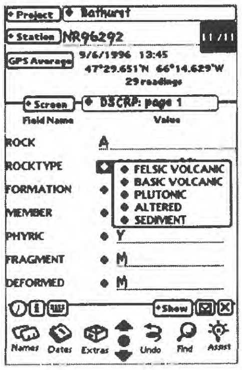


Figure 3. A Fieldlog project database on the Apple Newton, using the Fieldworker software for data entry.

to columns for data entry purposes (fig. 2) and for the maintenance of semantic consistency of terminology. Once a dictionary is attached to a column, the contents of the column are restricted to one or, optionally, more terms from the dictionary. Dictionaries are unlimited in the number of terms they may contain.

## MOBILE COMPUTING

Fieldlog v3.0 takes advantage of affordable pen-based data entry technology offered by the Apple Newton, by exporting a field database structure to the Newton and importing collected data from it. The Fieldlog database format is transferred to the Apple Newton where it is displayed intact, including all relevant hierarchical profiles (fig. 3). Commercial software (Fieldworker) operates on the Newton to receive the Fieldlog project template and present it for data entry. Data may be hand-written on a touch-sensitive screen, or typed on a small, screen resident keypad. A GPS can be connected to the Newton and its locations directly read by the Fieldworker software, permitting complete data entry to occur in the field. The resultant data are exported to Fieldlog in a specialized text file format, and are merged into the project database. Fieldlog can also interface to mobile computing devices other than the Apple Newton using standard import/export formats.

## GENERAL DATABASE MODEL

Underlying all Fieldlog components and functions is a data model which consists of geologic concepts and their rules of interaction (i.e. an articulation of intuitive geological heuristics). The data model is an abstraction of the geological mapping process where concepts common to most geologic mapping activities are identified and their general relationships defined. In this sense the mapping process is grossly distilled to a series of commonly performed activities and commonly observed geologic objects. Fieldlog provides this basic conceptual structure to the geologist and permits it to be implemented by individuals in very different ways by refining and adapting the concepts into a personalized database definition. In this process the data model's geologic concepts are translated into relational database constructs for data processing, and the geologist is insulated from many of the routine database operations.

The Fieldlog data model necessarily deals with spatial as well as geologic concepts. Observed data originates from a geographic location which may be a region (outcrop) or a site (field station). Often these observations are made along a traveled path which defines a geographic route (traverse). In the course of a survey, sites and regions are encountered on one or more routes, and sites may occur within regions. Some observations are further defined by a spatial partition, often vertical, within their site or region of origin such as a stratigraphic section at some field site or drill core segments within a drill hole. Once spatial positioning is accounted for, the relationships between observed data are semantic in nature as observers are discipline specific. Geologists observe rock, soil scientists observe soil, biologists observe flora or fauna, etc. These themes are generally described in terms of their composition or disposition, all of which may be sampled. Composition describes a theme's internal constitution, such as mineralogy or alteration within rocks, whereas disposition describes the theme in terms of its setting and the processes leading to its specific, often physical, configuration. Disposition may be described within a specific theme type or it may be macroscopic to the theme. For instance, structural processes display the following characteristic: it is possible to discuss faulting within a rock type at a site, and also to discuss regional scale faulting which encompasses the site. All of themes (rocks), compositions (minerals) or dispositions (structures) may be sampled. Samples may further undergo various analyses such as geochemical, geochronological,

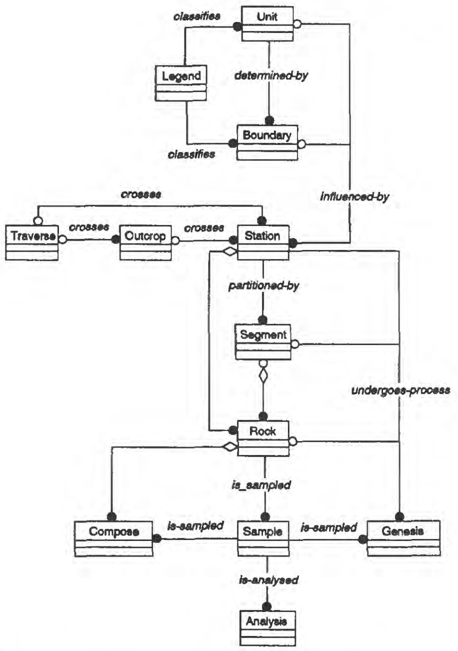


**Figure 4.** Fieldlog's General Field Data Model. Reference and Dictionary concepts have been omitted for presentation purposes. References and Dictionaries may be related to any of the general concepts portrayed in this diagram The influenced-by relation between units, boundaries and traverses, outcrops has also been omitted for presentation purposes.

petrographic, etc. Themes, compositions, dispositions, samples and analyses can be attributed to any spatial location, whether it is a site or partition within a site. Therefore, other than their vertical partitions, stratigraphic sections and drill hole segments can be described in the same general manner as non-partitioned sites or regions. This implies that field survey, drill hole and stratigraphic section data can coexist within one semantic model, and also within a single database structure. Fieldlog has indeed often been applied in these various situations. Finally, Fieldlog also recognizes geologic boundaries, units, legends, and references as valid data types. The data model is summarized below (fig. 4):

## OPERATING PLATFORMS

Fieldlog operates in AutoCAD's cartographic environment which it extends to include additional geographic and geologic processing capability. AutoCAD was initially chosen because of its wide usage, its cartographic excellence, its liberal development environment and its ability to operate on many hardware and operating system platforms. Of the many operating systems supported by AutoCAD, Fieldlog will currently function within DOS, Windows 3.1, 95 and NT. It also currently utilizes AutoCAD release 12, but it is expected to operate within AutoCAD release 13 by the 1997 summer field season.

Fieldlog is able to interact with a variety of database systems, primarily because all relational database activity is performed transparent to the geologist using SQL (Structured Query Language), which is platform independent. Relational databases such as dBase, ODBC (e.g. MS-Access), Oracle, etc., are thus accessible from this modern client-server environment.

## DATABASE QUERY

Queries are performed using a visual interface which permits the user to thematically filter the database and view the results in tabular form. Database filters are constructed using conditional statements which are composed of thematic, spatial or hierarchical components and which are connected with "AND" or "OR" logical operators (fig. 5a). Query results are displayed as a virtual table (fig. 5b). Row contents in the resulting table may be browsed, deleted and modified singly or globally. The results may also be plotted to the active AutoCAD map using customized geological map symbols (fig. 5c), they may be manipulated to produce custom diagrams (i.e. stereonet, rose, geochemical, and pie diagrams) and may be exported to a variety of formats. Supported query export formats include tabular representations as text files and database tables, as well as direct translations to GIS using the following exchange mechanisms: Arc/Info-ArcView E00, MapInfo MIF, and SPANS TBA formats. The user can designate which columns to export and can scale the symbology or alter the coordinate system for each type of format.

## COORDINATE SYSTEMS

Fieldlog permits ellipsoids, projections and transformations to be created and modified. In this way it is possible to create a personalized catalog of coordinate systems. Projections are restricted to variations of the following basic kinds: geographic, transverse mercator, universal transverse mercator, lambert conformal conic, double stereographic, and user defined coordinate systems. Coordinates and map entities may be converted from one projection to another. Transformations may further be defined to convert coordinates from a user grid to other grids or orthogonal projections.

## DISTRIBUTION

At present, fieldlog is distributed electronically, on an "as is" basis, at no cost from the following Internet address:

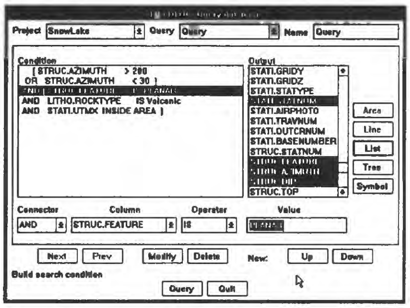

**Figure 5A.** Query menu.

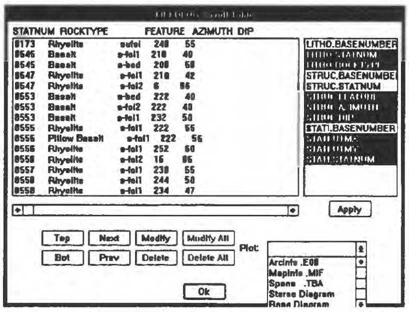

**Figure 5B.** Query results and plot options.

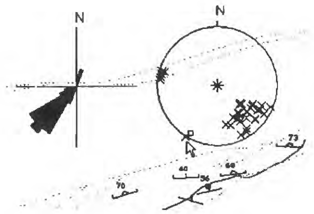

**Figure 5C.** Query results plotted as symbols, rose and stereo diagrams—overlain on geological contacts.

http://gis.nrcan.gc.ca. The Internet site presents a registration form which must be completed prior to downloading the software. A bound version of the users guide and tutorial will also be available for purchase as a GSC open file from the GSC Publications office after the 1997 summer field season. This manual is available, and will remain available in the future, in electronic formats on the Internet site. Formal software support is not provided by the GSC, but the author will respond to questions and comments regarding the software. Short courses on its use are occasionally presented at scientific meetings and at the GSC.

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# Using the GSMCAD Program with GPS for Data Collection in the Field and as a Quick and Efficient Way of Creating Arc/Info Geologic Map Coverages

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## INTRODUCTION

GSMCAD is a Microsoft Windows program designed specifically for field and office compilation of geologic maps. It was developed by the U.S. Geological Survey for in-house use and is made available to the general public for a nominal charge as Open-file report 96–007. It can also be downloaded for free on the internet at URL http:/ ncgmp.cr.usgs.gov/ncgmp/gsmcad/gsmcwww.htm. Documentation is in the form of a Windows help file, GSMCAD.HLP.

Line and point data can be entered from a digitizing tablet, by drawing on screen with a mouse, by reading in a table or DXF file, and by connecting to a GPS (global positioning satellite) radio receiver. The maps and drawings created can be plotted on an inkjet or a pen plotter, printed on any MS Windows-compatible printer, or exported to DXF files or Arc/Info coverages.

The program is designed to be efficient to use, easy to learn, and require minimal special equipment. It allows Arc/Info coverages to be created and color geologic maps produced from Arc/Info without the user having to be trained in the use of the Arc/Info program.

## GOALS

A primary goal in development of GSMCAD is to maximize productivity by simplifying procedures and minimizing unnecessary keystrokes, mouse movements, or body movements. The second goal is to minimize training time and mistakes by making the program intuitive and easy to learn, supplying comprehensive and context sensitive online help, and conforming to a layout similar to popular Windows and drafting programs. The third goal is to empower the field geologist and recruit him to join in digital data production by providing an easy and comprehensible way to create and control his own digital data without extensive recourse to "GIS experts". This must be done in such a way that the results will still meet quality standards and be available in industry-standard formats such as DXF and Arc/Info coverages. A fourth goal is to speed production and accuracy and minimize repeated trips to the same area by enabling the geologist to digitally collect point and line data and compile his map in the field. The fifth goal is to keep things simple so as to minimize the expense of equipment needed to run the program.

## WHY USE GSMCAD?

There are many possible techniques for digital compilation of geologic data into GIS data sets, and powerful commercial software at reasonable prices is increasingly available. Under what circumstances might GSMCAD still be a useful additional tool?

The most likely benefit is in situations where speed, simplicity, and economy are necessary, and resources are limited. Possible examples are as follows:

- Mapping programs just beginning conversion from conventional to digital methods might find it useful, to quickly become productive.
- When field geologists are reluctant to give much time to generating digital data but the "GIS experts" do not have enough time to do all the conversion to digital format for the geologists.

- When data entry is available only through temporary, semi-skilled students, whose turnover is rapid.
- For direct digital entry and compilation of data in the field using GPS and laptop computers
- For geologists or geology students that want to be able to work on their maps at home.
- For geologists working in isolated offices with little technical support.
- For geological surveys in developing countries where access to and understanding of technology is limited.
- Any geologist who wants to get typical geologic field data into digital format quickly and easily.

## FIELD DATA COLLECTION

GSMCAD can be used in combination with a GPS receiver for data collection in the field in two modes. In situations where most observations are made from a vehicle a GPS receiver outputting NMEA (National Marine Electronics Association standard for navigational data) $GPGGA sentences can be connected directly to the serial port on a laptop running GSMCAD. When the <GPS cursor> option under the DISPLAY menu is toggled on, the GPS position will drive the screen cursor just as the mouse or digitizer puck would. Observation points can be digitized with a keystroke. The points are linked either to notes typed into a text file on the spot, a table of values, structure symbols having azimuth and inclination attributes (such as strike and dip), or digital photographs. When the GPS cursor reaches the side of the screen window, the window will redraw centered on the current position.

A second mode is less "high-tech" but more practical. Observations are recorded in a simple field book as the positions are recorded as waypoints in the memory of the GPS receiver. At the end of the day the GPS unit is connected to the laptop and the day's waypoint coordinates are downloaded into a file that is subsequently read to generate observation points in the GSMCAD database. The station number from the fieldbook is an attribute of those points so they can be linked to data copied in from the fieldbook. In the future it may be possible to download files entered on the outcrop in a palm-size computer instead of in a fieldbook (such as Fieldlogger files on an Apple Newton).

Both methods work best if a preliminary map is digitized and printed over a basemap before going to the field. Lines sketched on the map or on airphotos in the field can be transferred to the database by digitizing on screen with the mouse, by reference to pre-existing digitized lines and GPS points. A digital orthophotoquad (DOQ) or vectorized basemap can be displayed behind the map vectors to guide line placement. At present digital raster graphics (DRG) cannot be displayed. If digital bases are not available, the same result can be achieved by taking a small or roll-up digitizer to the field.

## GENERAL CAPABILITIES

The following partial list summarizes some of the capabilities and characteristics of the GSMCAD program.

### Database Creation

New geodetic (lat, lon) databases corresponding to standard USGS series maps are quickly and simply created by specifying the type of map and entering coordinates for the northwest corner. An outline frame or grid of lines is automatically created. The program determines the projection parameters of the base map and stores them in a projection file. A preliminary plot file is generated listing the definition and plotting characteristics of the most common entities on geologic maps. Unusual projections and map outlines are also supported but require more user input. Projections supported include Mercator, Universal Transverse Mercator (UTM), Transverse Mercator, Oblique Mercator, Lambert Conformal Conic, Albers Equal Area, Equidistant Conic, and Polyconic. Cartesian databases in ground meters for cross sections and inches for correlation diagrams are also easily generated.

### Attribution of Lines and Points on Entry

All GSMCAD entities have three numeric attributes (CODE, P1, P2) stored in the database. Other attributes may be stored in associated lookup files. Before any entity can be created the three basic attributes must be entered (or continued from the previous entry). The first attribute (CODE) is linked in the plot file to a description of what that code represents, such as "thrust fault, certain" or "bedding attitude symbol." A pull-down menu listing the code next to the description allows the user to select the geologic feature to be represented without having to remember the code. Defining the entities from the manuscript map as they are entered is more efficient than classifying the spaghetti bowl of unclassified lines that sometimes results from scanning.

Attributed polygons can be created from lines and label points in a GSMCAD database using the GSMPBLD program (Selner and Taylor, 1993), but that step is done more easily in Arc/Info. The polygons to be created are attributed in GSMCAD by creating a text entity representing the geologic letter symbol within the polygon. These text entities may be visible or not. GSMCAD text entities can include any number of built in leaders, and the far end of a leader is sufficient to create an attributed label point in the polygon where the leader terminates. While text points are being created, buttons labeled with various geologic symbols appear on the side of the screen so that the user can switch from labeling one unit to labeling another by clicking on the appropriate button.

Types of entities supported by GSMCAD include lines, splined lines, 3-D (profile) lines, polygonal shapes, linkable data points, rotational data points (strike and dip), unlinked symbol points, text points with (optional) leaders, and splined text.

### Efficient Tablet Digitizing

Attribution of lines and points traced from original copy on a digitizing tablet is done using the keys on the digitizer keypad as the entities are created. Three standard numeric attributes of CODE, PARAMETER 1, and PARAMETER 2 are applied to all entities, but only need to be entered when there is a change from the previous entity. The speaker on the computer pronounces audible prompts for data entry and echoes the keys pressed for confirmation. This minimizes the need to look from the tablet to the screen. The <0> key starts an entity and sets additional points, and the <1> key ends the entity (creating or snapping to nodes for the first and last points of lines). The <4> and <5> keys have similar functions except that they snap to the nearest point before setting a coincident point, assuring a gap-less connection on lines even when points are set beyond the automatic snap distance. The <2> and <3> keys close polygons. The <8> key starts automatic collection of points that continues until some other key is pressed. The effect is similar to repeatedly pressing the <0> key or to holding the <0> key down while moving the puck, except that the program measures distance traveled and angle of inflection to minimize collection of unnecessary points. On curves, points may be as close as every 0.03 inches and on straight segments as distant as 0.3 inches. Use of the <8> key requires a steady hand but is the fastest way to enter line data. Entities partially digitized may be abandoned by pressing the <E> key. The screen window can be changed by digitizing new corners (<B> key) or a new center point (<C> key). Rotatable symbols can be entered either by keying in the rotation angle or by digitizing the observation point and a point on the end of the symbol so that the program can calculate the rotation.

Both mouse and digitizing tablet are active at the same time so that points digitized on screen can be combined with those from the tablet if convenient. Existing entities can be edited from the digitizing tablet.

### Symbol Sets and Fonts

The GSMCAD symbol set includes 155 of the most common symbols appearing on USGS geologic maps. Seventy of the symbols are rotating symbols that may have associated inclination angles posted nearby such as the bedding strike and dip symbol. Thirteen are symbols to be placed along a decorated line such as triangular teeth along a thrust fault. The remaining seventy two are miscellaneous symbols such as those representing quarries, drill holes, and mine shafts. Additional symbols can be defined by the user. The line decorations are automatically positioned at specified intervals along the appropriate line. Polygonal areas can be automatically filled with randomly oriented symbols or hatchures to produce a zipatone-like overprint. Posting points on the rotatable symbols are automatically positioned, but can be moved by hand to eliminate overposting. All symbols are carried as lines at the defined map scale on export to Arc/Info or DXF, eliminating the need for special symbol sets in Arc/Info, ArcView, AutoCad, or MapInfo. Observational symbols (in contrast to line decorations) are also carried as attributed points so that specialized Arc/Info symbol sets or AutoCad blocks can be used if desired.

GSMCAD fonts include many specialized geologic letter symbols as well as subscripts and superscripts in addition to the Cambrian, Triassic, and Pennsylvanian symbols. Unfortunately these letter symbols are not exportable. Various Arc/Info font sets include subsets of this collection, but I am unaware of any as comprehensive as the GSMCAD font set. The most common special symbols are translated from GSMCAD fonts to Arc/Info fonts in Arc/Info by the GSMDRAW.AML arc macro language program.

### CAD-Like Editing

A complete set of CAD editing functions is available. Entities can be moved, dragged, copied deleted, or changed; singly, in groups, or globally. Entities can also be queried and lines broken (nodes added). Points within entities can be moved, added, or deleted. Nodes can be moved. All editing features can be accessed via pull-down menus and most can be invoked with a single keystroke. Use of hot key commands and mouse pointer is the fastest way to edit and accounts for much of the efficiency of GSMCAD. Attributes can also be changed by on-screen editing of data tables.

### Node Editing

Correct topology for construction of polygons is partially achieved in GSMCAD by various operations on nodes. Nodes can be created by creating a line or by breaking a line. They can be selected and moved, carrying with them the ends of the associated lines. If one node is created or moved to a point within a defined snap distance of another, its position will be moved to coincide with the older node and it will merge with the older node and cease to exist separately. If the <nodes> option under the DISPLAY menu is toggled on, hanging nodes will be displayed as red squares and snapped nodes as black circles. Eliminating all hanging nodes on lines that should bound geologic units is the first step toward proper polygon topology.

### Export/Import

The general utility of GSMCAD is based on its ability to produce Arc/Info coverages and CAD drawings in DXF format through its export functions. Both exports transfer all the special symbols, and the export to Arc/Info transfers the most common special letter symbols. The export to Arc/Info process is a combination of the GSMCAD export function and two arc macro language (AML) programs that run under Arc/Info. The process is relatively quick and transparent, so the user does not have to be trained in Arc/Info to produce necessary coverages and a graphics file of a geologic map in about 20 minutes.

The GSMCAD to Arc/Info export produces 18 ASCII files that must be transferred to an Arc/Info workspace. Those files are mostly paired ARC generate files of ground meter coordinates and attributes, but include three lookup files and a partial metadata summary. Entities are placed in those files according to their code description in the active GSMCAD plot file. For example, lines described as contacts are placed in the files used to generate the polygon coverage. The GSMARC.AML program converts the arc generate files into four coverages. The first is a geologic unit polygon coverage, the second includes all faults and other lines, the third includes points defining the location and attributes of symbols and arcs that draw out the symbols, and the fourth includes the visible text and leaders similar to an annotation layer. The GSMDRAW.AML program reads these coverages, lookup tables, and optionally a basemap grid to produce a graphics (.GRA) file of a colored geologic map on a base. The .GRA file can be printed using the Arc/Info RTL or POSTSCRIPT commands.

The DXF import command is less sophisticated than the DXF export, so only lines, polylines, and text are brought into GSMCAD. The primary function is to bring in lines vectorized from scans or collected from air photos on a digital photogrammetric plotter. Additional import/export features beyond those built into GSMCAD are provided by the GSMGIS DOS program (Selner and others, 1995) included with GSMCAD.

### Printer or Plotter Output

GSMCAD uses the standard Windows printer drivers to print parts of the map at any scale or all of the map fit to page size. It also produces HPGL2 output to drive a pen plotter or inkjet plotter. Colored geologic maps can be produced directly from GSMCAD if the polygons shapes have been built. It also has the unusual capability of plotting a properly registered drawing on a paper or film basemap mounted in a pen plotter by using the included HPGLUTIL utility.

### Cross Section from Profile Line

A preliminary cross section diagram can be generated automatically from a profile line. A profile line is a special type of GSMCAD entity digitized with elevation values for each point. The points that should be digitized are where the line crosses known elevations such as topographic contours, ridge crests and valley bottoms, and geologic contacts and faults. The generated database will be in ground meter coordinates and includes a frame and labeled elevation tics. The ground profile is intersected by tics at geologic contacts and faults, and the tics project downward at the apparent dip calculated from the actual dip entered while digitizing the profile line.

## HISTORY

GSMCAD is a Microsoft Windows program based on the GSMAP system of programs developed by Gary I. Selner and Richard Taylor starting about 1985. GSMAP was developed because commercial software specialized for the production of geologic maps on personal computers was not available. GSMAP was continually improved as personal computer capabilities increased and the 9th version was released in 1993 as U.S. Geological survey Open-File Report 93–511 (Selner and Taylor, 1993). In the absence of alternatives there was considerable interest despite slowness and difficulty of use. Many geologists in the USGS, state surveys, and government surveys around the world were trained and used the software in the late 80's and early 90's.

The advent of MS Windows offered opportunities to increase the speed and ease of use of computer programs, but GSMAP could not take advantage of these opportunities because it is a MSDOS-based program compiled from Quickbasic code. The answer was Visual basic, which allowed Quickbasic code to be ported to the Windows environment. The author began working with Gary Selner on the conversion in 1994 and began testing in 1995. The first official version was released in 1996 as GSMCAD (GSMAP CAD) to distinguish it from the DOS line that Gary Selner intended to continue. In the Windows environment many enhancements were possible, and revised versions of GSMCAD have been released on the Web frequently as new features are added.

The utility of GSMCAD is sometimes questioned as the Arc/Info GIS program becomes more firmly established as the preferred (even required) method of producing digital geologic maps at the USGS and in the wider world. However, the difficulty of learning Arc/Info and the expense of required equipment made rapid conversion to Arc/Info difficult, so GSMCAD was enhanced to produce ARC generate files, and AML (arc macro language) programs were written to run within Arc/Info and produce Arc/Info coverages and graphic image files of geologic maps from GSMCAD databases. This allowed geologists and temporary student employees to produce good digital data without the intimidating challenge and training expense of learning Arc/Info. Additional benefits were that the easy step of learning GSMCAD was good preparation for learning Arc/Info as the geologists' confidence increased, and that digitizing and editing in GSMCAD was faster than in Arc/Info. The GSMCAD to ARC conversion was based on a method developed by Greg Green and Gary Selner (Selner and others, 1995). The structure of the Arc/Info coverages produced by the AMLs was influenced by the ALACARTE AML program (Fitzgibbon and Wentworth, 1991).

The latest enhancements to GSMCAD have emphasized direct digital collection of points and lines in the field using GPS receivers, laptop computers, and digital orthophoto images.

## THE FUTURE

The GSMCAD program is better optimized for the geologic data input needs of many USGS central region National Cooperative Geologic Mapping Team geologists than any available commercial program. The proliferation and sophistication of new commercial programs suggests that this may not be true in the future. Until that time the author intends to continue adding features to the program that facilitate his own mapping or that are requested by other users. The most likely features to be added next are background display of digital raster graphic topographic maps and linking with Apple Newton/Fieldlogger or palmtop data logger systems. Other possibilities include optimization for direct export to Adobe Illustrator/Avenza MapPublisher, export of Arc/Info shape files, and linking to Microsoft Access and dBase files.

## REFERENCES

Fitzgibbon, Todd, and Wentworth, Carl, 1991, ALACARTE User Interface—AML Code and Demonstration Maps, Version 1.0: U. S. Geological Survey Open-File Report 91–587A.

Selner, Gary. I., Green, Gregory N., and Hoffman, J.D., 1995, GSMGIS: A program to import and/or export data between GSMAP data bases and various commercial and public domain products including Arc/Info, GRASS, IDRISI, Earth-Vision, GIV, Rockware STEREO, and MAPINFO: U. S. Geological Survey Open-File Report 95–570, 34 p., one 3.5-inch disk.

Selner, Gary. I., and Taylor, Richard B., 1993, System 9, GSMAP, and other programs for the IBM PC and compatible microcomputers, to assist workers in the earth sciences: U. S. Geological Survey Open-File Report 93–511, 363 p.

Williams, V.S., Selner, G.I., and Taylor R. B., 1996, GSMCAD, a new computer program that combines the functions of the GSMAP and GSMEDIT programs and is compatible with Microsoft Windows and Arc/Info: U.S. Geological Survey Open-File Report 96–007, 18 p., one 3.5-inch disk.

# GIS and Digital Mapping at the South Dakota Geological Survey

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## ABSTRACT

The South Dakota Geological Survey collects a large amount of natural resources data across the state of South Dakota. Databases have been built to manage this data and provide an efficient means for retrieval and analysis. A GIS system is being implemented to enhance the analysis and management of this data. Improved access for the user is one of the benefits of standardizing databases for a GIS system.

A GIS system is also being used to assist in the production of digital aquifer boundary maps for the state. Maps are initially being generated at a small scale to provide general information about where the aquifer systems exist in the state. Larger scale maps will be produced to provide the user with detail that can be used for more specific determination of where the aquifer systems exist in the state.

## INTRODUCTION

The South Dakota Geological Survey (SDGS) is a program within the South Dakota Department of Environment and Natural Resources (DENR). SDGS is responsible for collecting and assembling information about the geologic and hydrologic resources of the state. Emphasis is placed on ground water quality and quantity and other resources of economic value to the state. This data is gathered through a structured program of county geology studies and various other studies focusing on regional resource assessment. The data collected and analyzed, along with the resulting reports and maps produced by SDGS enhance the understanding and use of the state's geologic and hydrologic resources.

The basic data collected by the SDGS consists of testhole and well lithologic data, water quality data, and water level data. The SDGS maintains a high level of field activity with various drilling and sampling operations. Drilling programs generate new testhole and well data each year. Data from testholes and wells are logged, coded, and entered into a lithologic logs database. This database currently consists of over 32,000 testhole and well entries, spreading across the entire state. Baseline water sampling for various projects generates inorganic and organic water analyses. Results from these analyses are stored in a water quality database, which currently contains about 3,000 analyses. Water level measurements from a network of about 2000 observation wells are taken on a frequent basis by the DENR-Water Rights Program. SDGS accesses the water levels database maintained by this program and relates the data into the previously mentioned databases.

## GIS IMPLEMENTATION

SDGS plays an integral role in implementing GIS throughout its parent organization, DENR. A GIS Advisory Group has been formed in DENR. It is responsible for implementing GIS, and coordinating GIS related activities between DENR and other entities. The general goals of the advisory group are:

- Acquire the necessary software, hardware, and training to utilize GIS for departmental activities.
- Enhance the awareness of how GIS can be used in DENR.
- Make departmental databases compatible with Arc/Info and ArcView software. Arc/Info and ArcView is used by DENR to manage and analyze data.
- Develop 1:100,000 scale base maps for South Dakota.
- Progress toward complete 1:24,000 DLG coverages for South Dakota.
- Coordinate GIS activities between DENR and federal, state, local, and private organizations.

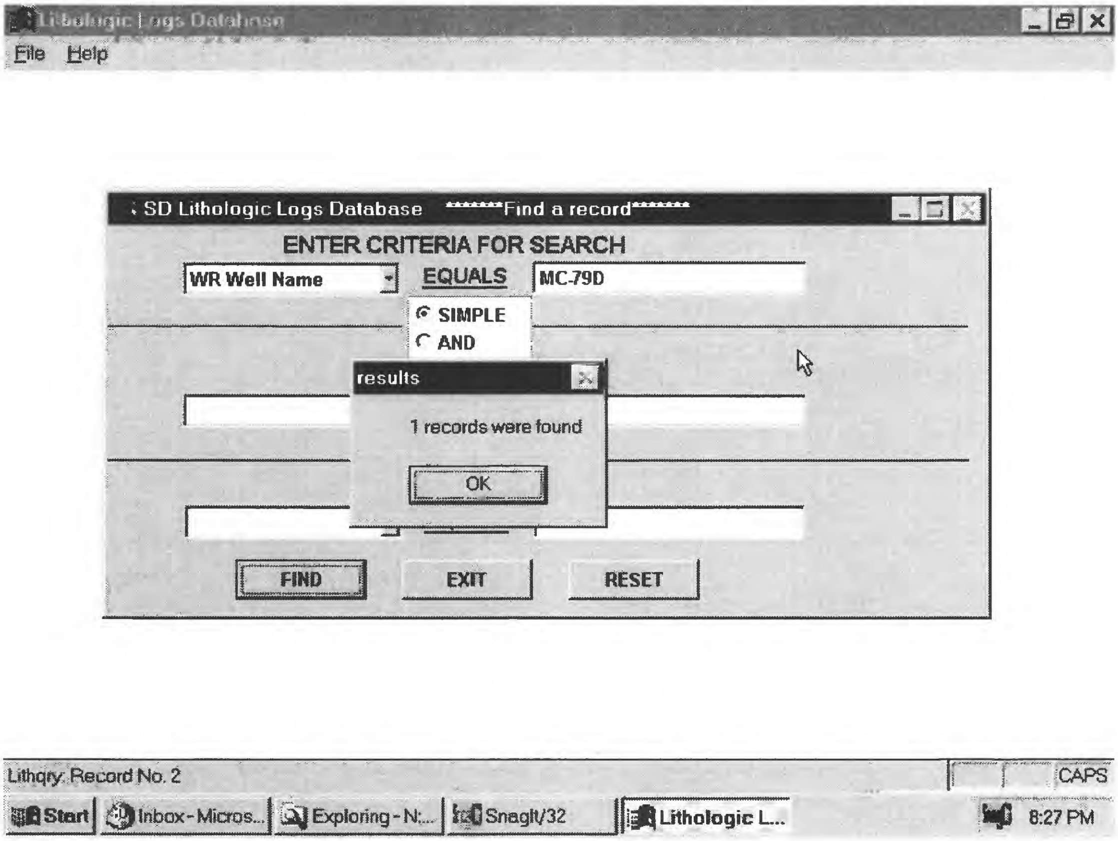



**Figure 1.** Lithologic logs query screen.

The Advisory Group is migrating primary DENR databases to Visual FoxPro under a Windows NT network. The purpose of this is to

- allow databases to be related to each other so that various types of data about any one entity can be retrieved easily
- improve access to databases through a common user interface
- move databases into a format that is compatible with GIS

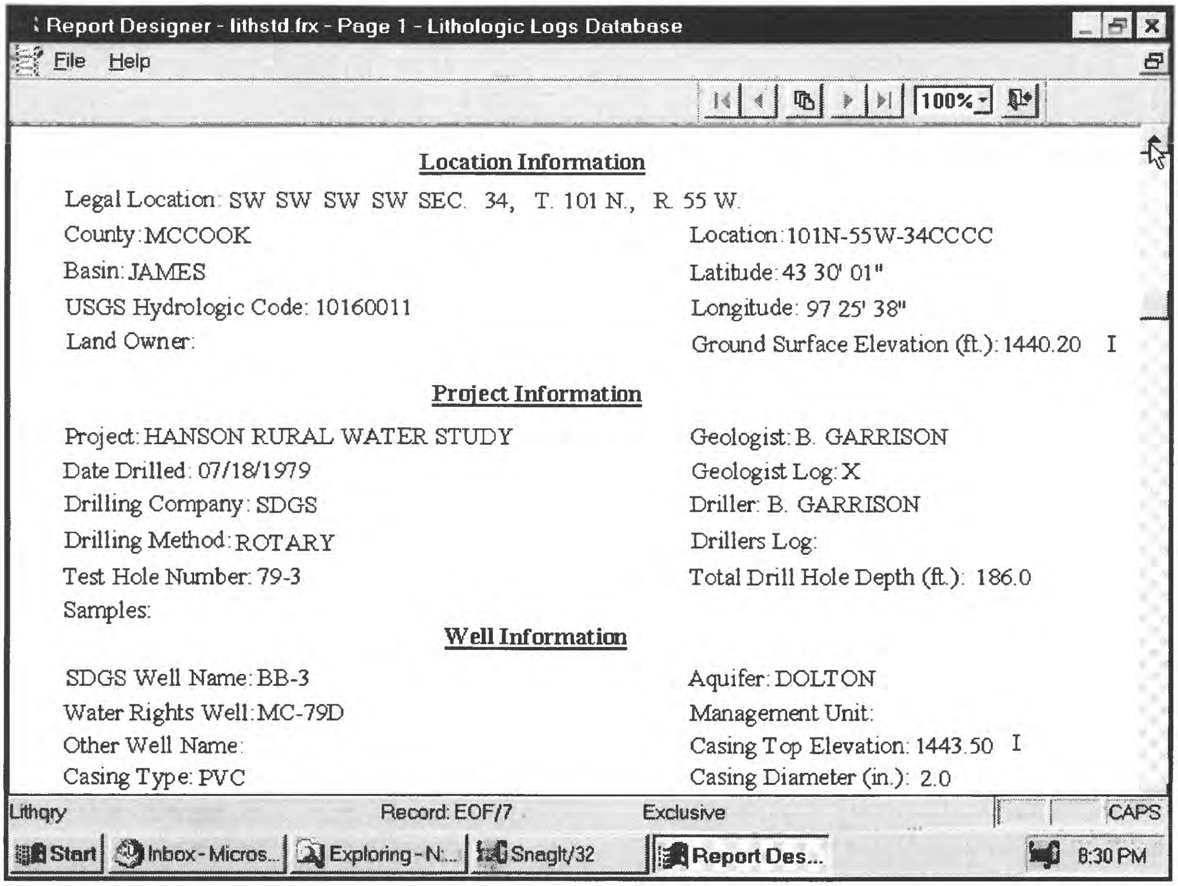
The SDGS lithologic logs database is an example of this effort. The database has an easy to use query screen so those users unfamiliar with database management software can still retrieve information from the database on their own. Currently, users can retrieve lithology and water level data from this interface. Access to the water quality database is being integrated into this system. Although the databases are currently only accessible online by departmental employees, methods are being developed to make online database access available to the general public. An example of the query screen and the results from the query are shown in figures 1 through 3.

The lithologic logs database is one of many databases being incorporated into GIS. The usefulness of GIS becomes apparent when users are able to perform queries and other analytical functions on a database such as the lithologic logs database. Figure 4 shows a representation of the database in ArcView. All of the 32,000 plus records are plotted in figure 4. This gives a visual indication of where the work has been done in South Dakota and where data is available. It is also a tool for pointing out areas where there are gaps in the data coverage.

## DIGITAL AQUIFER MAPPING

SDGS has been producing maps of the geology of the state for many years. In 1953, a generalized geologic map of the state was published at a scale of 1:500,000. Much more accurate data has been collected since that time as a result of the Survey's county study program and other projects. A newly revised and more detailed geologic map of the state is currently being published at a scale of 1:500,000.

It is also necessary, however, to produce maps which clearly delineate aquifer boundaries in the state. SDGS is in the process of producing a 1:500,000-scale map which shows a general view of the aquifer boundaries in the state (figure 5). Currently, the eastern half of the state has been completed and is being digitized into a GIS layer. This map is based on the recently revised 1:500,000-scale geology




**Location Information**

Legal Location: SW SW SW SW SEC. 34, T. 101 N., R. 55 W.
County: MCCOOK — Location: 101N-55W-34CCCC
Basin: JAMES — Latitude: 43 30' 01"
USGS Hydrologic Code: 10160011 — Longitude: 97 25' 38"
Land Owner: — Ground Surface Elevation (ft.): 1440.20

**Project Information**

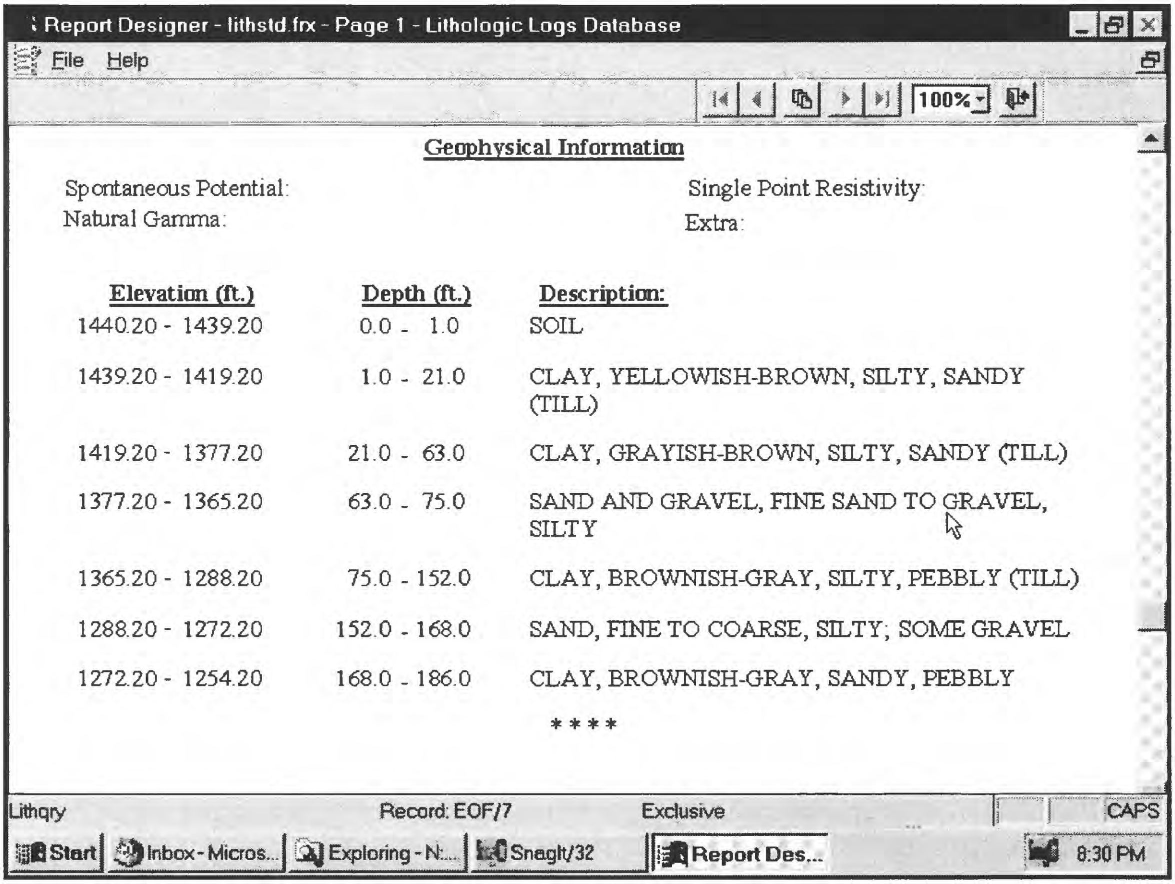
Project: HANSON RURAL WATER STUDY — Geologist: B. GARRISON
Date Drilled: 07/18/1979 — Geologist Log: X
Drilling Company: SDGS — Driller: B. GARRISON
Drilling Method: ROTARY — Drillers Log:
Test Hole Number: 79-3 — Total Drill Hole Depth (ft.): 186.0
Samples:

**Well Information**

SDGS Well Name: BB-3 — Aquifer: DOLTON
Water Rights Well: MC-79D — Management Unit:
Other Well Name: — Casing Top Elevation: 1443.50
Casing Type: PVC — Casing Diameter (in.): 2.0



**Figure 2.** Query output screen—part 1.




**Geophysical Information**

Spontaneous Potential: — Single Point Resistivity:
Natural Gamma: — Extra:

| Elevation (ft.) | Depth (ft.) | Description: |
|---|---|---|
| 1440.20 - 1439.20 | 0.0 - 1.0 | SOIL |
| 1439.20 - 1419.20 | 1.0 - 21.0 | CLAY, YELLOWISH-BROWN, SILTY, SANDY (TILL) |
| 1419.20 - 1377.20 | 21.0 - 63.0 | CLAY, GRAYISH-BROWN, SILTY, SANDY (TILL) |
| 1377.20 - 1365.20 | 63.0 - 75.0 | SAND AND GRAVEL, FINE SAND TO GRAVEL, SILTY |
| 1365.20 - 1288.20 | 75.0 - 152.0 | CLAY, BROWNISH-GRAY, SILTY, PEBBLY (TILL) |
| 1288.20 - 1272.20 | 152.0 - 168.0 | SAND, FINE TO COARSE, SILTY; SOME GRAVEL |
| 1272.20 - 1254.20 | 168.0 - 186.0 | CLAY, BROWNISH-GRAY, SANDY, PEBBLY |

****



**Figure 3.** Query output screen—part 2.

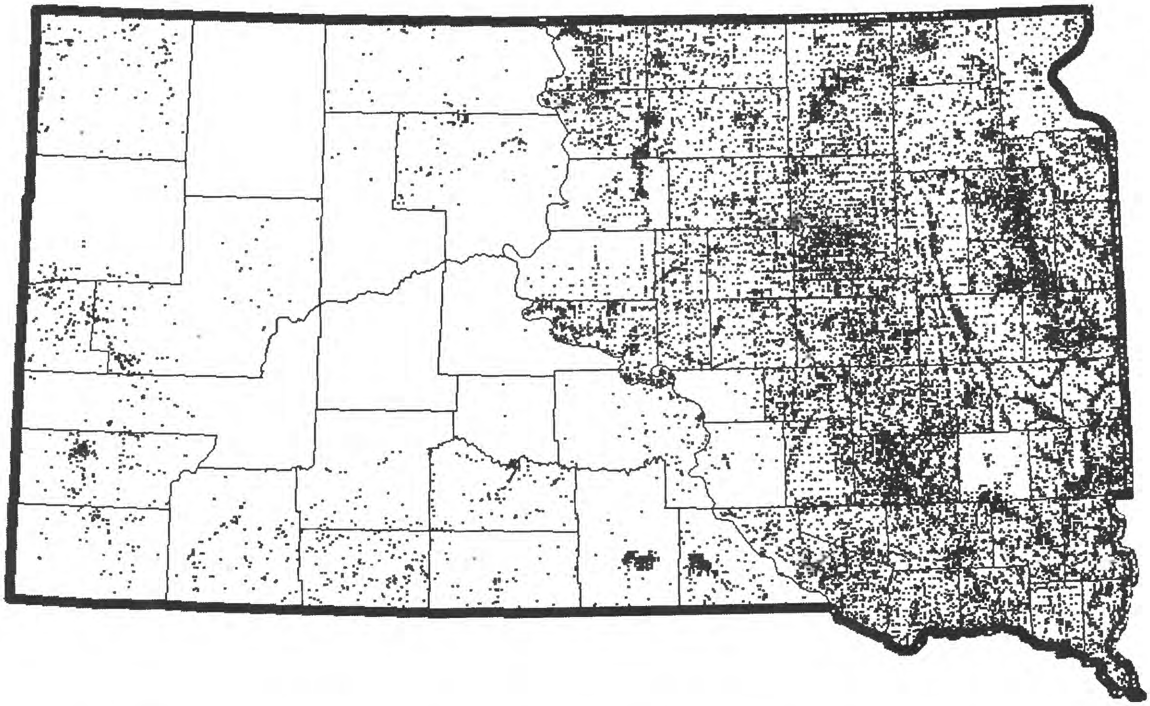


**Figure 4.** Plot of testhole and well locations.

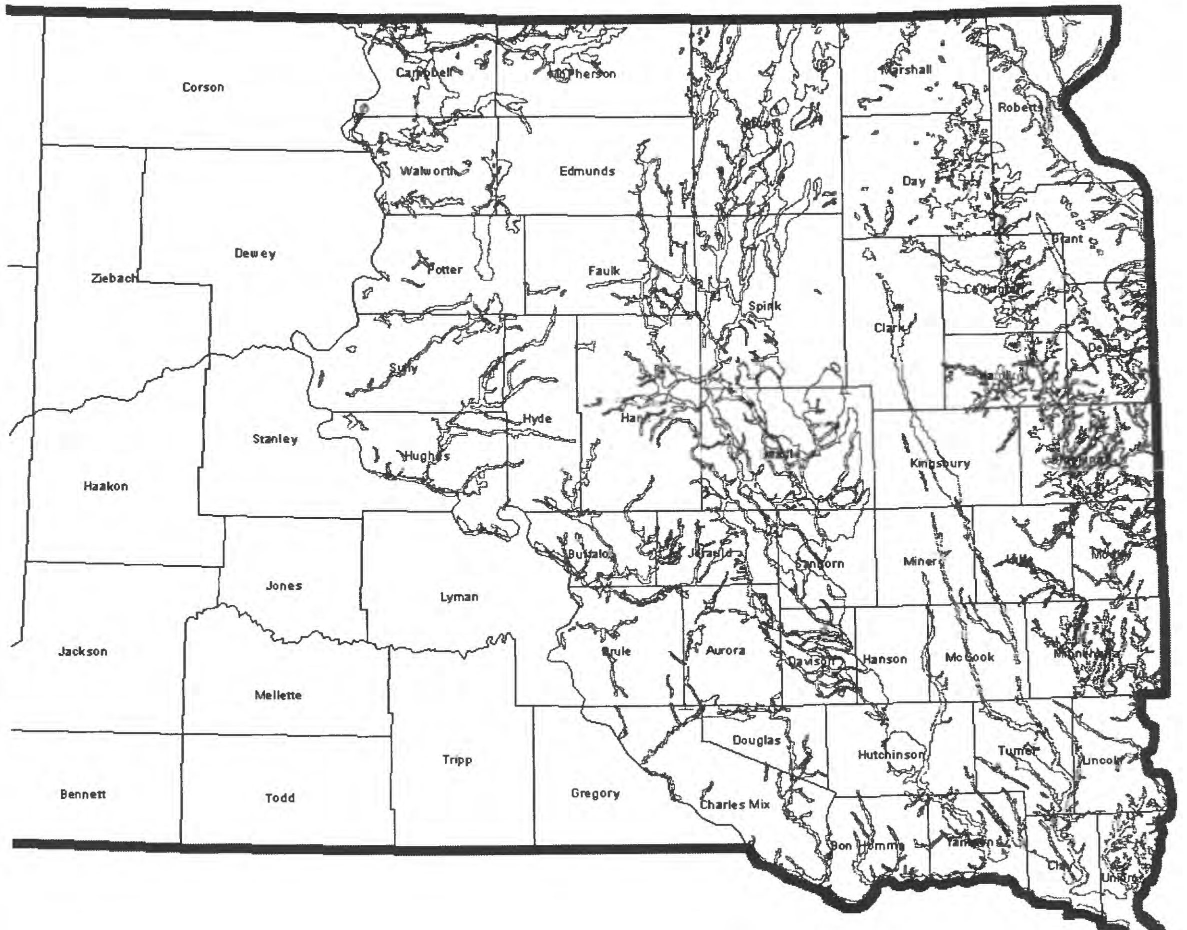



**Figure 5.** Aquifer boundaries at 1:500,000 scale.

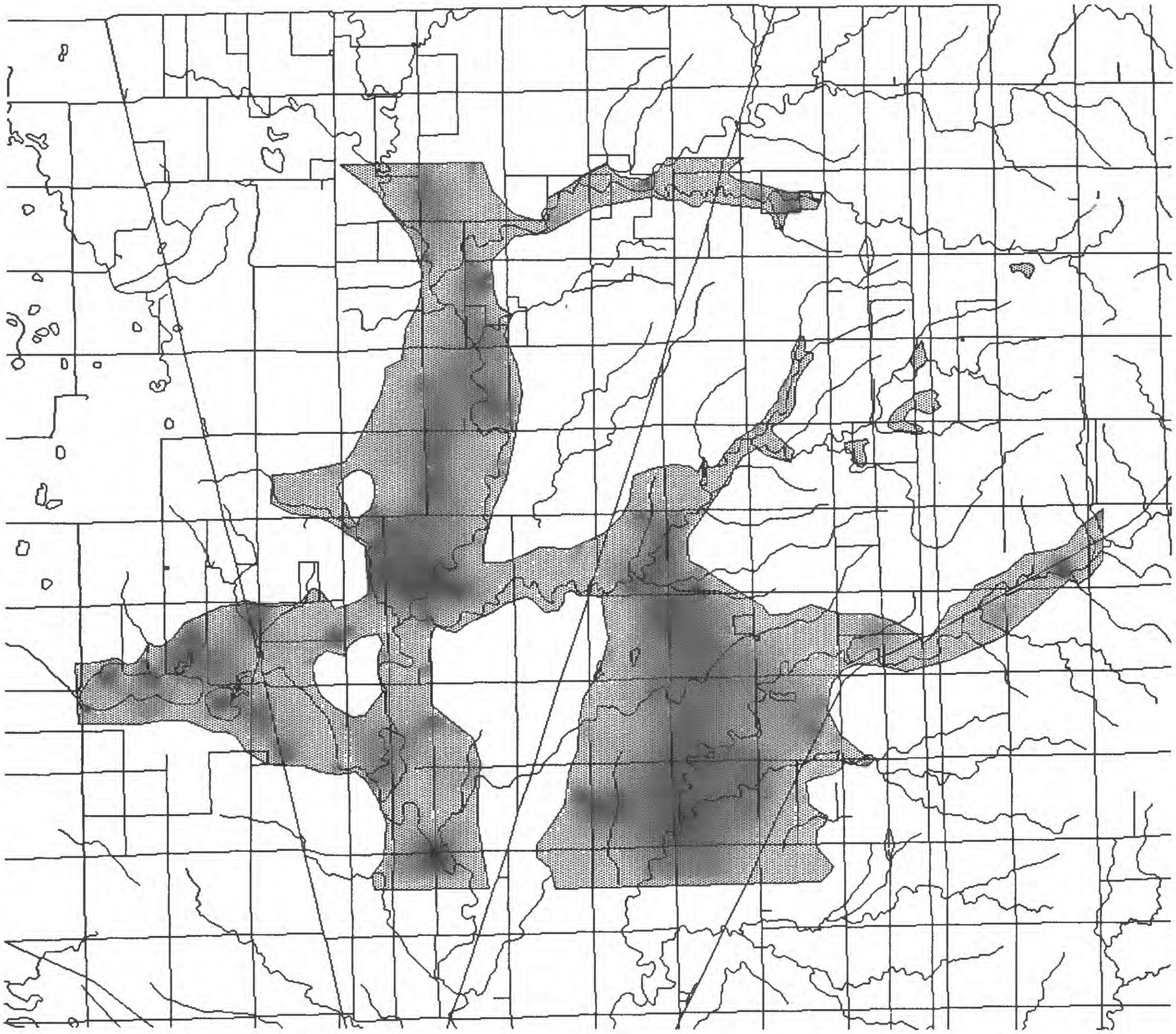


**Figure 6.** Aquifer boundaries at 1:100,000 scale.

map of the state. Boundaries of surficial aquifer materials were outlined and categorized to generate this map. The scale of the map limits its application. It will be used to depict the general location of surficial aquifers in the state. It should not be used for site specific aquifer boundaries. The availability of geologic data at this scale and the time frame required to produce the map made it a desirable product. It took approximately 160 man-hours to generate the boundaries and digitize the map into ArcView. It will serve as a precursor to larger scale aquifer maps.

SDGS is also beginning to incorporate 1:100,000 scale aquifer boundary maps on a county basis into digital form. The maps are based on the 1:100,000 scale geologic maps that are produced from the county study program. The level of detail that this scale of map provides allows the user to begin to define aquifer boundaries within the square mile. This makes the map useable on a project level. Siting of landfills, contaminant spills, and other environmentally sensitive subjects can be improved with these maps. It is estimated that each county map can be produced with about 120 man-hours of work. This includes generating surficial aquifer material boundaries and digitizing these boundaries into ArcView. Figure 6 is an example of 1:100,000 scale aquifer boundaries from the central portion of Codington County in northeastern South Dakota.

Aquifer boundary maps at a 1:24,000 scale are needed by many public and private entities. Generating a map of this scale for the entire state will be a major undertaking. The following list describes the basic data that will be used for generating accurate 1:24,000 scale aquifer boundary maps.

- Published 1:100,000 geology maps and unpublished 1:24,000 field geology maps
- Aerial photography
- Large scale digital soils maps

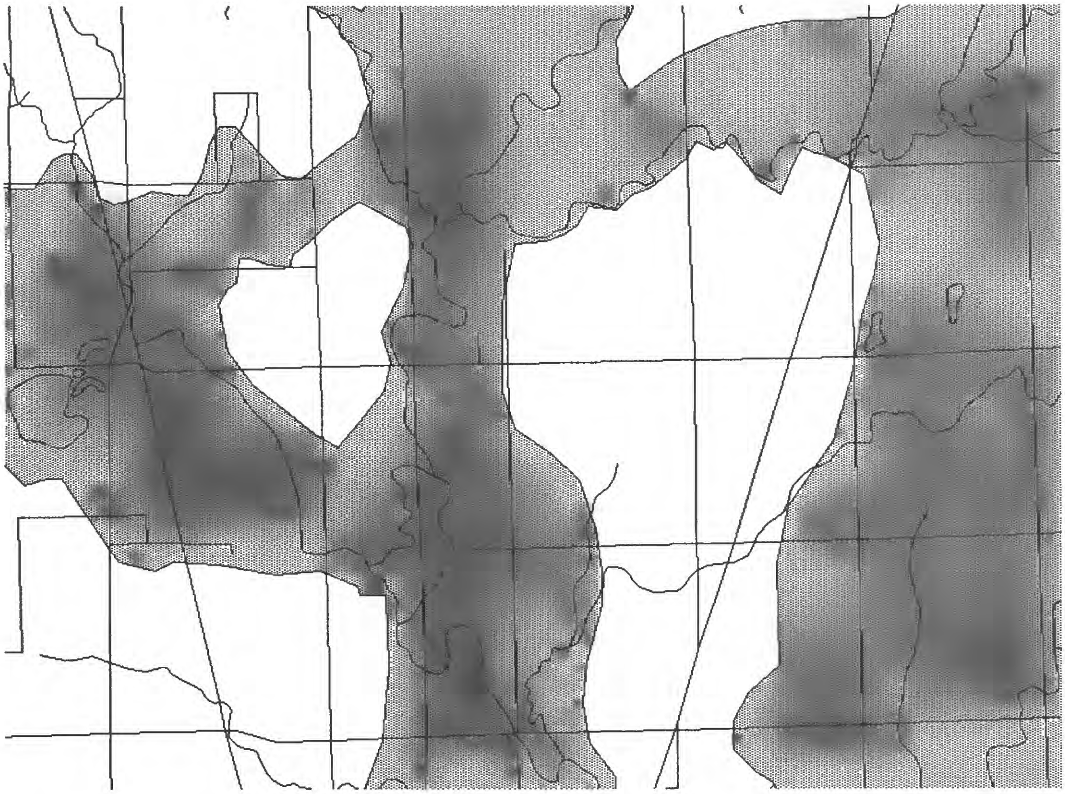


**Figure 7.** Aquifer boundaries at 1:24,000 scale.

- Data from the lithologic logs database
- Field checking at specific sites

Accurate 1:24,000 aquifer boundary maps will be used for site specific analysis of many environmental issues. The detail that will be available will allow users to make site-specific judgments with regard to aquifer locations. The time and effort involved to produce statewide coverage will be on the order of man-years. It is likely that some parts of the state will be designated high priority for 1:24,000 mapping and will be done long before other remote parts of the state. Complete statewide coverage of 1:24,000 aquifer maps, however, remains a goal of the state.

## CONCLUSIONS

The efforts of data collection, storage, and analysis by the DENR, including SDGS, warrant the development of a GIS system to assist in the management and analysis of data. Migrating primary databases into a common database management system and development of user friendly access system is an important part of developing the GIS system.

One of the products of the GIS system will be digital aquifer mapping. Digital aquifer maps are being generated at 1:500,000, 1:100,000, and 1:24,000. The detail and usefulness of each scale is inversely related to the time and human resources required to produce the map. Digital aquifer boundary maps at 1:500,000 scale are readily produced, but of limited value for anything but a general overview of where the state's surficial aquifers are. Digital aquifer boundary maps compiled at a 1:100,000 scale begin to provide enough detail for site specific use, and the time and cost of preparation is reasonable. It is a good investment of time and resources to produce this scale of map for the state. Large-scale maps, such as 1:24,000, are the ultimate product for this type of mapping. However, the time it will take to prepare them will be considerably longer.

# Digital Geologic Map Data Collection Using Photogrammetric and Raster Methods

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## ABSTRACT

The National Cooperative Geologic Mapping team (NCGM) in the Central Region of the U.S. Geological Survey (USGS) has some unique capabilities for collecting geologic data from old (printed) geologic maps, gathering information for new maps, and updating of existing digital maps. Maps on frosted or clear mylar (and in rare cases on paper) are scanned and vectorized almost automatically. Data gathered by both vectorization of scanned maps and by photogrammetric techniques from aerial and oblique photography are then imported into Arc/Info. Geologic map coverages are created and maintained in Arc/Info, and updates and corrections are made in Arc/Info from data captured by these techniques. Scanned mapping allows the measurement of line placement accuracy from pre-existing map materials. This measure may be totally unrelated to original line placement by a geologist in the field. Photogrammetric analysis of oblique photography of the land surface allows the capture of true three-dimensional geologic data. This technique can be especially useful in areas of rugged terrain and locations that are difficult to reach, or in field conditions where studies are possible only for a short time. Photogrammetric monitoring of volcanic activity is an ongoing research problem.

## INTRODUCTION

The USGS has produced digital maps for many years, but the earliest of these were representations of geophysical data or remotely sensed data. Traditionally, most geologic maps were drawn by hand from observations made on aerial photographs or directly on topographic map bases. These maps were first turned into a digital state when scribe coats or film positives of the line work and symbols were scanned with National Mapping Division's SCITEX equipment. Line work was "cleaned up" and correct symbols were added to make higher quality printed maps. The next step in vector data capture to make digital geologic maps for the Geologic Division scientists came with the USGS-developed software package called GSMAP. The last version of this software (Selner and Taylor, 1993), running on standard PC hardware allowed the geoscientist to digitize old and new geologic mapping and transfer the data set to the SCITEX environment or to Arc/Info, GRASS, or AutoCAD.

In 1972, the Central Regional Geologist's office established a plotter lab and funded the acquisition of the analog Kern PG-2 plotters. These devices allow the transfer of geologic information from stereo aerial photography to registered green line quadrangle or paper "ozalid" maps.

In the early 1990s, digital encoders were added to two of the PG-2 plotters and software was written to allow digital capture of the line work from the aerial photography and transfer of the resulting data into AutoCAD, GRASS, and Arc/Info. At roughly the same time a Kern analytic plotter was acquired by project activities sponsored by the U.S. Department of Energy (DOE) working at Yucca Mountain near the Nevada Test Site, Nevada. This instrument, depending on the quality of the photography, can capture quite usable data at a resolution of 3–4 microns on the photograph. The DOE supported this high-precision system in order to map geology over small areas in tunnel walls at Yucca Mountain (only briefly exposed during tunneling) and in trenches excavated for specific scientific studies.

Most recently a "Soft Plotter" hardware-software system from Zeiss, Inc. was added to the plotter laboratory. This system will allow for more photographic data to be used for the rapid collection of geologic data from many different image data sets. In one use, scanned aerial photography captured at a resolution that is a multiple of seven microns on the photograph (on Zeiss scanners) will allow as good a correction to be applied to rectify the photography to the ground as could be done using an analog plotter. The overall accuracy is probably better because hundreds of control points can be located on the photographs for a better approximation of the corrections necessary to register the photography to the ground.

## DATA SOURCES

Data arrives in the Data Acquisition Facility (DAF) in a number of ways. First, a geologist draws their line work representing their field observations on aerial photographs (stereo pairs) of the area in which they are working. For a 7 1/2' quadrangle this may mean 25 stereo pairs on average to cover the entire quadrangle. Some geologists record information directly onto the paper topographic sheets. These data are later digitized using a number of software packages including GSMCAD, AutoCAD, DesignCAD, and Arc/Info.

Pre-existing maps, both published and unpublished are additional sources of geologic data. To use the current scanner to its best advantage, these data must be either on a film positive (the best way) or on translucent mylar. Paper maps are usually not acceptable for scanning. For published maps, some of the original publication archive materials still exist and is suitable for scanning. For other maps, data must be traced onto mylar from the paper copies, a tedious procedure. Some data will probably be misrepresented in this process. Tracing geology works better when the data are generalized and compiled at a smaller scale.

In addition, the USGS and other civilian agencies have access to image data from National Technical Information sources. Data derived from these sources are usable on the "Soft Plotter" system.

## DATA CAPTURE

### Scans of Vector Maps

Scanned vector data from the USGS Central Region GIS Facility is turned into vector data by passing through the software package LT4X. It has been found that LT4X has more features that are quite useful and efficient to "vectorize" raster data than other commercial software packages that were investigated. First, the software computes a minimum horizontal accuracy with which lines can be located. For a 1:100,000-scale map that is scanned at 400 pixels/inch, the resolution is 15 meters. Another feature is a dynamic calculation of the accuracy with which the scan is geo-referenced. The coordinates of the map are produced in a number of map projections. In addition, when the appropriate zone numbers are furnished, conversions to UTM and State Plane grids are computed as well.

Before vectorization in LT4X is done, LT4X first reduces scans of individual lines to the width of one pixel, then spurs on lines are removed, holes in lines are filled and vectorization proceeds. After vectorization, the vectors can be checked against the original scan to allow differences between the vectorized map and the original scan to be corrected. Polygon closure is automatically checked for improper polygons, and when polygons are attributed, adjacent polygons with the same attribute set are noted to allow for correction if needed. When one is needed, a geographic quadrangle boundary in raster mode can be added before vectorization to allow for closure of polygons at the edge of a map.

### Photogrammetric Techniques

Geologic line work on stereo aerial photography can be collected in digital as well as analog form in the Photogrammetry laboratory of the DAF. In the standard photogrammetric procedure in use, the laboratory photogrammetrist, Jim Messerich, "sets" models on a PG-2 plotter using the field stereo pairs. Then for the digital PG-2 plotters, the line work is traced by the geologist and subsequently is transferred to a file on a Data General workstation using CADMAP, a software package from Zeiss, Inc. These data are displayed on a CRT screen as they are captured on top of hypsography or hydrography (when these are available) to act as a check on the registration of the geology and to insure that the line work "fits" well with the various data layers on a topographic quadrangle.

When an analog PG-2 is used, geologic data are transferred directly to a mylar sheet using a pantograph system. Usually the mylar has green-line drawing of the topographic quadrangle on it. Newer techniques use a punch-registered mylar sheet on top of the green line sheet. Data generated in this fashion are hand digitized, or scanned for use with the raster-to-vector process described above.

The "Soft Plotter" hardware/software subsystem is to be installed in the near future and should be of great utility when it is done. This system allows data to be collected from digitized photography or other appropriate imagery. The system also permits photogrammetric models to be more easily and quickly set. In addition to the capture of geologic data in a timely manner, the geologist can have a topographic contour map created dynamically to check the location of point and line data. When three-dimensional topography is generated and geologic data is collected on this surface, one additional problem must be solved. Differences occur between published topography and the topography generated by this technique. The proper placement of geologic data on one or the other of these two representations of the topography is difficult.

The resources needed to store high-resolution scans of aerial photography are substantial. One 9″×9″ photograph scanned at a resolution of 7 microns on the photograph and 256 gray levels occupies about 55 Mbytes of disk storage.

The photogrammetric laboratory has additional capabilities to collect geologic data from oblique photography shot by tripod-mounted hand-held cameras. The lab has a camera calibration room for such cameras that allow the measure of the correction factors for used camera-lens combinations. These corrections allow the use of photography taken with these cameras to be used to obtain three-dimensional geologic data. Photography generated this way is called oblique stereo photography. An explanation of how this photography is used will be given in the examples below.

## EXAMPLES

### Raster-to-Vector

The Digital Geologic Map of the Nevada Test Site (Wahl and others, 1997) is an example of a product that used multiple techniques to obtain vector data from raster scans or from photogrammetric plotters. Final editing of the vector data was done in Arc/Info, but seven of the nine coverages plotted on the map were initially captured using scans of existing map data or aerial photography on photogrammetric plotters. All the plotter data were captured digitally. The surficial geologic data in Yucca Flat and Gold Flat areas on the Pahute Mesa 1:100,000 part of the map were added into the database using LT4X and data from scanned film positives. In the Springdale 7.5′ quadrangle, in the south central part of the Pahute Mesa 1:100,000 sheet, data from the digital PG-2 were made into an Arc/Info coverage, and added to the map database from Arc/Info. The background topographic and planimetric map data were created from scans of the film positives of each 1:100,000 sheet and vectorized after the data were geo-referenced in.

### Photogrammetry

Three recent projects demonstrate the capabilities of the photogrammetric laboratory. The first project used a before-and-after study of the aerial photography of the Landers, California 1994 earthquake to document ground deformation patterns in detail. Photography at scales of 1:2500 and 1:6000 along with the new field control points allowed the motion along the fracture zones associated with the earthquake to be measured from the photography with an accuracy of from 2 cm to 3 cm. This study is in a research stage still and is being done by the Central Region Earthquake and Volcanic Hazards Team (EVH) and the photogrammetry laboratory. The collaborators are Robert Fleming, EVH, and Jim Messerich, NCGMP.

### Tartara-San Pedro, Chile

Work by Ren A. Thompson on the chronostratigraphy and eruptive history of this Chilean stratovolcano was successfully completed because the photogrammetric laboratory has the capability to capture geologic data from oblique photography (Singer and others, 1997). Because the rugged terrain would call for much time to gather three-dimensional geologic data (with less accuracy), tripod-mounted 35-mm cameras were used to make overlapping photographs of the canyon wall cross-sections through the volcanic edifice. The analytic stereo plotter was used to obtain not only horizontal positions but also altitudes at the same points. This means that true three-dimensional geology can be captured by this technique and is more timely and more accurate. This contrasts with the accuracy of vertical coordinates for measured horizontal positions derived from the interpolation of contour lines in a topographic base map.

### Merchants Exchange Building, Philadelphia

Oblique photogrammetry was used to measure the extent of decay from atmospheric pollution on the marble of the columns on the outside of the Merchants Exchange Building in Philadelphia, Pennsylvania. This was work was done for the National Park Service. When the photography was analyzed, the resolution of the plotter gave measurements accurate to within one millimeter. This is another situation in which oblique stereo photography, when analyzed with high accuracy photogrammetric plotters, can yield better accuracy and faster results than conventional methods in the same situation.

### Volcanic Monitoring

The volcanoes of the Aleutian Islands, particularly St. Augustine Island have been observed by oblique photography when helicopter availablility and weather conditions permitted. This was done as part of an experimental program to remotely measure ground surface motion on volcanoes. Now other stereo imagery could be used in the same manner. Control points were set and located for base locations. With imagery other than photography the imagery must have sufficient resolution to resolve such ground control points. As the surface of the island moves in response to volcanic activity, the size of the motion can be accurately measured from the imagery.

## CONCLUSIONS

Geologic data from old or new geology can be captured from scanned line work drawn on film positives or mylar sheets with the currently-owned scanner. These data can be quickly geo-referenced and converted to vector data suitable for use with CAD software or GIS software like Arc/Info.

Photogrammetry can be used to quite accurately and quickly capture geologic data drawn on aerial photographs that would be suitable for use with CAD or GIS software.

Photogrammetry can be used to capture unique data sets and provide insights into geologic processes. In the case of the Landers, 1994 earthquake photogrammetry provided an excellent way to document with great precision ground deformation associated with an earthquake fault zone rupture pattern.

Geologic data can be accurately collected from near-vertical exposures; assembled and analyzed in three-dimensions to precisely describe rock unit relationships especially in rugged terrain.

The capture of three-dimensional geologic data from stereo imagery provides a level of geologic information that GIS systems cannot handle yet, because all major GIS software systems store topology in two, not three, dimensions.

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# Utah Geological Survey Digital Mapping Using an Analytical Photogrammetric Plotter

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Like most state geological surveys, the Utah Geological Survey (UGS) is faced with the growing challenge of producing digital geologic maps. In 1991, the UGS made its first move into digital map production through the acquisition of an analytical photogrammetric stereoplotter. Traditional map production methods require hand-copying geologic features four or five times between field mapping and printing or digitizing. An analytical stereoplotter eliminates up to three of these steps. The UGS has digitally compiled 27 7.5′ geologic quadrangle maps directly from aerial photographs. The UGS is now entering the next phase of digital map production, converting maps into Geographic Information System (GIS) databases and using software to create high-resolution line work and color separates for hard-copy publication. The UGS hopes to do all stages of map production digitally within the next few years.

A typical method of producing geologic maps from the 1960s to the mid-1980s was to visually transfer field mapping directly from aerial photographs to mylar base maps. This was done by placing the base map and aerial photographs side-by-side and comparing contours with stream channels, ridges, and other topographic features to visually estimate the locations of contacts, faults, etc. As a result, the precision was commonly poor and inconsistent. The advent of ground-rectified 7.5′ orthophotoquadrangle maps in the 1980s was an improvement. Many more features could be seen on both aerial photographs and the orthophotoquads, aiding in properly locating geologic lines and symbols. In some cases, the formation contacts themselves can be seen. Transferring field mapping to orthophotoquads, and then tracing onto the topographic base map, is still a common method of creating geologic maps. However, geologic features are typically hand-drawn or copied five times between field mapping and final digital map production: (1) original field mapping on aerial photographs, (2) visually transferring to the orthophotoquad map, (3) tracing onto a mylar base map, (4) cartographic scribing for map publication, and (5) hand digitizing from the mylar or scribe plate. Each time, some detail is invariably lost and errors are introduced; even the most careful geologist or cartographer has a tendency to round corners, veer off lines, miss subtle line flexures, or introduce new lines, bends, or features.

Two ways to reduce hand-copying are to electronically scan the scribe or mylar plate, or digitally compile the field mapping directly from aerial photographs. Scanning, in which the scribed or mylar map is digitally scanned using a large-format scanner and then vectorized, eliminates the digitizing step. Results are mixed, depending primarily upon the amount of "noise" introduced during the scanning process. Cleanup of a scanned map commonly requires several hours to days of work.

Digital compilation of field mapping directly from aerial photographs using analytical photogrammetry offers four primary advantages over hand-copying: (1) map data are copied only twice instead of five times, saving time and reducing the loss of detail and introduction of errors; (2) the field geologists compile their own mapping directly from aerial photographs, allowing them to edit and correct their work in 3D stereo view, and reducing the possibility of cartographers misinterpreting their work; (3) analytical stereoplotters correct for inherent problems in aerial photographs, such as earth curvature, variations in aircraft altitude and attitude, and ground elevation changes. The resulting stereo model has great precision in the x, y, and z planes, allowing the geologist to actually improve placement of contacts, increase detail, and solve three-point problems; and (4) the digital map information is three-dimensional and amenable to either digital or hard-copy map production.

Primary disadvantages of digital compilation are: (1) contacts on steep slopes and cliffs can be difficult to see on aerial photographs because of shadows or "compression" of contacts into a small area; (2) locally, digital mapping may be more accurate than the topographic base maps, resulting in geologic contacts that do not fit the map contours properly; and (3) revisions late in the process may cause repetition of already-completed steps (though still less effort than making revisions after additional work is completed by hand).

After considering various options, the UGS purchased an Alpha 2000 analytical stereoplotter made by International Imaging Systems, Inc. Unfortunately, International Imaging Systems, Inc. was subsequently purchased by another company that discontinued stereoplotter production and support. However, other companies make similar analytical plotters for under $100,000. The stereoplotter is driven by a 25 MHz 386 personal computer. The proprietary software includes functions for rectifying aerial photographs and configuring digital data.

The stereoplotter software delivers a stream of three-dimensional UTM or state-plane coordinate data to a 166 MHz Pentium personal computer with CADMAP photogrammetry software, a product of Carl Zeiss, Inc. CADMAP is specifically designed for map preparation and contains many geologic map symbols and features. For example, it has a function to calculate strike and dip by digitizing three points on an inclined stratigraphic bed or fault directly from aerial photographs. Its type font selection is limited and unable to create special characters such as the Triassic and Pennsylvanian symbols. We use CADMAP to create all line work, geologic map symbols, and preliminary labels. Currently, the UGS is switching from a UNIX operating system to a Microsoft Windows NT based CADMAP system. CADMAP is excellent for geologic-map preparation, but it is not GIS software. For that purpose, the UGS uses Arc/Info software for Windows NT, which includes features for preparing maps for hard-copy publication.

# Digital Geologic Map Program of the Washington Division of Geology and Earth Resources


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## INTRODUCTION

The Division of Geology and Earth Resources (DGER) is Washington's state geological survey and a division of the Department of Natural Resources (DNR). The DNR began operating a geographic information system (GIS) in 1983. This system is used for a variety of land-management activities and includes such coverages as political boundaries, drainage and open water, transportation grid, section-township-range grid, land ownership, land cover-land use, and soils. DGER is preparing statewide digital geology coverages to add to the DNR GIS database.

The GIS runs on a platform of 67 Sun workstations with Solaris 2.5 as the operating system. There are over 700 users, and the main applications software is Arc/Info and Oracle. The system includes more than 200 GB of data storage and hundreds of X-Terminals, printers, plotters, and digitizers. DGER accesses this system through five X-Terminals (or emulators) and four digitizers. We produce plotted maps through a central facility located in the same building. Overall system administration, operation, training, and maintenance are department-level functions, but DGER is financially responsible for equipment upgrades and replacements for our terminals and digitizers and the "local" server.

Also in 1983 DGER began a program to reissue the state geologic map. Program objectives are: (1) Recompile and republish the state geologic map at 1:250,000 scale in full color in four quadrants using age-lithologic geologic unit symbology; (2) Compile the geology first at 1:100,000 scale and simplify it for presentation at 1:250,000; (3) Release the 1:100,000 maps as open-file reports with supporting descriptions of map units, index map(s) showing sources of geologic map data, references, and, in some reports, radiometric or other ages and geochemistry; and (4) If a U.S. Geological Survey (USGS) 1:100,000 geologic quadrangle map exists, use it instead of recompiling the quadrangle. Quadrant boundaries for the 1:250,000 maps are 47°15′ N. and 120°30′ W.

The 1:100,000 compilation geologic maps for the southwest quadrant of Washington were released in 1986 and 1987, and the southwest quadrant of the 1:250,000 state geologic map was printed in 1987. On this first set of 1:100,000 maps the geologic unit symbols differed from those used on the 1:250,000 map. By the time the 1:100,000 maps for northeastern Washington were being compiled, we concluded it would be easier to use the same basic symbology for both the 1:100,000 and 1:250,000 maps, arriving at the 1:250,000 unit symbols by dropping subscripts (which denote named geologic units) from the 1:100,000 unit symbols. The 1:100,000 geologic maps for the northeast quadrant were released in 1990, and the 1:250,000 geologic map was printed in 1991. The 1:100,000 geologic maps for the southeast quadrant were open-filed in 1993 and 1994, and the 1:250,000 geologic map will be printed by June 1997.

Work continues on 1:100,000 compilation geologic maps for the northwest quadrant. We hope to release all these maps in 1998 and publish the 1:250,000 geologic quadrant map promptly thereafter. However, budget cuts over the last five years have had serious effects on our state geologic map program, and we cannot predict map completion dates. Eight USGS 1:100,000 geologic maps (fig. 1) are available, as is the DGER 1:100,000 map for the Twisp quadrangle.

The DGER geologic maps were prepared using scale-stable copies of USGS topographic quadrangle maps as base maps. For most maps we drafted the geologic information on scale-stable overlays that were photographically composited with the base maps to produce master geologic maps; these are copied for distribution. The DGER scale-

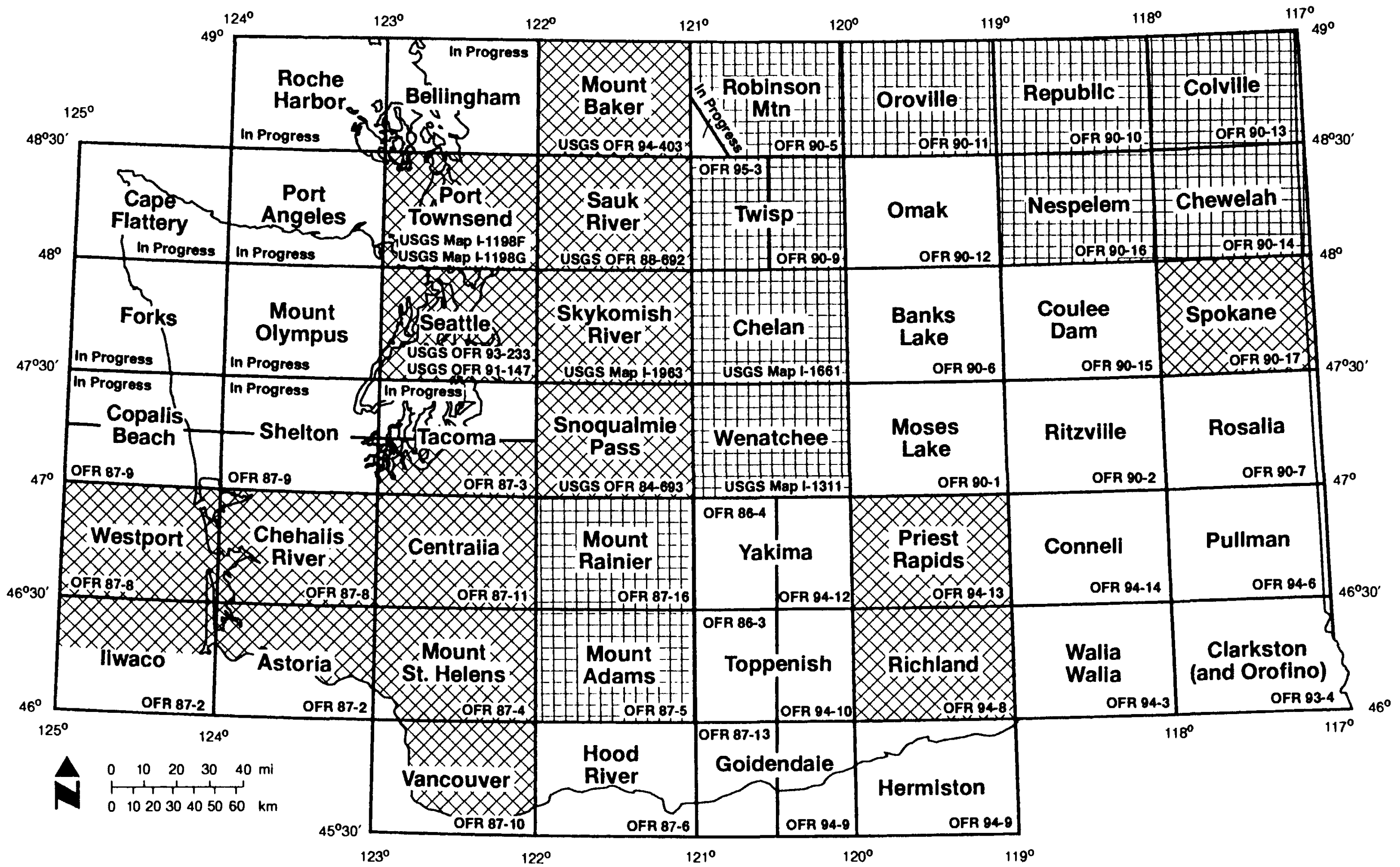



**Figure 1.** Status of 1:100,000 geologic mapping in Washington. For completed partial and whole quadrangles, the publication number is shown. "OFR" denotes a DGER open-file report; "USGS OFR" denotes a USGS open-file report; "USGS Map" denotes a USGS Miscellaneous Investigations Series Map, or I series. "In Progress" indicates that the geological compilation work is still under way. The crosshatch pattern marks the 17 quadrangles for which digital products are to be finished by June 30, 1997, and the grid pattern marks those to be finished June 30, 1998, both of these projects under USGS STATEMAP contracts.

stable composites or overlays are the data sources for the digital geologic coverages that we are currently preparing. For the USGS geologic maps, we typically work from digital files provided by the authors. At minimum, a change of geologic unit symbols is required, so that the USGS maps have the same geologic unit symbology as the DGER maps.

## PROGRESS TOWARD STATEWIDE DIGITAL GEOLOGY

DGER began working toward statewide 1:100,000 digital geologic coverage about four years ago when a contract from the Washington Department of Ecology allowed us to develop a data structure and to digitize the Richland and Priest Rapids quadrangles in eastern Washington. In the two years that followed that contract, we partially digitized several 1:100,000 quadrangles in southwestern Washington, using "spare" cartographer time.

Support from the STATEMAP component of the USGS National Cooperative Geologic Mapping program has radically improved the rate at which we generate digital geology. The initial STATEMAP contract calls for delivery of hard copy and digital geology for 17 1:100,000 quadrangles by June 30, 1997. The quadrangles were chosen on the basis of demand for digital geology, significant population, significant land-use issues, and at least partial availability of digital geologic information. These quadrangles are shown on figure 1. This contract requires a 50:50 match and has a total budget of $90,204. The USGS recently awarded us a second STATEMAP contract that calls for 11 more quadrangles by June 30, 1998 (Fig. 1). This contract also requires a 50:50 match and has total funding of $90,204. Two additional years of STATEMAP support should allow us to complete the remaining 24 full or partial quadrangles in Washington.

We will use about 17 months of cartographer and geologist time to complete the first 17 digital quadrangle maps, and another 17 to complete the second contract's 11 quadrangles. The difference is that some digital information was available for the first 17 quadrangles and several are only partial quadrangles, whereas 9 of the 11 quadrangles of the second contract will be digitized from hard copy and all the quadrangles are full size. These time estimates include about 3 months of geologist time for each contract to prepare materials for digitizing, convert old unit symbols to new ones where necessary, and review draft products. The remaining 14 months are spent digitizing, attributing, reviewing previous digital data and correcting errors and omissions, and editing the digital information.–Both cartographers and geologists contribute to the GIS tasks, with one cartographer concentrating on system development and design, training others, problem solving, and overall quality control, and one geologist and a second cartographer doing digitizing, attributing, editing, and error correction.

Our focus so far has been on generating statewide digital geology and supporting data. We have not used the digital geology for analysis, but we expect that many customers will do so.

## DIGITAL GEOLOGIC DATABASE DESIGN

The 1:100,000 quadrangle corner coordinates are fixed in state plane coordinates in the DNR GIS and provide the control points to which all geologic data are registered. For data entry, scale-stable originals are coordinated to the quadrangle corners to a root-mean-square error of 0.003 or better. Each 1:100,000 quadrangle is assigned a row-column grid number, and this number is the name of the directory in which all the digital data for that quadrangle are stored. For example, the Cape Flattery quadrangle is in row 2 and column 1, so it gets the number Q201; Clarkston is Q608 (row 6, column 8). See Figure 1 for quadrangle location.

The digital information for each quadrangle is stored in a set of seven Arc/Info coverages with associated INFO data files, all stored in that quadrangle's directory. The coverages contain different kinds of geologic map data, as shown in table 1. Statewide coverages are obtained by tiling the 1:100,000 quadrangles. The GUNIT, GFAULT, GFOLD, and GDIKE coverages have arc attribute tables with data items as shown in table 2. The GUNIT, GVENT, GATTUD,

**Table 1.** Coverage contents.

| Coverage | Type | Content |
|---|---|---|
| GUNIT | line and polygon | contacts, quadrangle boundaries, open-water boundaries, glacier boundaries, geologic unit polygon labels, open-water polygon labels, glacier polygon labels |
| GFAULT | line | faults |
| GFOLD | line | fold axes |
| GDIKE | line | dikes |
| GVENT | point | eruptive centers |
| GATTUD | point | structure symbols (strike and dip, foliation, lineation, etc.) |
| GDTSMPL | point | fossil and radiometric sample locations |

**Table 2.** Arc-attribute-table data items. X, present; —, absent.

| Item | Description | Coverage | | | |
|---|---|---|---|---|---|
| | | GUNIT | GFAULT | GFOLD | GDIKE |
| FNODE# | from-node number | X | X | X | X |
| TNODE# | to-node number | X | X | X | X |
| LPOLY# | left-polygon number | X | X | X | X |
| RPOLY# | right-polygon number | X | X | X | X |
| LENGTH | length | X | X | X | X |
| GUNIT# | ...# is a system-assigned number identifying each arc segment | X | — | — | — |
| GFAULT# | | — | X | — | — |
| GFOLD# | | — | — | X | — |
| GDIKE# | | — | — | — | X |
| GUNIT-ID | ...-ID is a user-assignable number identifying arc segments; used to populate other data items in the database | X | — | — | — |
| GFAULT-ID | | — | X | — | — |
| GFOLD-ID | | — | — | X | — |
| GDIKE-ID | | — | — | — | X |
| GCNTCT.ID | ... .ID is a number identifying all arc segments of a particular linear feature; used to distinguish that feature from any other linear feature; relates to a data file containing feature names | X | — | — | — |
| GFAULT.ID | | — | X | — | — |
| GFOLD.ID | | — | — | X | — |
| GDIKE.ID | | — | — | — | X |
| GCNTCT.TYPE.CD | ... .TYPE.CD is a user-assignable number identifying the arc segment type (certain contact, glacier boundary, normal fault, queried syncline, etc.) | X | — | — | — |
| GFLTSEG.TYPE.CD | | — | X | — | — |
| GFOLDSEG.TYPE.CD | | — | — | X | — |
| GDIKESEG.TYPE.CD | | — | — | — | X |
| GFLTSEG.NO | ...SEG.NO is a sequential number assigned to each arc segment to distinguish it from other segments of the same linear feature | — | X | — | — |
| GFOLD.SEG.NO | | — | — | X | — |
| GFLTSEG.ID | ...SEG.ID is a unique, system-assigned number attributed to each arc segment | — | X | — | — |
| GFOLDSEG.ID | | — | — | X | — |
| FLTCNT | "Y" if fault segment separates polygons with different labels; otherwise "N" or blank | X | X | — | — |
| GMAP.ID | The row-column code for the quadrangle | X | X | X | X |
| GUNIT.LABEL.CD | The geologic unit age-lithologic symbol | X | — | — | X |
| DIKE.NM | Dike name | — | — | — | X |

and GDTSMPL coverages have point or polygon attribute tables with data items as shown in table 3.

In practice, in the GUNIT coverage, the GCNTCT.TYPE.CD is the only data item that is typically populated when lines are digitized. We generally populate this item by assigning the proper line-type number to the GUNIT-ID data item in the arc attribute table from the digitizer keypad. After many lines are digitized, their GCNTCT.TYPE.CD's are all populated at once by calculating them equal to the GUNIT-ID's. If a line was digitized all at once, but the line type changes along its length (e.g., a contact going from exposed to concealed), then the segments different from the type assigned from the keypad must be selected and separately calculated to the proper GCNTCT.TYPE.CD. Likewise, geologic unit labels (GUNIT.LABEL.CD) in the GUNIT coverage can be indirectly assigned, through the GUNIT-ID data item, when the labels are digitized. We assign each geologic unit a unique number and enter the numbers from the keypad when digitizing polygon labels. When all unit labels have been added, the GUNIT.LABEL.CD's are populated, geologic unit by geologic unit, by selecting all polygons with the same GUNIT-ID number and calculating the appropriate GUNIT.LABEL.CD. For faults we let the program assign sequential numbers to the GFAULT-ID data item as we digitize the faults. Then we select all the fault arcs and calculate the GFAULT.ID data item to equal GFAULT-ID. This populates the GFAULT.ID data item for all the faults in one oper-

**Table 3.** Point- or polygon-attribute-table data items. X, present; —, absent.

| Item | Description | Coverage | | | |
|---|---|---|---|---|---|
| | | GUNIT | GFAULT | GFOLD | GDIKE |
| AREA | polygon area | X | X | X | X |
| PERIMETER | length of polygon perimeter | X | X | X | X |
| GUNIT# | ...# is a system-assigned number dentifying each point or polygon | X | — | — | — |
| GVENT# | | — | X | — | — |
| GATTUD# | | — | — | X | — |
| GDTSMPL# | | — | — | — | X |
| GUNIT-ID | ...-ID is a user-assignable number identifying points or polygons; used to populate other data items in the database | X | — | — | — |
| GVENT-ID | | — | X | — | — |
| GATTUD-ID | | — | — | X | — |
| GDTSMPL-ID | | — | — | — | X |
| GUNIT.ID | ... .ID is a system-assigned number identifying points or polygons | X | — | — | — |
| GVENT.ID | | — | X | — | — |
| GATTUD.ID | | — | — | X | — |
| GDTSMPL.ID | | — | — | — | X |
| GUNIT.LABEL.CD | the geologic unit age-lithologic symbol | X | X | — | X |
| GATTUD.CD | user-assigned number identifying the type of structural symbol (strike and dip of beds, strike and dip of foliation, etc.) | — | — | X | — |
| GATTUD.STRK.AZM | strike of planar structural feature or trend of linear structural feature, expressed as an azimuth | — | — | X | — |
| GATTUD.DIP.ANG | dip of planar structural feature or plunge of linear structural feature, in degrees below horizontal | — | — | X | — |
| GDTSMPL.METH.CD | number identifying the dating method (fossil or radiometric) | — | — | — | X |
| GDTSMPL.NO | sample location map number | — | — | — | X |

ation. We do the same with folds and dikes in the GFOLD and GDIKE coverages, and other time-saving uses of the ...-ID data items are possible.

We generally digitize faults into the GUNIT coverage, along with contacts and open-water and glacier boundaries. We assign the faults a GCNTCT.TYPE.CD of 0 so they are easy to separate from all the other arcs. Those fault segments that separate polygons with different geologic unit labels (GUNIT.LABEL.CD) are retained in the GUNIT coverage as contacts. All fault arcs are put into the GFAULT coverage, and those that do not separate polygons with different labels are removed from GUNIT. We treat the faults in this way so that the fault segments that remain in the GUNIT coverage will be exactly the same as the corresponding arc segments in the GFAULT coverage. Although it would have been easier to leave all arcs in just one coverage with coding to separate them by type, DNR prefers data designs that segregate different classes of items into different coverages.

In addition to the seven coverages, there are several data files that can be related to the coverages through shared INFO items. These provide additional information, such as the ages and lithologies of geologic units, named geologic units, named faults, named folds, source document citation(s), quadrangle title block, explanation of map symbols, radiometric ages, statement about the digital processing and who did it, and information on availability of the digital information. Rather than attempt to reproduce all the information in the source document(s), our intent is to capture the most important information, allowing most users to understand and use the coverages for analytical operations, but to direct users to source documents for details, especially for full descriptions of geologic units and additional references.

We are using the above approach to create digital geologic coverage, without subsurface data, for both bedrock and surficial geologic units. Surficial units include glacial and nonglacial deposits. Bedrock units include all rock types with ages from Quaternary to middle Proterozoic. When finished, statewide coverage will probably include 1,500–2,000 age-lithologic-name units.

## CLOSING NOTES

The STATEMAP component of the USGS National Cooperative Geologic Mapping program has made it possible for DGER to move toward a statewide digital 1:100,000 geologic database fairly quickly. However, we find that making digital geology easily available to the public is a significant undertaking. Especially because the USGS contributed funding for this mapping, we would be pleased if the USGS were to serve these 1:100,000-scale digital geologic maps to the public for free or nominal cost, through the Internet or other means of distribution.

We have worked with digital map files created by scanning and by digitizing, and we feel that digitizing gives us more control over the process and a greater ability to keep the electronic version true to the original map. We think this is so because digitizing requires examining and attending to arcs and labels one by one. This allows for detection and correction of many errors and problems in the original material, and it prevents small-scale "misinterpretation" of arcs that scanning sometimes introduces. This error detection and correction during digitizing is even more effective if the person doing the digitizing has geologic training, because that training allows a person to evaluate arcs and labels in geologic context in addition to spatial context. We have found that a good old-fashioned colored-pencil edit of a preliminary plotted map also allows a geologist to find many errors that would otherwise go undetected.

Finally, we have found it time-consuming and difficult to effectively deal with structural geologic data (strikes and dips, etc.) and to plot maps that look like the printed geologic maps to which geologists are accustomed. Some central repository or clearinghouse of ARC-macro-language routines to do such things would probably save lots of time and trouble and go far toward standardizing digital mapping practices.

# Appendix A.
# List of Attendees to the "Digital Mapping Techniques '97" Workshop (Grouped by Affiliation)

Berry H. Tew, Geological Survey of Alabama

Stephen M. Richard, Arizona Geological Survey

William D. Hanson, Arkansas Geological Commission

Boyan Brodaric, Geological Survey of Canada
Neil Rogers, Geological Survey of Canada
David W. Viljoen, Geological Survey of Canada

David L. Wagner, California Division of Mines and Geology

William S. Schenck, Delaware Geological Survey

Jonathan D. Arthur, Florida Geological Survey

Tim D Funderburg, Idaho Geological Survey
Loudon R. Stanford, Idaho Geological Survey

Pamella K. Carrillo, Illinois State Geological Survey
Rob Krumm, Illinois State Geological Survey
Barbara J. Stiff, Illinois State Geological Survey

James D. Giglierano, Iowa Geological Survey Bureau
Bernard E. Hoyer, Iowa Geological Survey Bureau

Nicholas J. Callaghan, Kansas Geological Survey
David R. Collins, Kansas Geological Survey
Elizabeth C. Crouse, Kansas Geological Survey
John C. Davis, Kansas Geological Survey
Scott F. Highby, Kansas Geological Survey
Gina Ross, Kansas Geological Survey
Joel Rotert, Kansas Geological Survey
Robert Sampson, Kansas Geological Survey

Warren H. Anderson, Kentucky Geological Survey
James C. Cobb, Kentucky Geological Survey
Lance G. Morris, Kentucky Geological Survey
Thomas N. Sparks, Kentucky Geological Survey

R. Hampton Peele, Dept. of Geography and Anthropology, LSU
John I. Snead, Louisiana Geological Survey

Robert A. Johnston, Maine Geological Survey
Robert D. Tucker, Maine Geological Survey

Richard S. Lively, Minnesota Geological Survey
Joyce Meints, Minnesota Geological Survey
Lynn Swanson, Minnesota Geological Survey

Thomas P. Hertel, Missouri DNR, Division of Geology and Land Survey
Mark A. Middendorf, Missouri DNR, Division of Geology and Land Survey
Thomas L. Thompson, Missouri DNR, Division of Geology and Land Survey

Larry N. Smith, Montana Bureau of Mines and Geology

Les Howard, University of Nebraska, Lincoln, Conservation and Survey Division
Mohan Khisty, University of Nebraska, Lincoln, Conservation and Survey Division
Sue Olafsen-Lackey, University of Nebraska, Lincoln, Conservation and Survey Division

Susan L. Tingley, Nevada Bureau of Mines and Geology

Ronald S. Pristas, New Jersey Geological Survey

Kathy Glesener, New Mexico Bureau of Mines and Mineral Resources
Glen E. Jones, New Mexico Bureau of Mines and Mineral Resources
David J. McCraw, New Mexico Bureau of Mines and Mineral Resources

P. Albert Carpenter, North Carolina Geological Survey
Robert H. Carpenter, North Carolina Geological Survey

Thomas M. Berg, Ohio Geological Survey

Paul E. Staub, Oregon Dept. of Geology and Mineral Industries

Thomas G. Whitfield, Pennsylvania Geological Survey

Tim Cowman, South Dakota Geological Survey

Taryn Lindquist, U.S. Geological Survey
Peter T. Lyttle, U.S. Geological Survey
David W. Moore, U.S. Geological Survey
Susan D. Price, U.S. Geological Survey
Gary L Raines, U. S. Geological Survey
David R. Soller, U. S. Geological Survey
Michael Starbuck, U. S. Geological Survey
Ronald R. Wahl, U. S. Geological Survey
Van S. Williams, U. S. Geological Survey

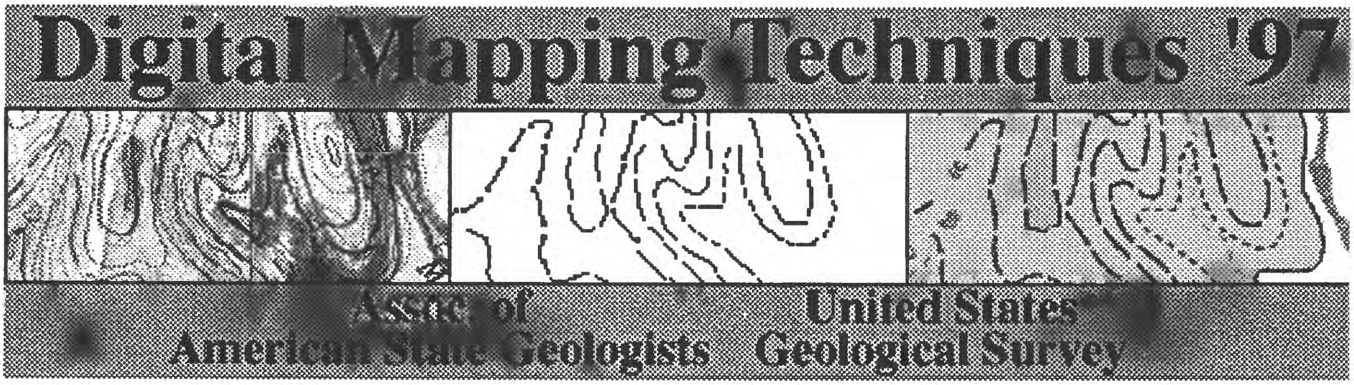
Kent D. Brown, Utah Geological Survey
Grant C. Willis, Utah Geological Survey

Rick Berquist, Virginia Division of Mineral Resources
Ian J. Duncan, Virginia Division of Mineral Resources
Stanley S. Johnson, Virginia Division of Mineral Resources

Gayle H. McColloch, Jr., West Virginia Geological Survey

Kathryn Barrett, Wisconsin Geological and Natural History Survey
Mindy C. James, Wisconsin Geological and Natural History Survey

# Appendix B.
# Workshop Website




**Hosted by the Kansas Geological Survey**
**June 2-5, 1997, Lawrence, Kansas**

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The Digital Mapping Techniques '97 conference is an Invitation-Only Conference to bring together those workers at state and federal agencies that are creating digital geologic maps in the U.S. This workshop will focus on methods of datacapture and digital map production. Topics will include data-capture methods, digital map publication, and management issues such as financial and personnel costs.

- Online registration form
- Paper registration form
- Lawrence Motel Information

- Schedule of Events
- Conference Attendees
- KU West Campus map

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Kansas Geological Survey, Digital Mapping Techniques Conference
Updated April 15, 1997
Send comments and/or suggestions to webadmin@crude2.kgs.ukans.edu
URL="http://www.kgs.ukans.edu/DMT97/index.html"

# Appendix C.

A list of addresses, telephone numbers, and URLs for software and hardware suppliers mentioned in the articles in this volume. Information contained herein was provided mostly by the authors of the various articles and has not been checked by the editor for accuracy.

**Abicas**—Innovative Technologies of America, Inc., P.O. Box 21212, Alexandria, VA 22320, (703) 548-1129.

**Adobe Illustrator and Adobe Photoshop**—Adobe Systems Inc., 345 Park Ave., San Jose, CA., 95110, http://www.adobe.com

**Agfa**—AFGA-Gevaert N.V., Septestrat 27, B-2640 Mortsel, Belgium, http://www.agfa.com

**Alacarte**—U. S. Geological Survey Open-File Report 91-587A, http://wrgis.wr.usgs.gov/docs/software/software.html

**Apple Newton and Messagepad**—Apple Computer, Inc., 1 Infinite Loop, Cupertino, CA 95014, (408) 996-1010, http://www.apple.com

**Arc/Info, ArcView, and ArcScan**—Environmental Systems Research Institute (ESRI), Inc., 380 New York St., Redlands, CA 92373, (714) 793-2853, http://www.esri.com

**AutoCAD**—Autodesk, Inc., 111 McInnis Parkway, San Rafael, CA 94903, 1-800-964-6432, http://www.autodesk.com

**CADCore**—Hitachi Software Engineering Co., Ltd., 4-6 Kanda Surugadai, Chiyodaku, Tokyo 101-10, Japan, http://www.hitachisoft-co.com/autopress.html

**CADMAP**—Carl Zeiss, Inc., 61 Inverness Drive East, Suite 102, Englewood, CO 80112, (303) 799-6838, http://www.czi.com/cmap_dgn.html

**CADMappr**—GeoLogiCAD Services, P.O. Box 461, Coeur d'Alene, ID 83816

**Calcomp**—Calcomp Technology, Inc., 2411 West La Palma Avenue, Anaheim, CA 92801-2689, (714) 821 -2000, http://www.calcomp.com/frontpage.html

**Canon**—Canon USA, Inc., One Canon Plaza, Lake Success, NY 11042, (516) 488-6700, http://www.usa.canon.com/canonusa.html

**Canvas**—Deneba Software, 3305 NW 74th Ave., Miami, FL 33122 http://www.deneba.com

**CorelDraw**—Corel Corp., Ottawa, Ontario, Canada, http://www.corel.com

**dBase**—Borland Corp., Borland International Inc., 100 Borland Way, Scotts Valley, CA 95066, (408) 431-1000, http://www.borland.com

**Datacopy**—Xerox Imaging Systems, 535 Oakmead Parkway, Sunnyvale, CA 94086 http://www.xerox.ca./factbook/products.com

**Excel (Alpha Workstation)**—Digital Equipment Corp., 1-800-722-9322; http://www.digital.com/info/contact.html

**Fieldlog**—Geological Survey of Canada, 601 Booth St., Ottawa, Ontario, Canada, K1A 0E9, http://gis.nrcan.gc.ca

**Fieldworker**—Fieldworker Products Ltd., 551 Millwood Road, Toronto, ON, M4S 1K7, (416)483-3485, http://www.fieldworker.com

**Freehand**—Macromedia, Inc., 600 Townsend St., San Francisco, CA 94103, (800) 470-7211, http://www.macromedia.com

**Generic CAD**—Generic Software, Inc., 8763 148th Ave., N.E., Redmond, WA 98052, (800) 228-3601, http://www.autodesk.com

**Ghostscript**—Alladin Enterprises, Menlo Park, CA ftp://ftp.cs.wisc.edu/ghost/alladin/com-mprod.doc

**GSMAP/GSDRAW**—U.S. Geological Survey Open-file Report 93-511 and 88-295a and b

**GSMCAD**—U.S. Geological Survey Open-file Report 96-007, http://ncgmp.cr.usgs.gov/ncgmp/gsmcad/gsmcwww.htm

**GTCO**—GTCO Corp., 7125 Riverwood Drive, Columbia, MD 21046, (410) 381-6688, http://www.GTCO.com

**HP**—Hewlett Packard Co., 8000 Foothills Blvd, Roseville CA 95747, 1-800-Packard)258-7777, http://www.hp.com

**ImageMagick**—http://www.wizards.dupont.com/cristy/ImageMagick.html

**Intergraph**—Intergraph Corporation Corporate Headquarters, Huntsville, Alabama, 35894-0001, (205) 730-2000, http://www.intergraph.com

**Larson Software**—Larson Software Technology, Houston, TX

**LT4X**—Pacer Infotec Inc., 4099 SE International Way, #206, Portland, OR 97222, (503) 794-1344, http://www.pacerinfotec.com/gis

**MapInfo**—MapInfo Corp., One Global View, Troy, NY, 12180-8399 (518)285-6000, http://www.mapinfo.com or http://www.mapinfor.com/world/office/intl.html#country6

**MapPublisher**—Avenza Software Marketing, 3385 Harvester Road, Burlington, L7 3N2,Ontario, Canada, (905) 639-3330, www.avenza.com

**ODBC, Windows95, Windows NT, and DOS**—Microsoft Corp., 1 Microsoft Way, Redmond Washington, 98052 6399, http://www.microsoft.com

**Oracle**—Oracle Corp., 500 Oracle Parkway, Redwood City, CA 94065,http://www.oracle.com/corporate/html/products.html

**PrePress**—PrePress Solutions, Inc., 11 Mt. Pleasant Ave., East Hanover, NJ 07936, (201) 884-6100, http://www.prepress.pps.com

**Scitex**—Scitext Corporate Headquarters, P.O. Box 330, Herzlia Industrial Park, 46103 Herzlia B, Israel, North American Phone (617) 275-5150, http://www.scitex.com

**SGI**—Silicon Graphics Inc., 2011 North Shoreline Blvd., Mountain View, CA, 94043, 1- (800) 800-7441, http://www.sgi.com/Overview/index.html

**SPANS**—Tydac Research Inc., 2 Gurdwara Rd., Suite 210, Nepean, ON, Canada K2E 1A2

**Sun**—Sun Microsystems, Inc., 2550 Garcia Ave., Mountain View, CA 94043, (415) 960-1300, http://access1.sun.com

**Tektronix**—Tektronix, Inc., P.O. Box 1000, M.S. 63-372, Wilsonville, OR 97070, 1-800-835-6100, http://www.tek.com

**Transverter Pro**—TechPool Software, 1463 Warrensville Center Road, Cleveland, OH 44121, (216) 291-1922, http://www.techpool.com

**Wacom**—Wacom Technology Corp., 501 SE Columbia Shore Blvd., Suite 300, Vancouver, WA 98661, http://www.wacom.com

**xv**—http://www.sun.com/sunsoft/catlink/xv/xv.html

# Appendix D. USGS Contract Digitizing in Support of the Mineral Resource Surveys Program

By Gary Raines

U.S. Geological Survey
MS 176
c/o MacKay School of Mines
Reno Laxalt Building, Room 271
Reno, NV 89557
Telephone: (702) 784–5596
Fax: (702) 784–5079
e-mail: graines@usgs.gov

The USGS Mineral Resource Surveys Program has since 1989 used contract services to produce digital versions of published and unpublished (manuscript) geologic maps at a variety of scales. For each map, the contractor is required to adhere to specifications that I developed (attachments A and B).

In each case, the contractor is supplied with the original publication separates or manuscript map. In some cases, the geology is separated from the base map information. In other cases, the geologic lines and base map features are contained on a single sheet; this increases the cost of map digitization.

Provided that scale-stable materials are available for scanning, the contractor is required to precisely register the digital map output to the original map. The contractor delivers Arc/Info export files with fully attributed coverages (according to Attachments, provided below). The attributes for all polygons, lines, and points are incorporated into the PATs and AATs of the coverages created. The contractor is requested to make proof plots of the map for us to check. In some cases, this is not possible due to the size of the map and plotting limitations of the contractor. If the contractor cannot plot the map, then I do so (using an HP650 plotter and mylar, not paper) to compare with the scanned materials.

The agreements state that upon delivery of map files and proofs, we must within four weeks examine the deliverables and accept or reject them. Proofing involves the following steps:

- verification that the proof plot exactly matches the source
- verification that all lines and points were digitized, and
- verification that all features were properly attributed.

The contractor has never failed to meet all of these tests. The contractor is to misattribute no more than 10 percent of the features; but they have never approached this level of error. Typically, no contractor errors in positioning or attributing are found. The more significant problem is attribution of tiny polygons that cannot be identified, even by a geologist familiar with the area.

Example costs for contract digitizing and production of attributed Arc/Info coverages is shown below.

| Map | Scale | Cost/Time |
|---|---|---|
| Washington/Idaho/ Montana state maps | 1:500,000 (4 plates) | $87K (3 months) |
| USGS Map I–667 (Swales Mtn.) | 1:24,000 (1.5 quads) | $2K (3 months) |
| USGS Map I–1028 (Carlin-Pinon Range) | 1:62,500 (4 quads) | $8K (3 months) |

# ATTACHMENT A

## STATEMENT OF WORK

## 1 BACKGROUND

The U.S. Geological Survey (USGS), Office of Mineral Resources, Branch of Western Mineral Resources (WMR) has a requirement for digital geologic map data production services. The service needed at this time is to digitize state geologic maps and production of topologically structured ARC/INFO (TSAI) files. TSAI data files include all geologic information on a geologic map including faults and other structural-geologic information and lithologic information at a scale of 1:500,000. The purpose of these data files are to provide the digital data necessary to reproduce any or all of the information contained in the published geologic map using ARC/INFO version 6.0 or newer software.

If any of the criteria or formats defined in this statement of work significantly impact the cost, the Contractor can propose a proven, most cost effective alternative that meets the Government's purpose.

## 2 REQUIREMENT

The contractor shall deliver TSAI data to USGS in accordance with the specifications described here. Completed work includes the digitization of all geologic information on the geologic map and the production of the TSAI data files meeting ARC/INFO data export file specification (version 6.0) or newer) and the USGS specifications detailed in Attachment B (Data structure for digital geologic maps).

The project addressed by this contract requires the production of TSAI data representing contacts, faults, fold axis, formation names, and other geologic information found of the specified state geologic map and defined in the legend of that map. All digitized data are to be complete, appropriately attributed, and topologically structured to allow for duplication of the published map using ARC/INFO software (version 6.0 or newer) or to allow for creation of a new map using any combination or selection of features and attribues.

## 3 GOVERNMENT FURNISHED MATERIALS (GFM)

3.1 Two (2) stable-base copies of the geologic map. The cleanest material available will be used; however in some case extraneous non-geologic information may be included on this material.

3.2 One published colored copy of the geologic map.

3.3 Shipment of GFM-Commercial shipment of the GFM by the government and the Contractor shall be by registered mail, return receipt requested. This requirement may be waived in the event other methods of shipment are more advantageous to the Government, e.g.,messenger, air freight, etc. If other than registered mail is used, a receipt shall be furnished by the Contractor to the Contracting Officer with a copy to the Contracting Officer's Representative (COR).

## 4 DELIVERABLE PRODUCTS—The following data and material shall be delivered by the Contractor for the geologic map digitized and processed:

4.1 Topologically Structured ARC/INFO (TSAI) Data

4.1.1 The Contractor shall produce two TSAI data files in ARC/INFO export format (version 6.0 or newer) for the supplied map. The first TSAI data product will be the lithologic polygons (a polygon coverage). The second TSAI data product will be the structural geologic information (an arc coverage). TSAI data produced must meet the format specifications detailed in Attachment B.

4.1.1.1 The polygon and arc coverage will have some duplicate arcs because many of the faults will also be boundaries of lithologic polygons. The Contractor should make every effort to make these duplicate arcs identical in both TSAI data files.

4.1.2 The Contractor shall record the TSAI files representing the geologic map on computer compatible one-half inch, 9-track magnetic tape at 6400 BPI or some other alternate format, such as Internet ftp, as agreed with the COB at time of delivery. A tape should have a label indicating the map name, the Contractor's name, and the name of the data files.

4.2 Verification Plots—A minimum of two plots are required. These plots will contain the polygon and arc coverages. If the contractor is not able to plot the map, the USGS may, at their discretion, produce the plots.

4.2.1 Line verification—One plot on stable-base material at the scale of the GFM published map shall be delivered for each TSAI geologic map. The purpose of this plot is to verify the positional accuracy and attributes of all lines. Each plot shall be provided as a positive image on clear or translucent media (film or frosted mylar) 0.004" or thicker. The elements which shall be shown on the plots and symbology to used are indicated below.

4.2.1.1 The selection of line weights and other symbols should be similar to those on the GFM. The numbers given below are only listed as approximate sizes.

4.2.1.2 Nodes, points where 3 or more arcs intersect, might be plotted using a circle with a line weight of 0.005" and diameter of 0.080". The circle shall be centered over the recorded coordinates of the node. For pseudo nodes, points where 2 arcs join, and for hanging nodes, end points of an arc which does not join another arc, symbols might be diamonds and squares respectively.

4.2.1.3 All lines should be plotted with a distinctive line weight similar to those on the GFM. For example, all geologic contact and fold axis might be plotted with a line weight of 0.005". All faults might be plotted with a line weight of 0.010".

4.2.1.4 All dashed and dotted lines should be reproduced similar to those displayed on the published map.

4.2.1.5 All thrust faults and other decorated lines should be plotted with decorations similar to the published geologic map. These decorations must be on the same side as shown on the published map. Colored lines could also be used to help differentiate line types. See Attachment B for more information of decorated lines.

4.2.1.6 Plotting material shall measure an appropriate size to get the proof print on the minimal number of pages. In the case that the map will not plot on one page, one smaller scale plot should be provided to verify the registration across plotting page boundaries.

4.2.1.7 Tick marks measuring 0.1″ in length and positioned and labeled with latitude and longitude on the latitude-longitude points shown on the GFM published geologic map shall appear on all plots with a distinctive fine line weight.

4.2.1.8 The following information shall be printed in the margin of all plots:

4.2.1.8.1 Plot generation date, plot scale, source-data map name, map authors, map scale, and map publication date (e.g. Geologic Map of Nevada, Stewart and Carlson, 1977)

4.2.1.8.2 Contractor name, name of the Contractors' contract, address, and phone number.

4.2.2 Polygon verification plot—one full color plot at the scale of the published map shall be delivered. The purpose of this plot is to verify the attributes of all polygons. Each plot shall be provided as a positive image on paper base or other appropriate media for good color display. The elements which shall be shown on the plots and the symbology to be used is indicated below.

4.2.2.1 All lines as defined above in section 4.3.1.

4.2.2.2 Because of the wide variety of hardware, there are many options how this might be colored. The purpose of the coloring is to provide a product with colors similar to the published map to facilitate verification of the assigned polygon (formation) attributes. Because these maps often combine colors and patterns the Contractor should select a display method that will make comparisons between the published map and the verification plot as easy and rapid as possible.

4.2.2.2.1 The coloring scheme should allow for easy identification of the attributes of small polygons. Solid colors are generally best for this objective.

4.2.2.2.2 The coloring scheme should be similar to the scheme used on the GFM published geologic map, but does not need to duplicate those colors. The objective is that similar colors will aid verification.

4.2.2.3 A colored legend should accompany this colored map which defines the relationship between colors and symbols on the map and the attributes of the lines and polygons.

4.2.3 Although the line weights specified may not be achievable, given the variety of plotting equipment and plotting media available, they should be as close to the original specifications as possible and must be completely legible and be precise enough to permit effective evaluation of the completeness and positional accuracy of the data produced.

4.3 Intermediate products—Other products, such as raster scanned images, that are made in the course of obtaining the TSAI data file could be of value to the Government. Such products would be considered in evaluation the Contractor.

4.4 Status Reports—Two (2) copies of a monthly status report shall be delivered to the COR by the tenth (10th) calendar day after the end of each month, beginning with the month following the delivery of the GFM to the Contractor. The content of the report is specified in Paragraph 6.9. A status report is not necessary if the Deliverable Products can be completed in 40 days or less.

4.5 Final Report—Four (4) copies of a final report shall be delivered to the COR at the completion of the project. The content of the report is specified in Paragraph 6.10.

## 5 QUALITY STANDARDS

The following standards shall be met by the Contractor to ensure the quality and accuracy of the digital cartographic data provided to the Government.

5.1 The government intends to use these TSAI with ARC/INFO software (version 5.0.1 or newer). Knowledge of the full details of the formats necessary so the TSAI data can be imported and directly used with the ARC/INFO software with the ARC/INFO import procedure are the responsibility of the Contractor. Information regarding the ARC/INFO software may be obtained from: Environmental Systems Research Institute, Inc., 380 New York Street, Redlands, California.

5.2 Category-defined features that appear on the state geologic map of the government furnished materials shall be digitized and assigned attribute codes. Ninety-eight percent (98%) of the coded elements will be as shown on the GFM published geologic map. All formats in attribute tables will be in accordance with the standards contained in Attachment B. When proper attribute codes cannot be determined using Attachment B, the Contractor shall notify the COR for resolution. Resolution of these problems will often require the Contractor to involve a geologist experienced with state geologic maps and access to people with the necessary information to correctly tag the attribute.

5.3 The positional accuracy of ninety percent (90%) of all nodes shall be inside the true position of the node defined by the intersecting lines on the GFM scale-stable source. The positional accuracy of ninety percent (90%) of all vertices shall be inside the line as found on the GFM scale-stable source. The remaining ten percent (10%) of all TSAI elements shall be within 0.010" in any direction from the true (correct) position shown on the GFM scale-stable source.

5.4 Linear features shall be digitized with a point density sufficient to preserve the graphic quality of the feature as represented on the GFM. Thus, angularity of lines that is not visible on the GFM scale-stable source should not be visible on the digitized product when plotted at the same scale as the GFM scale-stable source

## 6 TASK DEFINITION

6.1 The Contractor shall perform the following tasks to produce the required deliverable products detailed in section 4.0. The TSAI data produced shall comply with the ARC/INFO export format (version 5.0.1 or newer) and the content and quality standards stated in Section 5.0 and Attachment B.

6.2 The Contractor shall furnish all personnel, labor, facilities, material, and any other items, except as otherwise provided as GFM, required to produce the necessary TSAI files required as deliverable items.

6.3 The Contractor will require the services of a geologist experienced in the use of geologic maps in order to properly attribute all of the elements shown upon the map. The Contractor shall document that such an experienced person is available to assist in solving questions about attributing.

6.3.1 The COR will provide consultation with the Contractor's geologist at least by telephone to help resolve attributing problems.

6.4 Task A—Preparation

Due to the wide variety of computer equipment used by private industry to perform work of the type required, and the varied production techniques used to optimize the operation of these systems, all preparation of digitizing media is the responsibility of the Contractor. The Government will not prepare or furnish any materials other than those identified as GFM.

6.5 Task B—Data Collecting and Attributing

The Contractor shall digitize and attribute all features defined in the legend of the published GFM and any Contractor materials derived from GFM as a result of Task A.

6.6 Task C—Editing

The Contractor shall edit the data collected in Task B as necessary to correct all attributing errors and element misalignments, to delete duplication and extraneous information, to add missing data, and to provide topological structure necessary to digitally reproduce the GFM published geologic map.

6.7 Task D—Processing

The Contractor shall perform all data processing required using the data produced through Task C to generate the TSAI data files in the ARC/INFO export format (version 5.0.1 or newer), and with the content and quality standards detailed in Attachment B and Attachment A, section 5.

6.8 Task E—Verification

For each TSAI data produced, the Contractor shall generate the verification plots detailed in Section 4.0. The Contractor shall inspect each TSAI data file produced under this contract to ensure full compliance with the standards detailed in Section 5.0 and Attachments B prior to delivery to the Government.

6.9 Task F—Status Reports

The Contractor shall prepare monthly status reports outlining significant work accomplished during the reporting month, including a percent-of completion summary for the TSAI geologic map. The report shall also discuss problems encountered during the reporting month, corrective action taken, and impact, if any, on delivery schedules.

6.10 Task G—Final Report

The Contractor shall prepare a final report detailing the equipment used and the procedures and processes followed in the generation of the TSAI data specified in this contract. The report shall include, but not be limited to, a description of the resources required (personnel and equipment hours) for the completion of Tasks A–E. Developmental problems associated with computer hardware and software shall be addressed. All deviations from the formats outlined in these specifications as allowed by these specifications shall be clearly reported.

6.10.1 The Contractor shall assess the potential for improvement of the TSAI production process and recommend changes to Government specifications that would improve the efficiency of the digital cartographic data production.

6.10.2 Summary of specialized comments in the Final Report as referenced in other parts of these specification.

6.10.2.1 New words added to the word list of attributes.

6.10.2.2 Changes in attribute tables lengths.

6.10.2.3 Convention for digitizing decorated lines.

6.10.2.4 Map projection used and all associated parameters.

## 7 INSPECTION AND ACCEPTANCE PROCEDURES

Prior to acceptance by the Government, all products will be validated using one or more of the following types of inspection to determine the level of quality for each TSAI characteristics prior to acceptance. Failure of the delivered TSAI data file to pass all test and acceptance procedures described will result in a rejection of the entire product and the procedures detailed in Section 8.0 will apply.

7.1 Inspection Procedures for TSAI Characteristics The inspection procedures for the following TSAI characteristics will be performed by the Government for the verification of the TSAI data. In addition to the verification plots supplied by the Contractor, the Government will generate selected paper and scale-stable film plots from each delivered TSAI data file. ARC/INFO software (version 5.0.–1) will be used as part of the validation process. Inspections are intended to ensure compliance with stated standards for the following: 1) file format, 2) content completeness, 3) positional accuracy, 4) attribution accuracy and 5) topological fidelity. Specified objectives are indicated below:

7.1.1 Format—The ARC/INFO taperead and import commands will be used to import the data. Errors contained in the data that prevent the proper loading of the file into the ARC/INFO environment will cause the TSAI to be rejected.

7.1.2 Topology—Topology relationships contained in delivered TSAI data will be tested for logical consistency using ARC/INFO routines. Checks will be made for intersections such as extensions of lines through nodes, lines crossing other lines except nodes, and lines crossing themselves. Polygon (area) adjacency will be checked to ensure that area left and are right definitions of lines are consistent. Topological violations will cause the TSAI to be rejected.

7.1.3 Feature Content—Feature content will be performed by comparing both Contractor and Government generated verification plots against scale-stable and published GFM. All geologic map specified features appearing on the color proof must be represented on the plots. Extraneous, duplicate, or missing data will cause the TSAI to be rejected.

7.1.4 Positional Accuracy—A visual comparison will be made between Contractor supplied stable-base line-verification plot and GFM stable-base materials. A software comparison will be made between Government digitized test nodes and arcs and Contractor digitized features. Errors in position which exceed the accuracy standards detailed in Section 5.0 will cause the TSAI to be rejected.

7.1.5 Attributing—The attributing of elements contained in delivered TSAI data will be checked for conformance to specifications detailed in Attachment B. ARC/INFO software will be used to check the encoded data against a table of valid attribute codes to ensure that each code or combination of codes is valid for the category and element type. Further verification of the encoded data will be made by manual correlation of file listings, verification plots, and the color composites produced by the Government from GFM. Errors in attributing which exceed the standards in Section 5.0 will cause the TSAI to be rejected.

7.1.6 Corrections—The Government may choose to make minor edits, such as deleting extraneous and duplicate data, adding small amounts of missing data, or making minor positional corrections. This provision does not require the Government to make such correction, nor does it relieve the Contractor of responsibility for meeting all specifications of this contract. Edits may be made at the Government discretion when the number of elements to be edited does not exceed five percent (5%) of the total number of lines and nodes contained in the delivered file.

7.2 Acceptance Procedure

Products passing the inspections and test detailed in Section 7.0 will be accepted by the Government. The Contractor will be notified of acceptance, in writing, within thirty (30) calendar days from receipt by the COR of the deliverables.

## 8 REJECTION PROCEDURES

Upon receipt of any deliverable product by the COR, the following procedures will apply:

8.1 The Contractor will be notified in writing that the deliverable was rejected and the cause for rejection.

8.2 Written notice will be forwarded to the Contractor within thirty (30) calendar days from receipt of the deliverable. All Contract supplied materials will be returned to the Contractor with the rejection notice.

8.3 The Contractor agrees to correct and ship at no additional cost to the Government, the rejected deliverable within twenty (20) calendar days from the receipt of the rejection notice. Corrected deliverables must meet stated TSAI standards.

8.4 New verification plots shall be produced upon completion of all corrections to rejected deliverables.

8.5 The corrected deliverables and new verification plots shall be delivered to the Government for testing as described in Section 7.0

# ATTACHMENT B

## ARC/INFO GEOLOGIC-MAP DATA STRUCTURE

The terminology used here is that of ARC/INFO (version 6)

### 1 POLYGON ATTRIBUTES

1.1 Add to the polygon attribute table (PAT) as the last item, formation. The field length is 10, field width is 11, and the field type is character.

1.2 The information in this item will be formation symbol as shown on the GFM published map by a symbol or color. All of these names must appear in the legend associated with GFM published map. The symbol convention should reproduce the symbols as used on the map, e.g. Tv for Tertiary volcanics.

1.2.1 Certain characters used on the map will not have standard keyboard characters; so the following conventions should be used for these special symbols.

1.2.1.1 OL - Oligocene, EP - Paleocene, PL - Pliocene, CZ - Cenozoic, MZ - Mesozoic, PZ - Paleozoic, K - Cretaceous, TR - Triassic, PN - Pennsylvanian, PM - Carboniferous or Pennsylvanian-Mississippian, C - Cambrian, PC - Precambrian.

1.2.1.2 All superscripts or subscripts should be typed as normal characters, i.e. no superscripts or subscripts can be used. These should be lower case letters. The conventions used here should be noted in the final report.

1.2.1.3 Where the allowed work list does not include the appropriate word the Contractor should make an appropriate selection and document this in the final report on the project. If there seems to be confusion resulting from the selection of words, the selection should be discussed with the COB.

### 2 ARC ATTRIBUTES

2.1 Add to the arc attribute table (AAT) as the last four items, [type, modifier, accuracy, and name].

2.1.1 Field lengths can be increased if required and this change should be documented in the final report.

2.2 The item <u>ltype</u> is for the type of line. The item length is 30, the item width is 31, and the item type is character.

2.2.1 ltype can have the following values: contact, fault, fold, other.

2.3 The item <u>modifier</u> denotes the type of contact, fault, fold or other. The item length is 20, the item width is 21 and the item type is character.

2.3.1 The following words can be used with faults: normal, thrust, reverse, strike-slip, strike dextral, strike-sinistral, none.

2.3.2 The following words can be used with folds: anticline, syncline, overturned anticline.

2.3.3 The following words can be used with other: map boundary, water boundary, or glacier boundary.

2.4 The item <u>accuracy</u> is a modifier denoting the positional accuracy on the location of the geologic feature. This does not refer to any aspect of the digitizing accuracy. This is normally shown on the map by the type of line, such as solid, dashed, or dotted lines. The item length is 15, the item width is 16, and the item type is character.

2.4.1 The following words can be used: certain, approx. located, inferred, inferred ?, concealed, concealed ?, gradational.

2.4.1.1 The query (?) after the word denotes that the line had ? along the line.

2.4.1.2 Solid lines are normally certain. Dashed lines are generally approximately located. Dotted lines are generally concealed. However this should be verified with the explanation that accompanies the GFM published map.

2.5 The item <u>name</u> is used only for those faults or folds that have identified names shown on the map. This item should include both upper and lower case characters as in normal writing with proper names.

2.5.1 The field length is 20, the field width is 21, and the field type is character.

2.6 Where the allowed word list does not include the appropriate word, the Contractor should make an appropriate selection and document this in the final report on the project. Additions to the allowed word list must be documented in the final report. If there seems to be confusion resulting from the selection of words, the selection should be discussed with the COR.

2.7 Decorated lines, that is those lines with some sort of symbol on one side of the line such as thrust faults, require that the lines be digitized in a fixed direction relative to the decorations so the decoration will plot on the side shown on the GFM published map. The convention to use is that these lines will be digitized in the direction that puts the decoration on the right side, e.g. if the decoration is on the east side of the line, then digitize from south to north.

2.7.1 The important thing is that all decorated lines are digitized in a standardized manner relative to the side the decoration is drawn. The convention used should be documented in the final report.

## 3 MAP PROJECTION AND UNITS

3.1 All coordinates of the TSAI data set will be x-y digitizer coordinates.