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Digital Mapping Techniques '98 — Workshop Proceedings

Edited by David R. Soller

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Illinois State Geological Survey

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FOREWORD

The Geologic Mapping Act was reauthorized by the Congress and was signed by the President in 1997 (Public Law 105-36). This was a clear signal that our national leadership continues to recognize the urgent need for up-to-date, accurate, and detailed geologic mapping in the United States of America. The Association of American State Geologists (AASG) strongly supports and advocates accelerated geologic mapping throughout the nation. Both the U.S. Geological Survey (USGS) and AASG recognize that modern geologic maps are essential for dealing with critical public concerns including ground-water supplies, energy and mineral resources, geologic hazards, waste management, and environmental protection.

In addition, the USGS and AASG recognize that today's electronic world requires delivery of geologic-map information in digital form so that it can be used in geographic information systems (GIS). In response to that need and to the requirements of the Geologic Mapping Act, the USGS established the National Geologic Map Database (NGMDB) Project to deliver geologic spatial data in digital form. This requires the development of a whole suite of standards so that, "...archival information can be accessed, exchanged, and compared efficiently and accurately..." (PL 105-36). The AASG also responded by forming the Digital Geologic Mapping Committee to help establish and construct the NGMDB in cooperation with the USGS. Six cooperative NGMDB working groups were formed in 1996 and the progress of those groups is elaborated in *Progress Toward Development of the National Geologic Map Database* by Soller and Berg in this collection of papers.

In 1997, the Data-Capture Working Group convened a Digital Mapping Techniques '97 (DMT'97) workshop at Lawrence, Kansas (hosted by the Kansas Geological Survey). The workshop, which was documented in USGS Open-File Report 97-269, was so successful that a second USGS-AASG Digital Mapping Techniques '98 (DMT'98) workshop was held in Champaign, Illinois, hosted by the Illinois State Geological Survey. The results of the DMT'98 workshop are documented in this collection of papers. As the Digital Mapping Techniques workshops are evolving, one aspect seems to be very important in their success—informality. Lots of time is available for one-on-one discussions, and personal experience in the digital-mapping world is freely shared. We look forward to DMT'99.

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Chair, AASG Digital Geologic Mapping Committee

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The *Digital Mapping Techniques '98* workshop was held from May 27 to 30, 1998, with eighty-eight attendees mostly from twenty-five State geological surveys and the USGS participating (see attendees list in Appendix A). This workshop was similar in nature to the first such workshop, held in June, 1997, in Lawrence, Kansas (Soller, 1997), and allowed further collaboration among all participants. This year's meeting was hosted by the Illinois State Geological Survey, on the University of Illinois campus in Champaign, Illinois. Both the Kansas and Illinois workshops focused on methods for data capture and digital map production; their 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.

The public exchange of ideas and techniques is the workshop's primary objective. When, based on discussions at the workshop, an attendee adopts or modifies a newly learned technique, the workshop clearly has met that objective. According to this particular criterion, evidence for the success of last year's workshop is presented in this volume; referring to the paper in this volume by McCraw and others (New Mexico Bureau of Mines and Mineral Resources),

> "After attending the Digital Mapping Techniques '97 (DMT '97) conference in Lawrence, KS, we decided to model our digital cartographic production program after that of the Nevada Bureau of Mines and Geology ...[which] expedited our overall cartographic production. Months of trial-and-error digitizing and interaction between geologists and technicians were replaced by a single scanned image that could be quickly drafted. In about two weeks, the 1:24,000 Alameda geologic quadrangle went from an inked mylar to a multicolor plotted map sheet, complete with cross sections."

Such observations are quite gratifying and reflect the productive, collegial atmosphere of these two workshops. It has been a pleasure to participate in them.

These two workshops were coordinated by the AASG/USGS Data Capture Working Group, which was formed in August, 1996, to support the Association of American State Geologists and the USGS in their effort to build a National Geologic Map Database (Soller and Berg, this volume). The Working Group was formed because increased production efficiencies, standardization, and quality of digital map products were needed to help the Database, and the State and Federal geological surveys, provide more high-quality digital maps to the public.

ACKNOWLEDGMENTS

I thank the Illinois State Geological Survey, and their Chief and State Geologist, Bill Shilts, for hosting a productive and enjoyable meeting. I especially thank Jennifer Hines and Rob Krumm, who coordinated the meeting for the ISGS and provided excellent support for the attendees. Their enthusiasm and expertise are greatly appreciated. Thanks also to Sheena Beaverson, who built and maintained the Web site (Appendix B) that provided registration services and workshop information to the attendees. Other ISGS personnel who helped with the workshop are Chris Goldsmith, Kari Lynn Kirkham, Allison Lecouris, Joe Schoen, and Barbara Stiff. 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 National Geologic Map Database; 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 McColloch, 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; and Patricia Packard (USGS) for help with Appendix C.

PRESENTATIONS

The workshop included 19 oral presentations. Each was supported by a short paper contained in these Proceedings. Some presentations were coordinated with Discussion Sessions, described below. The papers represent approaches that currently meet some or all needs for digital mapping at the respective agency. There is not, of course, 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 we must deliver our information to the public require that each agency design their 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."

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 lead or 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. Nick Tew (Alabama Geological Survey)—converting to digital format the 1988 state geologic map, a process that involved some cooperation with a sister agency, the USGS.
2. Warren Anderson (Kentucky Geological Survey)—overview of digital mapping program, from data capture to production of derivative maps, with discussion of the need to generate funding.
3. Gail Davidson (Alaska Division of Geological & Geophysical Surveys)—in times of shrinking budgets, how can we justify and develop a digital mapping program?
4. Jim Giglierano (Iowa Geological Survey Bureau)—an update on the Linn County, Iowa project discussed at last year's workshop, focusing on control of map versions, development of a map data model, and interaction with map users.
5. Don Luman (Illinois State Geological Survey)—integration of remote sensing into the state geologic mapping program.
6. Carl Harris (Washington Division of Geology and Earth Resources)—designing a data model for a statewide digital mapping project.
7. David Soller (U.S. Geological Survey)—description of, and report of progress for, the National Geologic Map Database.
8. Ralph Haugerud (U.S. Geological Survey)—the philosophy of geologic mapping, the need for standards, and some suggestions.
9. Gary Raines (U.S. Geological Survey)—an introduction to the AASG/USGS Data Model Working Group, a report of progress, and discussion of the need to reach consensus on a standard data model.
10. Kimberly Sowder (Indiana Geological Survey)—method for creating high-quality map plates from digital files.
11. Barbara Stiff (Illinois State Geological Survey)—overview of ISGS data capture techniques, data structure, and output for on-demand publication.
12. Ron Wahl (U.S. Geological Survey)—proposed standard specifications for 1:100,000-scale quadrangle boundary files.
13. David Collins (Kansas Geological Survey)—development of software to support 3-D visualization of buried units mapped from well-log data.
14. Walter Hasenmueller (Indiana Geological Survey)—a county-level pilot study to build a stratigraphic database and generate contour maps from that database, with discussion of the data model.
15. Jonathan Arthur (Florida Geological Survey)—discussion of various methods for generating contour maps from well-log data.
16. David Soller (U.S. Geological Survey)—a method for developing an internally consistent set of structure contour and thickness maps for thin, discontinuous glacial deposits.
17. Jorgina Ross (Kansas Geological Survey)—providing an interactive Web interface, for spatial query of maps and data (an "Internet Map Server").
18. Dan Nelson (Illinois State Geological Survey)—building an NSDI Clearinghouse node and serving data, images, and metadata to the public.
19. Peter Schweitzer (U.S. Geological Survey)—metadata in the National Geologic Map Database; an overview of the AASG/USGS Metadata Working Group's report.

POSTERS

Twenty agencies exhibited posters throughout the workshop. These posters provided an excellent focus for technical discussions and support for oral presentations. They are documented in these Proceedings by information ranging from brief descriptions to more formal papers similar in length to those for the oral presentations. In an introductory section following the oral papers, the brief poster descriptions are given; they are followed by the more lengthy contributions.

DISCUSSION SESSIONS

The formal presentations were interspersed with general discussion sessions on selected topics. These sessions mostly were led by Rob Krumm (ISGS), Tom Berg (Ohio Geological Survey), and Dave Soller (USGS). The topics were:

- The National Geologic Map Database
- Development of a standard geologic map data model
- Data capture parameters
- Writing and managing metadata
- Techniques for data capture
- Publication costs and distribution

CONCLUSIONS

The workshop concluded with a general discussion of the meeting's agenda and content. Attendees expressed a strong desire for a similar workshop next year, because this venue provides a rare opportunity for specialists in digital mapping to interact with a large group of their peers and to be exposed to new techniques and philosophies. A variety of issues were raised, many of which are related to increasing societal demands on the geological surveys concurrent with declines in funding: 1) the difficulties in balancing the reduction in budgets at the geological surveys with the expanded demand for digital mapping expertise and services; 2) strategies for cost-effective data capture, including GIS services available, for example, through private firms, the prison system, other government agencies; and 3) the continuing need to demonstrate the relevance of geoscience information to society. Some map products that demonstrate such relevance were cited.

The quality and availability of both paper and digital topographic maps were other topics of significant concern. It was resolved that we would: 1) ask the USGS National Mapping Division to clarify for us their policies on availability and revision of topographic maps and related digital products and 2) work to ensure their participation at next year's workshop.

The topic of most concern was one raised at last year's meeting -- the costs of map publication and distribution, and the relative merits of conventional map printing and the emerging print-on-demand technologies. Because there is no single publication strategy that will best apply to all categories of maps or geological surveys, detailed and well-focused discussions are needed. The various issues, technologies, personal experiences, and costs and benefits must be explored and debated to help each agency determine their most appropriate strategy. Attendees suggested that this topic should be a primary focus for next year's workshop. We will design the 1999 workshop with this suggestion clearly in mind.

REFERENCE

Soller, D.R., editor, 1997, Proceedings of a workshop on digital mapping techniques: Methods for geologic map data capture, management, and publication: U.S. Geological Survey Open-File Report 97-269, 120 p.

ORAL PRESENTATIONS

Production of the 1:250,000-Scale Digital Geologic Map of Alabama

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INTRODUCTION

In 1988, the Geological Survey of Alabama (GSA) published the first statewide geologic map of Alabama based on new mapping and compilation since 1926, when the now classic and collectable lithograph, *Geologic Map of Alabama*, was prepared in cooperation with the United States Geological Survey (USGS) and released as part of GSA Special Report 14, *Geology of Alabama* (Adams et al., 1926). The publication of GSA Special Map (SM) 220, *Geologic Map of Alabama* (Szabo et al., 1988) was the culmination of decades of work by numerous geologists, including not only those affiliated with GSA, but a number of others involved in mapping the geology of Alabama for various purposes. SM 220 was published as four map sheets, representing the four quadrants of Alabama, at the scale of 1:250,000, plus a fifth sheet of explanatory information, and comprises the largest scale and most accurate border-to-border depiction of Alabama's geology as presently understood. The map is now in wide distribution and has been generally acknowledged as a significant contribution to the science.

The decade that has passed since the publication of SM 220 has seen an explosive expansion in the routine use of Geographic Information Systems (GIS) and digital geospatial data for various applications, including: geologic, hydrologic, and environmental research; mineral exploration; land use planning; industrial development; and others. Soon after publication of the map, GSA began to receive inquiries about plans for release of a digital version of SM 220. We realized that demand for digital products would continue to increase as more and more agencies and organizations incorporated digital geospatial data into their routine operations. Further, GSA recognized an obligation to produce a digital version of SM 220 that carried the agency's imprimatur as the "official" digital rendition of Alabama's geology.

Owing to circumstances, production of the digital version of SM 220 languished until 1996, when GSA developed a project with USGS-Eastern Mineral Resources Survey Team (USGS-EMRST) to evaluate the quality of data contained in the Mineral Resource Data System (MRDS) for Alabama, to correct obvious errors, and to classify major groups of deposits and mineral occurrences by deposit type. To assist in this assessment program, it was determined that a digital lithofacies map of Alabama was a necessary component and that this map would be developed on the basis of the geologic units shown on SM 220. Thus, the MRDS project provided a vehicle for production of the Digital Geologic Map of Alabama as a cooperative effort between GSA and USGS.

PRODUCTION OF THE DIGITAL GEOLOGIC MAP

The production of the digital geologic map of Alabama is being undertaken as a joint project of the GIS Group (GSA-GIS) and the Economic Geology Division (GSA-EGD) of GSA, with support from USGS-EMRST.

GSA-GIS has assumed responsibility for data capture and GIS development, whereas GSA-EGD is providing final review and quality control. The primary goal of the project has been to produce an accurate, fully georeferenced and attributed rendition of SM 220. Initial data capture, georeferencing, and attribution have been completed and the digital data is now being reviewed for completeness and accuracy.

Much discussion went into deciding the most accurate and efficient method for capturing vector data from SM 220. The final published version of the map consists only of offset-printed, full-color, paper copies and, thus, was deemed less than desirable for data acquisition due primarily to the inherent problem of scale-instability. In Alabama's subtropical climate, which is characterized by relatively rapid fluctuations in humidity and temperature, paper is subject to dramatic and significant variations due to swelling and shrinking over the course of hours and days due to changing environmental conditions. Changes of 0.125" to 0.25" in the dimensions of a standard USGS 7.5-minute quadrangle sheet over the course of a day are not uncommon and, for this reason, we try to avoid using paper maps for data capture whenever possible. Therefore, we decided against using "off-the-shelf" copies of SM 220 for data capture.

Fortunately, after production of SM 220, GSA had archived the original scale-stable film scribe coats onto which the geologic contacts had been hand drawn and scribed, thus providing negative images of the geologic line work for the four map sheets. It was decided to: (1) use these scribe coats to produce scale-stable, contact-print film positives of the geologic line work; (2) add tic marks from the original map base to the film positives for subsequent georeferencing purposes; (3) have the film positives scanned; (4) convert the resulting raster images to vector format; and (5) process the vectorized data into useable, georeferenced, topologically structured GIS data sets. USGS-EMRST agreed to the scan the map quadrants, make a automated, unsupervised "first-pass" vectorization of the raster images, and provide GSA with the resulting data sets in Arc/Info (ESRI, Inc., Redlands, CA) format.

Upon receiving the vectorized data sets from USGS, GSA-GIS staff set about the task of georeferencing the four map quadrants and correcting the errors (undershoots, overshoots, missing lines, misconnected lines, unclosed polygons, etc.) contained in the data. Georeferencing was accomplished by the addition of real world coordinate tics at the intersection of the lines representing the original base map tics and transforming the data to the real world coordinate system. Error correction was a somewhat more significant chore, but proceeded in a relatively timely fashion using a combination of on-screen and manual digitization techniques to edit the line errors in each map quadrant.

After several iterations of editing and check plotting to assure accuracy, polygon topology was established for the corrected geologic contact data sets, feature label points were generated, and feature attribute tables were created. SM 220 depicts 163 unique geologic units in Alabama. Each of these units was assigned a numerical code (1-163), a field for the unit codes was added to the polygon attribute tables, and each polygon was attributed with the code corresponding to the unit that it represents. Again, an iterative process of check plots and edits was employed to find and correct any erroneous unit code assignments. All subsequent attribution was handled automatically on the basis of the unit codes, as described below.

At this point, the four quadrants were joined into a seamless layer for the entire state, polygon topology was re-established for the joined data set, and errors introduced in the joining process were identified and corrected. To facilitate detailed review of geologic unit codes for polygons prior to final attribution, a look-up table was constructed to assign colors to polygons on the basis of the unit codes. A standard Arc/Info color palette (shadeset) was used and colors were chosen from this palette to match as closely as possible those depicted for units on SM 220. Color plots at the 1:250,000 scale were then generated and used to check for incorrectly coded polygons.

The completed draft statewide geologic unit polygon data set contained over 6000 polygons that needed to be attributed with data regarding the geologic province in which they occur, a hierarchical arrangement of geologic nomenclature (system, series, group, formation, member, etc.), an alphabetic map symbol, and predominant rock types. For example, the Cusseta Sand Member of the Ripley Formation of the Selma Group of the Upper Series of the Cretaceous System occurs in the Coastal Plain province, is designated by the alphabetic symbol Krc, and consists primarily of sand and clay. Further, as stated above, there are 163 unique possibilities for these descriptive values. To accommodate these data, eight fields were added to the polygon attribute table for the geologic unit coverage and an Arc Macro Language (AML) script was written to automatically populate these fields on the basis of the geologic unit code entered earlier. The AML, written by the second author of this paper, was designed to take advantage of the cursor processing functionality of Arc/Info and essentially "steps through" the attribute record for each polygon, evaluates the geologic code in the record, and searches through a loop directive in the script until a match for the code is found. The AML then populates the fields in the attribute table with the appropriate data and proceeds to the next polygon until all polygons are attributed. In addition to the obvious savings in time spent on data entry, use of the AML also substantially reduced the possibility of inaccuracies being introduced into the data set due to inconsistencies (e.g., Pottsville Formation vs. Pottsville Fm.), misspellings, omissions, and other common data entry errors.

After completion of the attribution process, GSA-GIS plotted the digital map data in color on a county by county basis at the scale of 1:100,000 and closely checked these plots against SM 220. Identified errors and discrepancies were corrected. This process was then repeated at the 1:250,000 scale. At this point, GSA-GIS deemed the Digital Geologic Map of Alabama ready for final review by GSA-EGD.

GSA-EGD is the coordinating and principal reviewing entity for geologic mapping in Alabama and also oversees the State's stratigraphic nomenclature and, therefore, has the responsibility to approve the Digital Geologic Map of Alabama before its release to the public. Final review of the data is now underway and is being facilitated with a combination of color plots on paper and black and white geologic contact plots on film for comparison and overlay with SM 220. As with all steps above, errors identified with each check will be corrected and the process will be repeated until all reviewers are satisfied that the data set is ready for release.

PLANS FOR THE DIGITAL GEOLOGIC MAP OF ALABAMA

GSA plans to release the Digital Geologic Map of Alabama as the initial offering in our CD-ROM series before the end of 1998. Publication this year of the first large-scale digital geologic map of Alabama as the first CD-ROM product of the agency is very appropriate in that GSA is celebrating its sesquicentennial in 1998. Since its inception in 1848, it has been the agency's mission to provide quality, accurate, timely, useful information regarding the mineral, energy, water, and biologic resources of Alabama to aid in economic and social development. The production of the Digital Geologic Map of Alabama is a continuation of this proud tradition and the harbinger of the direction that GSA will follow as we move into the 21st century. Digital data formats for both geospatial and tabular data, as well as text-based reports, will become the norm and electronic delivery of information via various media, including the World Wide Web, will evolve into our primary mode of data distribution. By utilizing these rapidly expanding technologies, GSA hopes to better serve the needs of the State of Alabama and its citizens.

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History of Geologic Mapping at the Kentucky Geological Survey

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ABSTRACT

The Kentucky Geological Survey (KGS) has a long history of and strong commitment to geologic mapping. A cooperative program with the U.S. Geological Survey from 1960 to 1978 resulted in the entire state of Kentucky being completely mapped geologically at a scale of 1:24,000. Currently, KGS is participating in the USGS National Cooperative Geologic Mapping Program's STATEMAP component, which will help us convert all published maps into digital format; and will provide Kentucky with complete digital geologic quadrangle map coverage by the year 2005.

For a mapping program to succeed, state government officials must be persuaded to provide sustained funding and the state geological survey must commit personnel and resources to complete such a large task. One of the most important issues is to educate the legislature and politicians about the importance of geologic mapping to society. Also important is the support of leaders in the mining, mineral, petroleum, industrial, environmental, and academic communities, who understand the need for geologic mapping and can convince their legislators. The industry and academic-community involvement creates a broad base of support for legislative funding. Earth scientists must continue to be more proactive, educating the public and politicians about the value of geologic mapping.

INTRODUCTION AND HISTORY

Kentucky was completely mapped by the Kentucky Geological Survey–U.S. Geological Survey cooperative mapping program from 1960–1978. That geologic quadrangle mapping program can trace its roots to the 1940's, when the topographic mapping program began and the Cub Run quadrangle in western Kentucky was mapped geologically. Wallace Hagan mapped the Cub Run quadrangle in 1942 as part of his Ph.D. dissertation. In 1960 Dr. Hagan became the tenth director of the Kentucky Geological Survey and began the program to geologically map the entire state of Kentucky. Donald Haney, who became the eleventh director of the Kentucky Geological Survey in 1978, began a project in conjunction with the USGS National Cooperative Geologic Mapping Program's STATEMAP component to convert all published geologic quadrangle maps into digital format.

In 1960, Dr. Hagan was able to demonstrate the benefits of geologic mapping and to educate the leaders, government officials, and politicians about the significance of these maps. The State legislature agreed to match federal funding, and as a result 707 quadrangles were mapped during this program at a total cost of $20 million. Since the last geologic map was published in 1978, the demand for them has remained great, and more than 150,000 of the maps have been sold. Some of the maps are now out of print. The benefit for the State has been tremendous, and a benefit-cost ratio has been conservatively estimated at 100:1, based on the discovery of new oil and gas deposits, coal beds, mineral deposits, and cost savings for strategic planning in highway and engineering construction. This does not even include the secondary benefits derived from a growing economy spawned by new discoveries and associated development.

Dr. Haney continued the commitment to geologic mapping and its digital component by participating on state and federal government committees, councils and boards to promote geologic mapping. This proactive approach assisted in negotiating with various segments of government. For example, Dr. Haney was active on the Governor's Geographic Information Advisory Council to lobby for the establishment of an Office of Geographic

Information Systems for the state. This high level office is responsible for coordinating statewide GIS activities, creating statewide maps and dispensing digital mapping information. This office is critical for unifying diverse GIS products throughout the state. Dr. Haney was also working with various agencies such as the Kentucky River Authority, Illinois Basin Consortium, seismic networks and other geologic or environmental programs to create cooperative programs that benefit from geologic mapping.

Dr. Haney also began aligning KGS research priorities to meet the need for digital information by initiating well record data scanning programs, other map scanning programs, establishing a relational data base of geologic information and participation in the Statemap component of the National Cooperative Geologic Mapping Program.

In March, 1998, in conjunction with the Association of American State Geologists (AASG), Kentucky participated in a Congressional reception in Washington, D.C., whose purpose was to educate Congress and staff members about geologic mapping, as well as to emphasize the importance of geologic mapping for the nation, so that full funding for the National Geologic Mapping Act of 1992 would be appropriated. This type of exposure is essential to maintain a high profile for mapping programs such as STATEMAP.

The success of a geologic mapping program requires the commitment of the state geological survey, politicians, educational institutions, mining, mineral, petroleum, and environmental communities. It is the responsibility of all earth science professionals to be more proactive in governmental affairs and to be more politically involved with their legislatures. The state surveys, particularly their directors and assistant directors, must have a priority and plan of action for mapping the state, must be able to explain the benefits and costs of geologic mapping, and must lobby their legislatures for funding. In Kentucky, both Dr. Hagan and Dr. Haney worked with and educated upper-level administration officials at the University of Kentucky, political leaders, and the State legislature about the importance of geologic mapping. These efforts have led Kentucky to be the best geologically mapped area in the world, and provided an economic stimulus for future development.

CURRENT ACTIVITIES AT THE KENTUCKY GEOLOGICAL SURVEY

Digital Geologic Mapping

Digital geologic mapping continues to be a high priority for the KGS. Many of the Survey's fiscal, equipment, and personnel resources are committed to completing this project by the year 2005.

The Kentucky Geological Survey has established a successful method of converting published maps into digital format and currently has completed 60 digital 7.5-minute geologic quadrangle maps. This conversion procedure collects accurate vector data, which is linked to the KGS's main database. KGS currently uses a semi-automated vectorizing system to convert published geologic maps into digital format. This process is a multi-step procedure, and completing a map usually takes 3 to 6 weeks, depending on how complex the quadrangle is and the operator's speed. Details of this procedure were presented at the Digital Mapping Techniques Conference in Lawrence, Kans., in June 1997 (Anderson and others, 1997).

Mapping and Analysis

A new geologic mapping database is being created to allow for search and retrieval of information about the geologic maps. An important part of the database is the attribute data associated with the digital information. These attributes are geologic contacts, faults, structure contours, and fossil locations. These attributes give definition, values, and descriptions of the digital data as well as location and direction information. In addition, quantitative attributes about these features can be easily determined, such as volumetrics, resource, and reserve estimates. Such analyses are of significant value for site-specific assessments for coal, mineral, and petroleum resources. Tonnage and cost estimates for transportation highway engineering projects and construction planning and development can also be easily calculated in a geographic information system (GIS).

Additional information from KGS main databases such as locations of oil, gas, or water wells, coal mines, or other mineral resources can be added to the mapping database to create custom geologic maps. Some of the main databases files contain previously scanned images, records, documents, tables, and figures, which can be attached to the digital map files to create a powerful GIS for analysis and manipulation of geologic data for a particular quadrangle.

Data Capture Techniques

From 1995 to 1998, KGS examined several different types of software that will make possible full automation of its digital mapping program. Full automatic vectorization takes only seconds or minutes to complete, but extensive postprocessing time, clean up, and attribution may take as much as 8 weeks. Geologic maps are usually very complex and highly detailed, with text, symbols, branching or coalescing lines that may be dashed, and fault lines that may be depicted with a different line weight. These features create the most problems for any automatic vectorization package.

Most of these software packages require custom routines or other methods of postprocessing data which requires more time for completion than for the traditional semi-automated method of digitizing. Most of these packages will vectorize everything including text or symbols, which results in the text being jagged or angular and not of publication quality. Some conversion packages have an optical character recognition (OCR) function, which recognizes text and numerical values. This requires adjusting parameter settings and experimenting to achieve the desired results. Some packages also have a pattern or symbol recognition function, which only partially worked; some symbols were not vectorized. Some packages have an attribution function that recognizes line weight or thickness. They can color code certain attributes to distinguish each layer. This software was unable to resolve fine differences between line weights, which became apparent when some of the same contour lines were interpreted as two distinct vector layers.

Some of these packages would work well with simple geologic maps or cross sections, but would not be appropriate with complex maps, which would require extensive postprocessing and clean up to produce a publication-quality map. Currently, our semiautomatic vectorization procedure is still the most accurate and efficient.

Staffing

The KGS digital geologic mapping program is staffed by one full-time professional to manage the digital program, one GIS professional, one geologist professional, one stratigrapher, several professionals, technicians and students to vectorize quadrangles. KGS provides office space, computer facilities, and clerical support.

Recently, the 1998 Kentucky legislature approved a significant increase in temporary funding for digital geological mapping in its biennual budget. We are preparing to hire new geologists, including personnel with GIS and database experience, making the total professional personnel for the KGS digital mapping project about 15 to 20.

THE FUTURE

Digital information from the KGS consists of geologic map information in digital format and a database of geologic map information. This geologic map information database will be linked with the main KGS database containing information on coal, minerals, petroleum, and water. Secondary databases containing information on stratigraphy (stratigraphic tops), paleontology, structure, geophysics, geochemistry, and engineering will also be incorporated into a complex GIS, making them available for the user to manipulate and analyze these data sets. These information sets will be among the most comprehensive, detailed digital geologic data sets in the world, and will provide immense data for earth science computations. The database and digital products will provide three-dimensional or data-cube analysis and will be georeferenced to contain details of map-element attributes. This will allow other digital products, such as the secondary databases and digital ortho-quarter quadrangles (DOQQ), digital elevation models (DEM), digital raster graphic (DRG) images, and satellite imagery to be overlain, registered, and plotted with the digital geology.

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Can We Get There from Here? Experiences of the Alaska Division of Geological and Geophysical Surveys

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THE PAST

More than 15 years ago, the Alaska Division of Geological and Geophysical Surveys (DGGS) acquired a minicomputer to assist in geochemical modeling. Included with the modeling software was a GIS system. Over the next several years, use of the GIS system grew, while use of the modeling software stagnated. We first used the GIS to locate geochemical sample locations and attach analytical data to them, then ran various statistical programs outside the GIS and used the results to produce maps of geochemical anomalies. Concurrently we began to digitize geologic contacts and produce black and white maps that were as similar as possible to maps made by older cartographic methods. One staff member, supplemented by student interns, was involved in the GIS effort. The remainder of the DGGS staff, 150 strong at the time, showed little interest in the possibilities for the new method.

THE PRESENT

The present DGGS staff of 25 is illustrated in Figure 1. At this time, DGGS uses Arc/Info to produce all of its geologic maps. These maps are made to resemble as closely as possible the maps formerly made by hand. The GIS is being used as a cartographic output system with the added advantage of easier updates. In the past, project geologists have passed their completed geologic work to a Publications Section to put it into publishable form. With so few staff members in the Survey, we no longer have that luxury.

Under the present scheme, project teams include a cartographer, the editor, and the GIS manager as well as field mappers and student interns. Few of the geologists have used the'GIS system to date. Only one of the cartographers is GIS-literate. In theory, projects are responsible for their own GIS work from start to finish. The GIS manager and the cartographer are teaching student interns to digitize and edit maps, then to make final output copy. Unfortunately, students are transitive, and several months worth of training time is often used for only one project, then we start over with training a new student. Project geologists are complaining that the GIS is too hard to learn, that they don't have time to do this work on top of everything else, and that we need more cartographers to do this work for them. GIS work is seen as mundane digitizing only. There is little knowledge of what databases can do for data analysis, or of what projects can contribute to a growing spatial database. Although we are adding new types of data with each project, there is a very little geospatial analysis being done, barring a few derivative maps from surficial geology.

THE FUTURE

Our dream for the future includes having the entire GIS database available to all geologists on their desktops for them to use in data analysis. We dream of a user-friendly interface with which geologists can pull together all types of data gathered in the field and from the literature to construct and improve the database of geologic mapping. We envision a relational database that is driven by the needs of geologists for the geographic component of the data. All the geologists and support staff of the Survey will have access to the data and be adding to it. The database will be the basis for creating maps and reports as well as publishing them. All of the geologists will be intimately involved in data entry and analysis.

DEPARTMENT OF NATURAL RESOURCES
DIVISION OF GEOLOGICAL & GEOPHYSICAL SURVEYS
ORGANIZATIONAL CHART

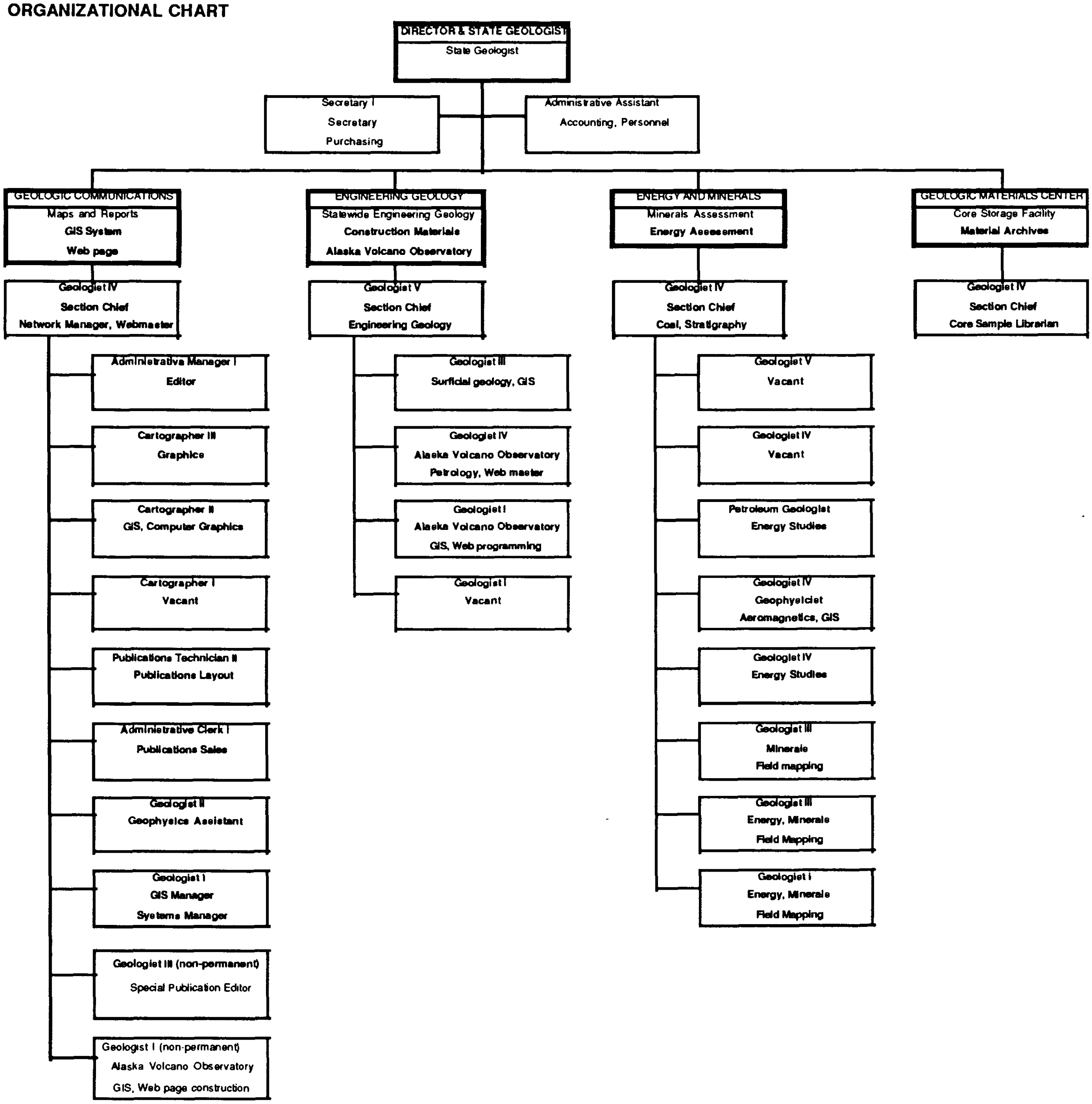

Figure 1. Organizational chart of the Alaska Division of Geological and Geophysical Surveys.

Most importantly, the growing database will be available to our customers, the public, over the World Wide Web.

How do we get there from here? How do we convince the geologic population that not only are databases important, but that their direct involvement with those databases is critical to the success of the agency?

So far we don't have answers for these questions. One obvious answer to the workload problem is to hire more staff to input data. This, however, is a funding problem in the present scenario of budget cuts, and it removes geologists from direct contact with the data. Partnering with other agencies is a popular concept, though in practice, geologists are reluctant to give up territory. As more talks at geological conferences emphasize a use of GIS databases to solve problems, the importance of the technology should grow.

Issues in the Application of Digital Geologic Data

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The Iowa Geological Survey Bureau (GSB) has recently completed a three year STATEMAP project which included mapping the surficial geology of five 1:24,000 quadrangles, and the bedrock and surficial geology of Linn County at 1:100,000 scale. STATEMAP is a component of the National Cooperative Geologic Mapping Program. The results of this project were many: the development of new computer-aided geologic mapping techniques; training of staff geologists in geologic mapping particularly of surficial materials; and the digital compilation and collection, storage, and analysis of new and existing subsurface data into GSB archival databases. We also focused on the development and use of geologic data and derivative products for local decision making and working closely with local government, training them to use and understand geologic data.

REVIEW OF MAPPING METHODOLOGY

The Linn County project was a great learning tool for GSB and allowed us to develop numerous techniques for producing and using digital geologic data. These included use of digital soils, terrain, orthophotos and digital raster graphics as background material for on-screen digitizing by mapping geologists to compile their original line work. On-screen compilation required more time by the mapping geologist, especially when learning to use the system. However, the mapping geologist created better interpretations through integration of many data sources while also mapping at a larger scale than the target scale. Over the course of the three year project, desktop tools developed significantly and allowed us to move away from using high-end Arc/Info products on UNIX workstations by GIS professional staff, and move to ArcView 2 and ArcView 3 products on desktop PCs with the mapping geologist doing the digitizing on-screen with little or no help from GIS staff. This last year, nearly all of the digital work was done using ArcView 3 with Avenue scripts for editing and merging line and polygon data. Some gridding of bedrock surface contours and structural surfaces was still done using the high-end Arc/Info Topogrid tool because the ArcView Spatial Analyst module was not fully developed enough to perform this task. Geologic mapping done on the geologist's desktop computer with relatively inexpensive and easy to use software is a viable alternative to traditional methods requiring field mappers to draw their maps on paper or mylar first and then having GIS staff digitize and edit the paper map.

Finished geologic maps were produced with ArcView 3 software by GIS staff. The ArcView map layout functions are less comprehensive than the high-end workstation Arc/Info product, but were successfully used in the production environment to make interim products for error checking and finished products for distribution. The ability to create a reasonable printed product with inexpensive desktop hardware and software was seen as an advance in the methodology and a viable alternative to traditional printing methods. The software for printing maps should greatly improve with time just as the on-screen digitizing features already have. STATEMAP products for Linn County were not formally published and printed in large quantities because it was anticipated that there would not be a large demand for paper products requiring the cost efficiency of mass printing. Instead, digital project maps are printed on-demand at the cost of reproduction, which were calculated at $2 per linear foot, or generally $5 to $10 per map sheet. Printer files are stored on the network and sent to the printer when needed. It is estimated that a dozen or so have been sold this way. It is anticipated that front office secretarial staff can take the necessary steps to send the stored printer files to the printer when needed by a customer, and this will eventually include standard 24k topo quads stored as DRGs as well as more specialized maps, thus saving shelf space, printing and restocking costs and staff time. This process will become more viable with the development of more durable printer paper and inks that are not sensitive to moisture.

The Linn County project also allowed us to work closely with local users of geologic data including the county departments of planning and zoning, health, engineer, and the solid waste authority, local National Resource and Conservation Service office, plus local quarry operators and citizens. Linn County has a good mixture of urban and rural natural resource issues, including development pressures in the county and urbanization around Cedar Rapids, water quality and quantity, protection of aggregate resources, and environmentally sensitive areas. After the Linn County project began, a local users group was formed which also provided some financial support for additional geologic well data entry, not covered by STATEMAP resources. Members of the local users group were provided interim products for comments and feedback, and finished products at the end of yearly mapping phases. Interim digital products were provided on CD-ROM to the county planning and zoning and health departments who were developing their own GIS capabilities concurrently with our project. The planning and zoning department particularly showed serious commitment to developing their own GIS, by hiring a new planner with GIS experience, purchasing ArcView 3 and ArcCad, and an E-size Hewlett-Packard inkjet plotter.

THE "VERSION" ISSUE

During the course of the Linn County project, several versions of the geologic GIS coverage and geologic map were produced for various purposes. This led to some confusion as to which version was current or which version was used to produce a map. During the actual mapping, editing and revisions were made on a working copy of the GIS coverage. From this working coverage, several test plots were printed to check for errors and omissions. At the time of the STATEMAP contract deadline, no further changes were made to the working coverage; documentation or metadata was written, a good quality map was composed and printed with all the necessary collar and ancillary information, and everything sent to USGS. To help local cooperators use the geologic data, several derivative products were tried, using combinations of bedrock and surficial geologic coverages and attributes to produce various scenarios for aggregate resources, groundwater aquifers, potential hazards, and groundwater vulnerability. Some of these derivative maps were sent to the local cooperators for comment and evaluation. When new quad maps were completed during the project, the derivatives had to be updated, thus creating more versions of the same GIS coverages and maps. Final versions of the GIS coverages and the maps made directly from them will be produced and distributed to the local cooperators and the public. Questions arise as to how to name and cite the initial versions to distinguish them from the final versions, and whether the earlier version should be archived. Obviously, the interim products could have been withheld until completed versions were available at the end of the project. Because events within the county were moving faster than the mapping, we felt obligated to distribute incomplete geologic and derivative maps and GIS coverages to local users, who knew that they were not using the final products. Many of these questions have not been satisfactorily resolved. Plans for the next large-scale STATEMAP project involve maintaining a creation or modification date attribute connected to individual features of geologic and derivative coverages, and displaying a coverage history on printed maps to indicate which version was used.

GEOLOGIC DATA MODELS

One topic that was not fully explored during this project was the development of a good geologic data model for the geology of Linn County. There is much current interest within the geologic mapping community in developing a geologic map data model and standards for digital geologic maps and data. It is this author's opinion that the emphasis should be on development of simple data models that allow the exchange and combination of geologic GIS coverages between projects, states and regions of the country, including standardization of attribution such as lithology, stratigraphy, age and other physical descriptions of geologic/hydrogeologic properties. Development of standards or models for geologic maps including symbols, legends, text and other ancillary information, while important in the long run, should not overwhelm efforts to develop geologic data models. The geologic data model should be the framework around which standardized procedures for data capture, metadata creation, database storage schemas, planned analysis activities and map display would be constructed. For example, GSB currently needs a digital Quaternary geology data model that can describe the extent and physical characteristics of surficial materials in three dimensions and will easily transfer into a groundwater model to determine source water recharge zones for 1800 public water supplies in Iowa. Here the planned analysis function is the major, driving force behind development of the geologic data. A standard set of map symbols won't help do that.

In Linn County, GSB created a rather simple geologic data model and used it to produce maps showing aggregate and groundwater resources, hazards, and ground vulnerability, which were all derived from three geologic data layers: surficial geology, bedrock geology and depth to bedrock. This geologic data model consisted of physically merging all three vector GIS coverages and using queries of the combined attributes to define zones for the desired derivative model (for example, sandy surface units overlying karst forming bedrock units within 50 feet of surface equals highly vulnerable groundwater area). Not very elegant, but a simple geologic data model that provided useful results. However, this model would not be very effective in describing the three dimensional distribution of the surficial materials, and basically would not allow for any variation within the surface units at depth. For example, a simple geologic data model based on a 2-d surficial geologic map can only tell what the geology is at point x, y on the earth's surface. A better data model would need to be able to answer a query that asked what geology exists at point x, y and z. Relatively simple, horizontal geology such as that found in Linn County can be described with layers of gridded surfaces or vector overlays, but probably would not work well for complex faulted and folded terrains. Undoubtedly there exists in the petroleum industry geologic data systems that can handle complexity for a price. What is needed for small agencies is something usable on the desktop that combines simplicity, ease of use, compatibility with existing data, and relative longevity within advancing computer technology. Hopefully somewhere within the framework of the National Cooperative Geologic Mapping Program some of this research can be undertaken, either at the federal, state or university level.

USER ISSUES

Justification for the National Cooperative Geologic Mapping Program (NCGMP) has largely been that the massive development of new geologic maps is critical to the nation for making important natural resource decisions. While STATEMAP has provided the impetus and means for GSB to renew its geologic mapping activities in Iowa, producing new geologic maps for the sake of having new or better maps was never viewed by GSB as a total justification for pursuing this activity. Experience in Linn County has shown us that geologic maps in the traditional form of printed paper maps are by themselves of relatively little value to local officials faced with natural resource decisions. Digital geologic data in the form of GIS coverages are of marginally limited use as well, unless the local users really know how to use them, which involves some geologic training, or the digital coverages are transformed into some derivative products that are understandable to non-geologists. The act of creating and making available a new geologic map of an area does not by itself insure that good resource or environmental decisions will eventually be made. It is true that there are some persons within a local area who can make direct use of geologic maps, such as quarry operators and consultants, but mostly the local officials we have encountered are a new market for geologic information. They generally haven't had access to pertinent geologic information for their jurisdiction and don't have the training or resources to hire consultants for every issue that requires understanding geology. The NCGMP and STATEMAP do provide much needed resources for the creation of new geologic maps, but allow no resources to be used to produce useful derivative products or the development of educational or instructional materials or training for local officials in how to use these new geologic information resources. This is by no means a criticism of NCGMP or STATEMAP, merely a recognition that additional resources must be found to make the circuit complete and assure that local officials are aware of this information and can make use of it. It is up to the state surveys to find additional resources to train local officials to be geologically literate in order for the goals of the NCGMP to be fulfilled.

During the Linn County project, the solid waste authority started a new landfill siting process, and while GSB data was not complete for the whole county, it did become a crucial component used by the engineering consultant to run preliminary siting criteria for selection of 13 sites. In connection with a strategic planning process for the GSB, working with local decision makers and providing them with quality geologic information was identified as a high priority item. The Linn County project and the landfill siting process became a crucial test of this strategy, and an object lesson in the process of decision making. The landfill siting process is currently finishing its second round. Originally, depth to bedrock was a major limiting factor in the selection of the 13 preliminary sites. Public pressure has led to the addition of corn suitability rating as an exclusionary criterion and removal of depth to bedrock. Despite our best efforts to provide the best available information for choosing an environmentally appropriate site for the new landfill, the decision making process was able to avoid geological issues. Again, producing new geologic maps intended for use in natural resource decision making does not in itself guarantee that it will be used for that purpose or used well.

CONCLUSIONS

It's a new world in several ways for those trying to provide good quality geologic information, both in terms of new technology, and how geologic information can and is applied to society's environmental problems. Inexpensive desktop hardware and software is making it possible for small agencies to create and print their own digital geologic maps. Local government agencies are attempting to create their own GIS capabilities and want to integrate digital geologic data with their databases. Research is needed to develop consistent, reasonable geologic data models that can be plugged into groundwater and other environmental modeling software. While the ability to create digital geologic databases is progressing, local users are a new market for this information and frequently require training and educational opportunities to effectively use it. Finally, geologists need to realize that despite their best efforts at providing good information to decision makers, local resource decisions are commonly made on the basis of many criteria besides geology.

Remote Sensing Inputs to a Geologic Mapping Program for Illinois

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INTRODUCTION

Geologists use a variety of map data sources to assist in interpreting surficial characteristics; and while maps expressly provide several types of information, they are, nevertheless, abstractions and represent the physical landscape in a generalized manner. In contrast, image-based data are a singularly unique information source that provide an ungeneralized portrayal of landscapes, and the usefulness of aerial image interpretation for mapping geologic features has been long recognized (Watson and Knepper, eds., 1994).

In Illinois, agricultural lands account for three-fourths of the surface area of the state (Illinois Department of Natural Resources, 1996) and surficial geologic features are obscured during much of the year. However, during the late winter and early spring period, and under optimum drainage conditions, remote sensing imagery can detect subtle changes in the uppermost few feet of geologic materials that are directly related to surficial processes.

SOURCES OF DIGITAL IMAGE-BASED INFORMATION

Earth resources-based remote sensing began over twenty-five years ago with the commissioning of the Landsat 1 satellite in June, 1972. Since then, there have been significant improvements in sensors, especially with regards to the spatial and spectral resolution available from an increasing number of satellite-based systems. For comparison, in 1972 Landsat 1 was capable of resolving a ground area of approximately 79 x 79 meters (0.58 hectare or 1.4 acres); in 1996, the Indian Remote Sensing (IRS-1C) satellite was successfully launched with a panchromatic sensor that resolves a ground area of 5.8 x 5.8 meters (0.003 hectare or 0.01 acre). This represents more than a 185x improvement in the discrimination of areal features. During the same period, the spectral resolution of sensors has improved from a restriction to the optical wavelengths (0.38-1.3 micrometers; e.g., visible and near infrared) to including the middle infrared and microwave regions of the electromagnetic spectrum.

In terms of geology, satellite-based imagery have been proven to be of value in the mapping of major features such as folds, faults, intrusions, volcanic flows, discrimination of differing lithologies, and the analysis of dynamic surface processes. Satellite imagery have been especially effective in inaccessible or remote geographic regions for which little or no good-quality maps were available (Szekielda, 1988). In Illinois, there has been only limited use of satellite imagery for geological mapping due to a combination of factors including, a) predominance of agricultural land use obscuring surface features; b) prevalence of extensive, and in many locations, thick glacial deposits; c) spatial resolution considerations, and d) availability and cost of imagery. Despite these factors, carefully selected satellite imagery can provide dramatic portrayals of regional-scale, surficial geologic conditions that prevail in Midwestern glaciated landscapes (Figure 1).

Developments in airborne remote sensor systems have also been significant during the past twenty-five years, and applications using airborne systems are proliferating in natural resource sciences. However, the availability and cost of digital airborne imagery remain as limiting factors to the more widespread use of such information for large-scale geological mapping (e.g., 1"=2000' and larger). Kramer (1994) provides an excellent review, although somewhat dated, of satellite and airborne remote sensor systems.

One cost-effective source of digital imagery is the U.S. Geological Survey's Digital Orthophoto Quadrangle

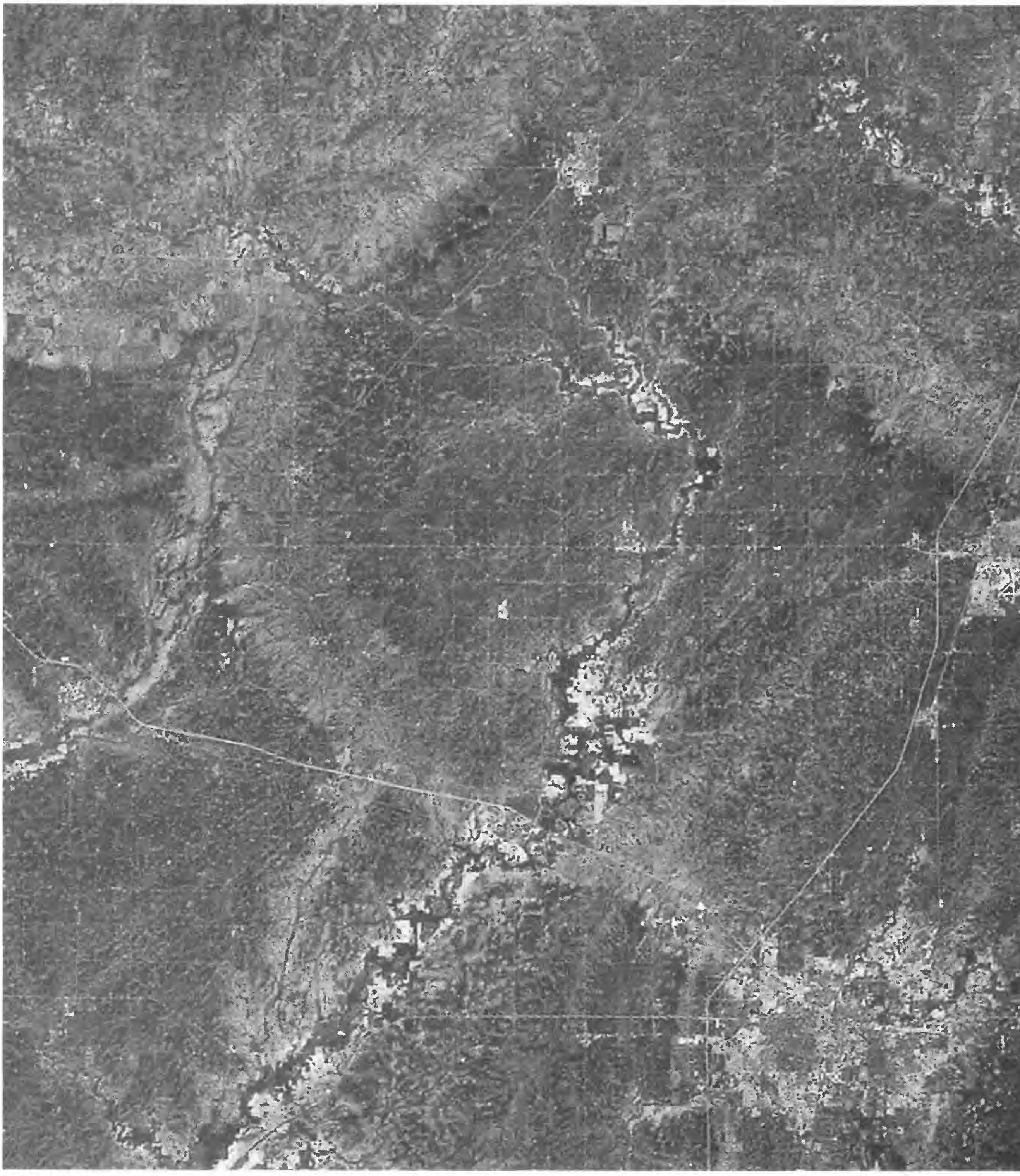

Figure 1. Portion of a Landsat 1 MSS satellite image acquired over east-central Illinois on June 11, 1978. The city of Champaign-Urbana is at lower right of image. The arcuate, lighter toned patterns evident on this image denote the positions of end moraines. This graphic portrayal of glacial features is unusual on such imagery in an area dominated by agricultural land use, and the image acquisition coincides with optimal drainage conditions and early crop stage.

(DOQ) product. Currently, 72 percent of the area of the conterminous United States is either contracted or already available, and the USGS is progressing towards its goal of complete nationwide coverage by 2002. DOQs are coincident with the USGS 7.5-minute quadrangle map coverage, have been geometrically corrected to conform to a standard cartographic map projection, and possess a 1x1 meter ground spatial resolution (USGS, 1991). Black-and-white (B&W) or color infrared (CIR),1:40,000 (nominal) scale, National Aerial Photography Program (NAPP) and NAPP-like aerial photography are the primary imagery sources used in the production of DOQs. Approximately 10 percent of the DOQs currently available or in production are being developed from CIR source aerial photography, with the remaining 90 percent using B&W source aerial photography.

WHAT IS DIGITAL ORTHOPHOTOGRAPHY?

Orthophotography combines the image characteristics of an aerial photograph with the geometric qualities of a map. Unlike a typical aerial photograph, distortions due to relief displacement (hills, stream valleys, buildings, etc.), camera lens, and aircraft attitude have been removed so that all ground features are shown in their correct ground positions. This makes possible a true image map, permitting direct measurement of distance, areas, angles, and detailed positions of ground features, many of which may be omitted or generalized on traditional maps. In a digital format, orthophotography can fulfill a fundamental role as a planimetrically accurate base map onto which additional spatial information can be readily incorporated using a geographic information system (GIS).

Produced from recent NAPP aerial photography, USGS DOQs are also frequently a more up-to-date representation of cultural and physical features than the published USGS 7.5-minute quadrangle map, especially within geographic areas that are experiencing rapid urbanization or extractive activities. For example, in Illinois 42 percent of the state's USGS 7.5-minute quadrangle maps possess publication dates that are more than 20 years old (Table 1). In contrast, Illinois' NAPP 2 aerial photography was acquired in 1993-1995, and at the date of this writing, approximately 75 percent of Illinois' 1998 NAPP 3 aerial photography has been collected. While the prioritization and funding for the update and revision of Illinois' USGS 7.5-minute quadrangle base data will continue to be a problematic issue for many years, the use of DOQs as a surrogate for up-to-date base maps is an affordable alternative available to many states, especially given the federal cost-sharing incentives available for statewide DOQ production.

INTEGRATING DOQS INTO GEOLOGIC MAPPING

Although black-and-white aerial photography has long been used as the standard for geologic interpretation, most applications are improved using color and CIR aerial photography. This is because the human eye can discriminate many more shades of color than gray tones, and the interpretation of color on standard color aerial photography more closely mimics human experience in everyday interpretation of the environment. While standard color aerial photography records the "visible" portion of electromagnetic energy, the same reflected radiation that the human eye can sense, CIR aerial photography extends the range of sensitivity into the "invisible", reflected near infrared. What this means is that the discrimination of many landscape features is enhanced using CIR photography, including such phenomena as:

Table 1. Status of USGS 7.5-minute quadrangle maps for Illinois.

Publication date	Number of quads	Percentage
1987–97	205	19
1977–86	421	39
1967–76	256	24
1957–66	160	15
1947–56	29	3
Totals	1,071	100

- Better delineation of soil moisture gradients across parent material boundaries due to increased sensitivity of the near infrared to surface moisture conditions;
- Changes in surface color, principally controlled by the green and red emulsions, are emphasized with the addition of the near infrared;
- Surface water condition, such as turbidity and presence of chemical or vegetative matter;
- Differences in vegetation types and relative vigor in response to the cell structure type and condition.

In 1996, the Illinois State Geological Survey (ISGS) began an initiative referred to as the Illinois Geologic Mapping Program (IGMaP), an extension of the existing large-scale geologic mapping program. One of the primary objectives of IGMaP is to derive GIS-based maps and ancillary data for a wide variety of geologic factors for each of the state's 1,071 USGS 7.5-minute quadrangles by the year 2025. The USGS 7.5-minute Villa Grove, IL and Vincennes, IN-IL Quadrangles were selected for the original IGMaP pilot project. As one of the IGMaP base data components, DOQs were produced for these two quadrangle areas based upon 1988 NAPP 1 CIR aerial photography. As additional 7.5-minute quadrangle areas have been added to IGMaP, image base maps are being developed from already existing B&W DOQs, and the production of CIR-based DOQs for the same areas was not deemed necessary.

Because of their high level of feature detail, DOQ-based reconnaissance maps produced at scales of 1"=1000' and 1"=500' (RF 1:12,000 and 1:6,000, respectively) are being used effectively for conducting tasks such as well verification, documenting outcrop locations, guiding field traverses, and as an interpretive base for surficial geologic mapping. When selected USGS Digital Line Graph (DLG) feature data are incorporated with DOQs, such reconnaissance maps provide an excellent base for geologic mapping (Figure 2). ISGS field geologists are adopting this new form of base map as an additional, and sometimes a replacement to the published USGS 7.5-minute topographic quadrangle map.

HOW ACCURATE SHOULD WE BE?

An informal experiment was conducted by ISGS scientists to ascertain the relative usefulness and accuracy of digital map and image base products for large-scale geologic mapping. The principal source materials included the Digital Raster Graphic (DRG), DLG Hydrography and Hypsography, and DOQ for a portion of the USGS 7.5-minute Kellerville, IL Quadrangle. The source information used to produce the DRG was the published Kellerville, IL Quadrangle (1981 publication date; source aerial photography dated 1974). The same published quadrangle was used to compile the USGS DLG category data. Lastly, the DOQ was developed from B&W NAPP 2 aerial photography acquired in March, 1994.

All of the key bedrock outcrop locations within the study area were described and located in the field using a reconnaissance map similar to that shown in Figure 2. In addition, an accurate location was determined for each described outcrop using global positioning systems technology (GPS). Subsequent to the field mapping, the Pennsylvanian bedrock surface was interpreted and delineated on the DRG in a "heads-up" digitizing approach using ArcView (Figure 3A). This trace was then transferred directly to the DOQ image base containing the GPS-based outcrop locations (Figure 3B). The DRG was preferred by the mapping geologist because of its significantly smaller file size as compared to the DOQ, requiring only modest computer resources. USGS 7.5-minute DRGs typically range from approximately 3 to 30 megabytes in size (dependent upon pattern density) as compared to approximately 165 megabytes for a single channel, B&W DOQ and approximately 500 megabytes for a three channel, CIR DOQ.

It was discovered that positional errors occurred in transferring the field information to the DRG. This can be explained in part due to the lack of feature detail inherent in the DRG as compared to the DOQ. However, a more important factor is the 20-year difference in the source materials used for the DRG and DOQ. Not only are there noticeable differences in the generalization of the stream course as seen on the DRG and DLG Hydrography as compared to the DOQ (compare Figures 3A and 3B), but changes in the position of the thalweg of the stream have also occurred. The largest positional errors occur at the GPS outcrop locations k164 and k168 (Figures 4 and 5), where discrepancies between DRG/DLG and DOQ hydrography delineation are evident. Since Quaternary exposure and bedrock outcrop locations are typically referenced to identifiable map features in rural areas such as stream meanders, prominent slope segments, etc., it is not surprising that such positional errors can occur when using outdated base maps.

The measured positional error is approximately 50 feet, which is not discernable on a 1:24,000-scale topographic quadrangle map. However, at larger scales such as 1"=500', the error averages 0.1 inch, and therefore is of concern when producing geological maps at larger publication scales. The potential for error can therefore be minimized by ensuring that published quadrangle maps being used as the primary base for geological mapping are updated and revised using more recent NAPP source material to reflect current landscape features. If this is cost-prohibitive, an affordable alternative is to use the DOQ for the primary feature interpretation.

PROCESSING CONSIDERATIONS INVOLVING IMAGE DATA

Since CIR aerial photography was used for the production of the DOQs for the Villa Grove, IL, and Vincennes, IN-IL, Quadrangles, a three-band image data set resulted, with each band representing the spectral information for the green, red, and near-infrared wavelength bands, respectively. Because of the large file size, approximately 500 megabytes, specialized image processing procedures were used to transform the original 1x1 meter ground resolution cells (grc) to a 2x2 meter grc, reducing the DOQ image data set to one-quarter of the original file size. The resampling was deemed appropriate because the spatial dimension of ground features being represented on 1"=1000' to 1"=2000' (RF 1:12,000 and 1:24,000, respectively) map products exceed 1x1 meter, and therefore the high spatial resolution is not necessary. This resampling procedure was also imposed on the B&W, single-band DOQs, which similarly reduced the DOQ file size from approximately 165 megabytes to slightly more than 40 megabytes. Only when 1"=500' scale (RF 1:6,000) image maps are being prepared for field reconnaissance of portions of the quadrangle map, is it then necessary to use the original 1x1 meter grc DOQ for map compilation and printing.

Subsequent to the resampling, the reflectance (brightness) values contained within the three-band, CIR-based DOQs were transformed to a single thematic layer of information that can be used to directly interpret surficial geologic conditions within the study area. Using the three spectral bands as input variables, multivariate clustering

Figure 2. Portion of a 1" = 500' scale base map used for reconnaissance geologic mapping, developed from the USGS Digital Orthophoto Quadrangle and Digital Line Graph data for the 7.5-minute Fishhook, Illinois Quadrangle. Unverified well locations from the ISGS are also shown.

Figure 3. (A) Portion of the 7.5-minute USGS Digital Raster Graphic for the Kellerville, Illinois Quadrangle used as a preliminary base map for delineating surface geology. Trace of the Pennsylvanian contact shown as bold, dashed line. (B) Portion of the USGS Digital Orthophoto Quadrangle (DOQ) and 7.5-minute Digital Line Graph Hypsography and Hydrography (bold solid line) for the same geographic area as shown above. White line represents the current hydrography delineated using the DOQ. Points define Pennsylvanian bedrock exposure locations as determined from field-based GPS survey. Discussion in text.

Figure 4A. Stop k164. Diamicton over Pennsylvanian dark gray shale with marine fossils, including a limey zone with brachiopods and molluscs. Septarian limestone nodules at top of shale.

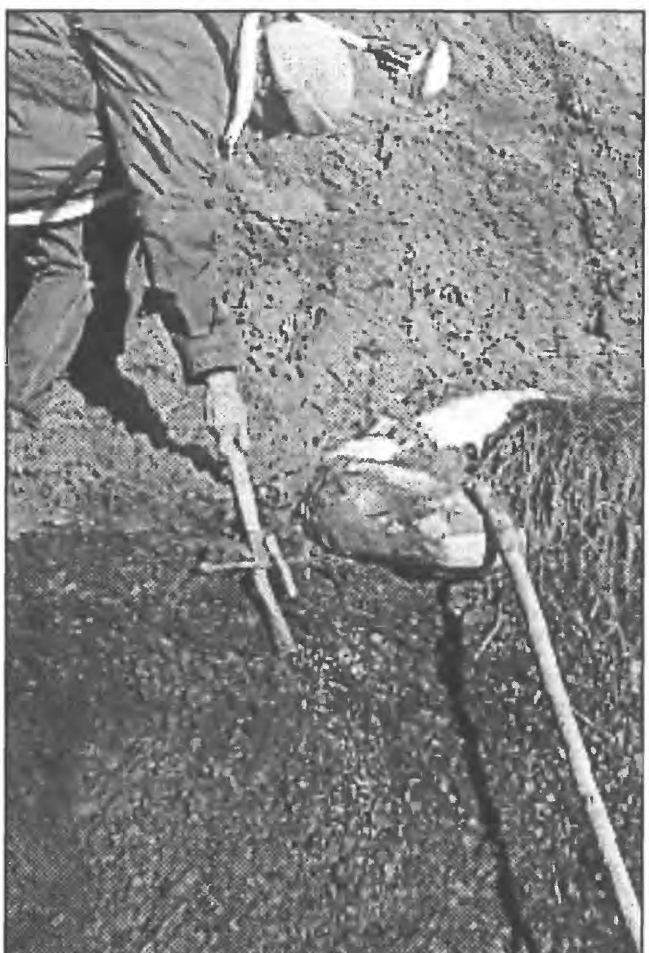

Figure 4B. Stop k164. Closeup view of contact showing septarian nodule at base of diamicton over Pennsylvanian dark gray shale.

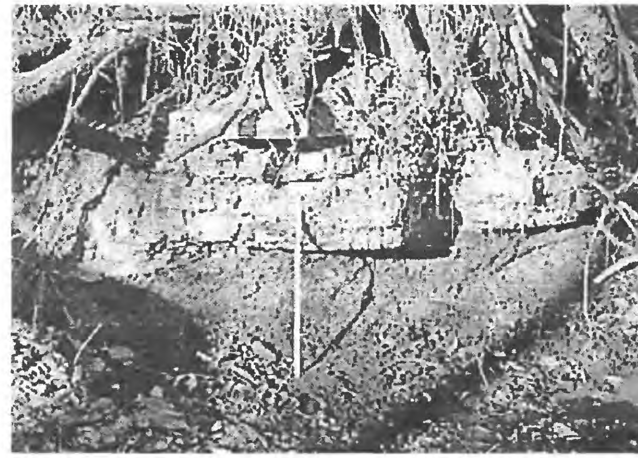

Figure 5. Stop k168. Colchester Coal, 1.3 ft. thick, overlain by 1.3 ft. of black Mecca Quarry Shale.

and image classification routines (Campbell, 1987) produced a spectral map denoting 100 statistically separable, "spectral" classes of information. In traditional applications of image classification, a large number of spectral classes are typically generalized to several, known information classes through field checks and/or direct inspection of large-scale aerial photography. In contrast, the generalization of spectral classes was minimized in the creation of the DOQ "spectral image maps" to ensure that subtle geologic features were preserved. Comparison of the resulting spectral image maps with the original, unprocessed DOQ image data revealed little or no difference in information content. This final transformation further reduced the file size of the CIR-based DOQs to approximately 10 percent of the original, 1x1 meter grc DOQ, or less than 50 megabytes. This hybrid approach facilitates the use of such imagery as an additional component in a large-scale, geologic mapping program.

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Washington State's 1:100,000-Scale Geologic Map Database: An Arc/Info Data Model Example

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Over the last 15 to 20 years, the role of the cartographer has expanded from making maps to creating relational databases, thereby broadening the use of maps as analytical tools. The discipline has moved away from creating historical documents and moved toward creating data sets that represent the most current spatial and temporal relations. These complex relations are best represented and accessed with the aid of computer hardware and software. In the field of cartography, this equipment is known as a Geographic Information System (GIS).

The power of a good GIS is not that it can generate a map but that it can be queried to find answers to complex questions. The Division of Geology and Earth Resources (DGER) has long recognized the potential of GIS technology as a tool for geologic investigation. In 1994, DGER began working toward the goal of 1:100,000-scale digital geologic coverage under a contract from the Washington Department of Ecology. The contract gave us the financial means to develop a GIS data model that would accommodate all of the Division's 1:100,000-scale geologic maps. Digital versions of two of these maps were produced as deliverables under this contract. These two maps, Priest Rapids and Richland, were a pilot project to determine the feasibility of continuing with data entry on the 50 remaining quadrangles in Washington.

With financial support from the STATEMAP component of the National Cooperative Geologic Mapping Program administered by the U.S. Geological Survey (USGS), we have been able to continue with this project. DGER has completed 29 quadrangles and has financial support to finish 11 more quadrangles by June 30, 1999. We are projecting digital conversion for all 1:100,000-scale geologic maps by June 30, 2000.

It took about 34 months of cartographer and geologist time to finish the 29 digital quadrangle maps completed so far. This includes about 6 months of geologist time to prepare materials for digitizing, convert polygon unit labels to a new standardized statewide nomenclature, and review draft products. The GIS Manager concentrates on system development, database design and integrity, training others in the use of GIS technology, problem solving, application software programming, and overall quality control. The cartographers focus on digitizing, attributing, editing, and error correction. The geologists perform data input, but are also responsible for ensuring the geologic integrity and correctness of the database.

The focus of this project has been on the production of a geologic database in Arc/Info coverage format, not on digital cartography. We have discovered that if the database is well constructed, the cartography can be applied to the database to produce map products. If we had focused on the cartography up front, the database may have been limited to only generating hardcopy output. Each map is a composite of several topologically integrated coverages. Each set of similar map features is awarded its own coverage and unique set of attributes. Depending on the complexity of the geology in a given area, a quadrangle may be composed of a few or several coverages.

The source geologic maps for this project were prepared manually using scale-stable copies of published USGS 1:100,000-scale topographic quadrangle maps as base maps. For most maps, geologists drafted the geologic information onto Mylar overlays that were photographically composited with the base maps to produce master geologic maps on Mylar; these were copied for distribution as open file reports by running them through an Ozalid machine. In a few cases, we have obtained digital line work from the USGS to convert and incorporate into our database. At a minimum, a change to DGER geologic unit nomenclature is required to incorporate these files. The 1:100,000-scale quadrangle boundaries were taken directly from the corporate GIS database of our parent organization, the Washington Department of Natural Resources (DNR), who acquired them from the USGS. DGER used this base to assure GIS integration with data from DNR as well as federal agencies. The coastline was digitized directly off the USGS topographic map to ensure a faithful replication of the original source map. All other open water features were captured directly from the USGS 1:100,000-scale DLG and enhanced by hydrographic data from the USGS quadrangles captured by DNRs Resource Mapping Section.

We believe the most important task of a state geological survey is to keep the state geologic map up to date and readily available in its most useful form. Good geologic maps are essential to a states economic development, hazard assessment, and aid in the protection of ground water and other environmental assets. We are pleased to be able to make this information available to the citizens of Washington.

THE DATA MODEL

The spatial information in the geology GIS database is comprised of the 10 topologically integrated ARC/INFO coverages listed on the following pages. Additional tabular information pertaining to lithology, map authorship, and feature names is contained in several INFO files that relate to the coverages through the use of primary and secondary keys.

COVERAGES

GUNIT Geologic units or main geological spatial data; contains both polygon information describing the age and lithology of geologic units and linear information describing the interface between those units.

GFAULT Faults and their descriptions.

GFOLD Linear fold axes and their descriptions.

GATTUD Attitude observation points used to describe the structural characteristics of rocks at a given location.

GDTSMPL Age date sample location points (fossil or radiometric age estimates).

GVENT Volcanic vents and eruptive centers and their descriptive lithology.

GDIKE Individual lithologic dikes and their descriptive lithology.

GDIKESWARM Areas of lithologic dikes too numerous to map as individual segments.

GUNITPT Location and description of geologic units that, due to map scale limitations, are represented as points on a geologic map.

GUNITLN Location and description of geologic units that, due to map scale limitations, are represented as linear features on a geologic map. These linear features are not lithologic dikes. They are more commonly rock beds tipped in such a way as to expose their ends at the surface.

COVERAGE STRUCTURE

GUNIT (network coverage containing both arc(.AAT) and polygon(.PAT) attribution)

DATAFILE NAME: **GUNIT.AAT** 10/27/1997
11 ITEMS: STARTING IN POSITION 1

COL	ITEM NAME	WDTH	OPUT	TYP	N.DEC	
1	FNODE#	4	5	B	-	
5	TNODE#	4	5	B	-	
9	LPOLY#	4	5	B	-	
13	RPOLY#	4	5	B	-	
17	LENGTH	4	12	F	3	
21	GUNIT#	4	5	B	-	
25	GUNIT-ID	4	5	B	-	
29	GCNTCT.ID	7	7	I		*- unique number for each arc segment*
36	GCNTCT.TYPE.CD	1	1	I		*- code value to differentiate types of polygon boundaries(contacts)*
37	FLTCNT	1	1	C		*- flags lithologic contacts that are also faults*
38	GMAP.ID	4	4	I		*- unique quadrangle identifier based on row and column*

GCNTCT.TYPE.CD (*geologic contact.type.code)*

1	*known location*	4	*gradational boundary*	7	*quadrangle boundary*
2	*concealed location*	5	*shoreline*	8	*ice boundary*
3	*scratch boundary*	6	*approximate location*	9	*inferred location*

FLTCNT (*fault contact)*

Y	*Yes, the lithologic contact is also a fault*	N	*No, the lithologic contact is not a fault*

GMAP.ID *(geologic map.id)*

102	*Roche Harbor*	205	*Twisp*	308	*Spokane*	503	*Centralia*	605	*Toppenish*
103	*Bellingham*	206	*Omak*	401	*Copalis Beach*	504	*Mount Rainier*	606	*Richland*
111	*Mount Baker*	207	*Nespelem*	402	*Shelton*	505	*Yakima*	607	*Walla Walla*
105	*Robinson Mountain*	208	*Chewelah*	403	*Tacoma*	506	*Priest Rapids*	608	*Clarkston*
106	*Oroville*	301	*Forks*	404	*Snoqualmie Pass*	507	*Connell*	609	*Orofino*
107	*Republic*	302	*Mount Olympus*	405	*Wenatchee*	508	*Pullman*	703	*Vancouver*
108	*Colville*	303	*Seattle*	406	*Moses Lake*	601	*Ilwaco*	704	*Hood River*
201	*Cape Flattery*	304	*Skykomish River*	407	*Ritzville*	602	*Astoria*	705	*Goldendale*
202	*Port Angeles*	305	*Chelan*	408	*Rosalia*	603	*Mount St. Helens*	706	*Hermiston*
203	*Port Townsend*	306	*Banks Lake*	501	*Westport*	604	*Mount Adams*	707	*Pendleton*
204	*Sauk River*	307	*Coulee Dam*	502	*Chehalis River*				

DATAFILE NAME: **GUNIT.PAT** 10/27/1997

7 ITEMS: STARTING IN POSITION 1

COL	ITEM NAME	WDTH	OPUT	TYP	N.DEC
1	AREA	4	12	F	3
5	PERIMETER	4	12	F	3
9	GUNIT#	4	5	B	-
13	GUNIT-ID	4	5	B	-
17	GUNIT.ID	6	6	I	- *unique number for each polygon occurrence*
23	GUNIT.LABEL.CD	12	12	C	- *age-lithology unit polygon label*
35	GMAP.ID	4	4	I	- *unique quadrangle identifier based on row and column*

GUNIT.LABEL.CD *(geologic unit.label.code)*

Age-lithology unit polygon labels. This item is the key used to establish the relationship between the GUNIT coverage and an INFO file called GUNIT.MAIN that contains more detailed information about the geologic characteristics of a polygon.

GFAULT *(arc coverage)*

DATAFILE NAME: **GFAULT.AAT** 10/27/1997

12 ITEMS: STARTING IN POSITION 1

COL	ITEM NAME	WDTH	OPUT	TYP	N.DEC
1	FNODE#	4	5	B	-
5	TNODE#	4	5	B	-
9	LPOLY#	4	5	B	-
13	RPOLY#	4	5	B	-
17	LENGTH	4	12	F	3
21	GFAULT#	4	5	B	-
25	GFAULT-ID	4	5	B	-
29	GFAULT.ID	5	5	I	- *unique number for each fault in the coverage*
34	GFLTSEG.NO	4	4	I	- *unique number for each fault segment in the coverage*
38	GFLTSEG.TYPE.CD	3	3	I	- *code value used to differentiate fault types and changes in the characteristics of the fault at the segment level*
41	GMAP.ID	4	4	I	- *unique quadrangle identifier based on row and column*
45	FLTCNT	1	1	C	- *used to flag those faults that are also lithologic contacts*

GFAULT.ID *(geologic fault.id)*

A geologic fault is commonly segmented as a result of intersecting differing lithologic polygons. We populate this item in order to keep track of an individual fault regardless of how many segments it consists of. This item is also a key used to establish the relationship to an INFO file called GFAULT that contains the names of faults, if any.

GFLTSEG.TYPE.CD *(geologic fault segment.type.code)*

1 *fault, unknown offset*
2 *fault, unknown offset, approximate location*
3 *fault , unknown offset, concealed*
4 *fault, unknown offset, queried*
5 *fault, unknown offset, approximate location, queried*
6 *fault, unknown offset, concealed, queried*
And so on to 83 entries

FLTCNT *(fault contact)*

Y *Yes, the fault is also a lithologic contact*
N *No, the fault is not a lithologic contact*

GFOLD *(arc coverage)*

DATAFILE NAME: **GFOLD.AAT** 10/27/1997
11 ITEMS: STARTING IN POSITION 1

COL	ITEM NAME	WDTH	OPUT	TYP	N.DEC
1	FNODE#	4	5	B	-
5	TNODE#	4	5	B	-
9	LPOLY#	4	5	B	-
13	RPOLY#	4	5	B	-
17	LENGTH	4	12	F	3
21	GFOLD#	4	5	B	-
25	GFOLD-ID	4	5	B	-
29	GFOLD.ID	6	6	I	- *unique number for each fold in the coverage*
35	GFOLDSEG.NO	3	3	I	- *unique number for each fold segment in the coverage*
38	GFOLDSEG.TYPE.CD	2	2	I	- *code value used to differentiate fold types and changes in the characteristics of the fold at the segment level*
40	GMAP.ID	4	4	I	- *unique quadrangle identifier based on row and column*

GFOLD.ID *(geologic fold.id)*

A geologic fold is commonly segmented as a result of intersecting differing lithologic polygons. We populate this item in order to keep track of an individual fold regardless of how many segments it is consists of. This item is also a key used to establish the relationship to an INFO file called GFOLD that contains the names of folds, if any.

GFOLDSEG.TYPE.CD *(geologic fold segment.type.code)*

1 *anticline*
2 *anticline, approximate location*
3 *anticline, concealed*
4 *anticline, queried*
5 *anticline, approximate location, queried*
6 *anticline, concealed, queried*
And so on to 42 entries

GATTUD *(point coverage)*

DATAFILE NAME: **GATTUD.PAT** 10/27/1997
9 ITEMS: STARTING IN POSITION 1

COL	ITEM NAME	WDTH	OPUT	TYP	N.DEC
1	AREA	4	12	F	3
5	PERIMETER	4	12	F	3
9	GATTUD#	4	5	B	-
13	GATTUD-ID	4	5	B	-
17	GATTUD.ID	5	5	I	- *unique number for each structural attitude observation point in the coverage*
22	GMAP.ID	4	4	1	- *unique quadrangle identifier based on row and column*
26	GATTUD.CD	2	2	I	- *code value used to differentiate between structural attitude observation point types*
28	GATTUD.STRK.AZM	3	3	I	- *strike of feature based on north=0° (or 360°) azimuth measured clockwise*
31	GATTUD.DIP.ANG	2	2	I	- *dip or plunge of feature based on decimal degrees below horizontal*

GATTUD.CD *(geologic structural attitude observation point.code)*

1 *strike and dip of beds*
2 *strike and dip of overturned beds*
3 *strike of vertical beds*
4 *strike and dip of beds, dip amount unspecified*
5 *approximate strike and dip of beds*
6 *horizontal beds*
7 *strike and dip of foliation*
And so on to 24 entries

GDTSMPL *(point coverage)*

DATAFILE NAME: **GDTSMPL.PAT** 10/27/1997
10 ITEMS: STARTING IN POSITION 1

COL	ITEM NAME	WDTH	OPUT	TYP	N.DEC	
1	AREA	4	12	F	3	
5	PERIMETER	4	12	F	3	
9	GDTSMPL#	4	5	B	-	
13	GDTSMPL-ID	4	5	B	-	
17	GMAP.ID	4	4	I		*- unique quadrangle identifier based on row and column*
21	GDTSMPL.METH.CD	2	2	I		*- code value used to differentiate between geologic age-determination methods*
23	GDTSMPL.NO	3	3	I		*- unique number for each geologic age determination sample location point in the coverage*
26	GUNIT.LABEL.CD	12	12	C		*- age-lithology unit sampled*
38	AGE	80	80	C		*- relative or absolute age of rock sampled*
118	REMARKS	80	80	C		*- notes about a specific age date sample*

GDTSMPL.METH.CD *(geologic date sample.methodology.code)*

1 *radiometric* 2 *fossil*

GDTSMPL.NO *(geologic date sample.number)*

This item contains the sample number that is found on the original source map. The number is used to reference additional information found in the map's explanatory text.

GUNIT.LABEL.CD *(geologic unit.label.code)*

Age-lithology unit polygon labels. This item is the key used to establish the relationship between the GUNIT coverage and an INFO file called GUNIT.MAIN that contains more detailed information about the geologic characteristics of a polygon where the sample originated.

AGE

The age of the rock sampled. Expressed as a relative geologic age, such as Jurassic, or an absolute age, such as 5,000,000 years before present.

REMARKS

This field contains notes about the sample, such as the specific tests performed to determine the age of the sample.

GVENT *(point coverage)*

DATAFILE NAME: **GVENT.PAT** 10/27/1997
7 ITEMS: STARTING IN POSITION 1

COL	ITEM NAME	WDTH	OPUT	TYP	N.DEC	
1	AREA	4	12	F	3	
5	PERIMETER	4	12	F	3	
9	GVENT#	4	5	B	-	
13	GVENT-ID	4	5	B	-	
17	GVENT.ID	3	3	I		*- unique number for each volcanic vent point location in the coverage*
20	GUNIT.LABEL.CD	12	12	C		*- age-lithology unit of the material erupted at the vent*
32	GMAP.ID	4	4	I		*- unique quadrangle identifier based on row and column*

GUNIT.LABEL.CD *(geologic unit.label.code)*

Age-lithology unit labels. This item is the key used to establish the relationship between the GVENT coverage and an INFO file called GUNIT.MAIN that contains more detailed information about the geologic characteristics of a volcanic vent.

GDIKE *(arc coverage)* [dikes?]

DATAFILE NAME: **GDIKE.AAT** 10/27/1997

12 ITEMS: STARTING IN POSITION 1

COL	ITEM NAME	WDTH	OPUT	TYP	N.DEC	
1	FNODE#	4	5	B	-	
5	TNODE#	4	5	B	-	
9	LPOLY#	4	5	B	-	
13	RPOLY#	4	5	B	-	
17	LENGTH	4	12	F	3	
21	GDIKE#	4	5	B	-	
25	GDIKE-ID	4	5	B	-	
29	GDIKE.ID	5	5	I		*- unique number for each dike segment in the coverage*
34	GDIKESEG.TYPE.CD	1	1	I		*- code value used to describe changes in the characteristics of the dike at the segment level*
35	GUNIT.LABEL.CD	12	12	C		*- age-lithology unit material of which the dike is composed*
47	DIKE.NM	60	60	C		*- name of dike, if any*
107	GMAP.ID	4	4	I		*- unique quadrangle identifier based on row and column*

GDIKESEG.TYPE.CD *(geologic dike segment.type.code)*

1 *known location*
2 *concealed location*
3 *approximate location*

GUNIT.LABEL.CD *(geologic unit.label.code)*

Age-lithology unit labels. This item is the key used to establish the relationship between the GDIKE coverage and an INFO file called GUNIT.MAIN that contains more detailed information about the geologic characteristics of a dike.

GDIKESWARM *(network coverage containing both arc and polygon attribution)*

DATAFILE NAME: **GDIKESWARM.AAT** 10/27/1997

10 ITEMS: STARTING IN POSITION 1

COL	ITEM NAME	WDTH	OPUT	TYP	N.DEC	
1	FNODE#	4	5	B	-	
5	TNODE#	4	5	B	-	
9	LPOLY#	4	5	B	-	
13	RPOLY#	4	5	B	-	
17	LENGTH	4	12	F	3	
21	GDIKESWARM#	4	5	B	-	
25	GDIKESWARM-ID	4	5	B	-	
29	GDSCNT.ID	7	7	I		*- unique number for each dike swarm arc segment in the coverage*
36	GDSCNT.TYPE.CD	1	1	I		*- code value used to describe changes in the characteristics of a dike swarm polygon arc segment*
37	GMAP.ID	4	4	I		*- unique quadrangle identifier based on row and column*

GDSCNT.TYPE.CD

1 *known location (no others are identified at this time)*

DATAFILE NAME: **GDIKESWARM.PAT** 10/27/1997

6 ITEMS: STARTING IN POSITION 1

COL	ITEM NAME	WDTH	OPUT	TYP	N.DEC	
1	AREA	4	12	F	3	
5	PERIMETER	4	12	F	3	
9	GDIKESWARM#	4	5	B	-	
13	GDIKESWARM-ID	5	5	I	-	
17	GDIKESWARM.ID	6	6	I		*- unique number for each dike swarm in the coverage*
22	GUNIT.LABEL.CD	12	12	C		*- age-lithology unit material of which the dike swarm is composed*
34	GMAP.ID	4	4	I		*- unique quadrangle identifier based on row and column*

GUNITLN *(arc coverage)*

DATAFILE NAME: **GUNITLN.AAT** 10/27/1997
8 ITEMS: STARTING IN POSITION 1

COL	ITEM NAME	WDTH	OPUT	TYP	N.DEC
1	FNODE#	4	5	B	-
5	TNODE#	4	5	B	-
9	LPOLY#	4	5	B	-
13	RPOLY#	4	5	B	-
17	LENGTH	4	12	F	3
21	GUNITLN#	4	5	B	-
25	GUNITLN-ID	4	5	B	-
29	GUNITLN.ID	5	5	I	*- unique number for each linear age-lithology unit feature in the coverage*
34	GUNIT.LABEL.CD	12	12	C	*- non-dike, age-lithology unit material represented as a linear feature on a geologic map*
46	GMAP.ID	3	3	I	*- unique quadrangle identifier based on row and column*

GUNIT.LABEL.CD *(geologic unit.label.code)*

Age-lithology unit labels. This item is the key used to establish the relationship between the GUNITLN coverage and an INFO file called GUNIT.MAIN that contains more detailed information about the geologic characteristics of a linear feature.

GUNITPT *(point coverage)*

DATAFILE NAME: **GUNITPT.AAT** 10/27/1997
7 ITEMS: STARTING IN POSITION 1

COL	ITEM NAME	WDTH	OPUT	TYP	N.DEC
1	AREA	4	12	F	3
5	PERIMETER	4	12	F	3
9	GUNITPT#	4	5	B	-
13	GUNITPT-ID	4	5	B	-
17	GUNITPT.ID	5	5	I	*- unique number for each age-lithology unit point feature in the coverage*
22	GUNIT.LABEL.CD	12	12	C	*- age-lithology unit material represented as a point feature on a geologic map*
34	GMAP.ID	3	3	I	*- unique quadrangle identifier based on row and column*

GUNIT.LABEL.CD *(geologic unit.label.code)*

Age-lithology unit labels. This item is the key used to establish the relationship between the GUNITPT coverage and an INFO file called GUNIT.MAIN that contains more detailed information about the geologic characteristics of a point feature.

INFO DATA FILES

GMAP

DATAFILE NAME: **GMAP** 10/27/1997
4 ITEMS: STARTING IN POSITION 1

COL	ITEM NAME	WDTH	OPUT	TYP	N.DEC
1	GMAP.SCL	7	7	I	*- source map scale*
8	GMAP.COMPILE.YR	4	4	I	*- compilation date*
12	GMAP.AUTHOR.NM	100	100	C	*- author's name*
112	GMAP.ID	4	4	I	*- unique quadrangle identifier based on row and column*

GMAP.TXT

DATAFILE NAME: **GMAP.TXT** 10/27/1997
2 ITEMS: STARTING IN POSITION 1

COL	ITEM NAME	WDTH	OPUT	TYP	N.DEC
1	GMAP.REF.TXT	80	80	C	*- map title*
81	GMAP.ID	4	4	I	*- unique quadrangle identifier based on row and column*

GUNIT.MAIN

DATAFILE NAME: **GUNIT.MAIN** 10/27/1997
10 ITEMS: STARTING IN POSITION 1

COL	ITEM NAME	WDTH	OPUT	TYP	N.DEC
1	GUNIT.LABEL.CD	12	12	C	*- age-lithology feature unit label*
13	GUNIT.REL.AGE.CD	5	5	C	*- relative age code*
18	GUNIT.MJ.LITH.CD	3	3	C	*- major lithology*
21	GUNIT.SSCRPT.TXT	4	4	C	*- geologic unit subscript*
25	GUNIT.AGE.NO	5	5	N	2 *code used to sort on age of rocks (this is not the age)*
30	GUNIT.AGE.TXT	40	40	C	*- geologic time period attributed to rock*
70	GUNIT.LITH.NO	5	5	N	2 *code used to sort on lithology*
75	GUNIT.LITH.CD	10	10	C	*- code used to describe lithology*
85	GUNIT.LITH.TXT	100	100	C	*- text describing lithology*
185	GUNIT.NOTE.TXT	100	100	C	*- name of geologic unit, if any; alphabetic geologic unit subscripts are abbreviations of geologic names; numeric subscripts are finer distinctions of age than those found in GUNIT.AGE.TXT.*

GUNIT.MJ.LITH.CD *(geologic unit.major.lithology.code)*

EXT *extrusive igneous*
INT *intrusive igneous*
MET *metamorphic*
SED *sedimentary*
VAS *volcanic and sedimentary*
UNC *unconsolidated*

Example Record from GUNIT.MAIN *for unit **Q**uaternary **V**olcanic **B**asaltic **A**ndesite of **P**uny **C**reek*

GUNIT.LABEL.CD = Qvba(pc)
GUNIT.REL.AGE.CD = Q
GUNIT.MJ.LITH.CD = EXT
GUNIT.SSCRPT.TXT = pc
GUNIT.AGE.NO = 1.00
GUNIT.AGE.TXT = Holocene
GUNIT.LITH.NO = 39.10
GUNIT.LITH.CD = vba
GUNIT.LITH.TXT = basaltic andesite flows
GUNIT.NOTE.TXT = Puny Creek, basaltic andesite flows of

GFAULT

DATAFILE NAME: **GFAULT** 10/27/1997
3 ITEMS: STARTING IN POSITION 1

COL	ITEM NAME	WDTH	OPUT	TYP	N.DEC
1	GFAULT.ID	5	5	I	*- fault.id from GFAULT coverage*
6	GFAULT.NM	60	60	C	*- fault name*
66	GMAP.ID	4	4	I	*- unique quadrangle identifier based on row and column*

GFOLD

DATAFILE NAME: **GFOLD** 10/27/1997
3 ITEMS: STARTING IN POSITION 1

COL	ITEM NAME	WDTH	OPUT	TYP	N.DEC
1	GFOLD.ID	6	6	I	*- fold.id from GFOLD coverage*
7	GFOLD.NM	60	60	C	*- fold name*
67	GMAP.ID	4	4	I	*- unique quadrangle identifier based on row and column*

Progress Toward Development of the National Geologic Map Database

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The Geologic Mapping Act of 1992 and its reauthorization in 1997 (PL105-36) requires that a National Geologic Map Database (NGMDB) be designed and built by the U.S. Geological Survey (USGS), the state geological surveys, and other entities participating in the National Cooperative Geologic Mapping Program. The Act notes that the NGMDB is intended to serve as a "national archive" of geologic maps, to provide the information needed to address various societal issues. The Act required the NGMDB to also include the following related map themes: geophysics, geochemistry, paleontology, and geochronology. In this progress report, the term "geoscience" is used to refer to these five map themes.

In mid-1995, the general stipulations in the Act were addressed in the proposed design and implementation plan developed within the USGS and the Association of American State Geologists (AASG). This plan was summarized in Soller and Berg (1995). Because most maps are not yet in digital form and because many organizations produce and distribute geologic maps, it was decided to develop the NGMDB in several phases. The first two phases are addressed here. The first and most fundamental phase is a comprehensive, searchable catalog of all geoscience maps in the United States, in either paper or digital format. The users, upon searching the NGMDB catalog and identifying the map(s) they need, are to be linked to the appropriate organization for further information and how to procure the map. That organization could be a participating state or federal agency, association, or private company. The second phase of the project focuses on public access to digital geoscience maps, and on the development of digital map standards and guidelines needed to improve the utility of those digital maps.

In late 1995, work began on phase one. The formation of several Standards Working Groups in mid-1996 initiated work on phase two. Progress through mid-1997 is summarized in Soller and Berg (1997). At the Digital Mapping Techniques '98 workshop, a series of presentations and discussion sessions provided updates on the NGMDB and, specifically, on the activities of the Standards Working Groups. This report summarizes progress since mid-1997. Further and more current information may be found at the NGMDB project-information Web site, at http://ncgmp.usgs.gov/ngmdbproject. The searchable database is available at http://ngmdb.usgs.gov.

THE MAP CATALOG

The catalog now contains bibliographic information for most formal series USGS maps, USGS maps contained in book publications, and many maps from the USGS open-file series. The catalog is estimated to be about 32% complete, and contains georeferenced information for about 53% of all USGS maps (about 12,000 in the catalog) and 2% of state geological survey maps. This represents more than a six-fold increase in information since last year. Through development of a Web-based data-entry form, we are now working with state geological surveys to bring their map information into the catalog; this has begun as a pilot effort, with cooperation of the Illinois State Geological Survey and the West Virginia Geological and Economic Survey. Entry of state geological survey publications will now become a top priority.

STANDARDS DEVELOPMENT

The following summaries concern activities of the AASG/USGS Standards Working Groups formed in mid-1996. General information about the Working Groups, and details of their activities, are available at http://ncgmp.usgs.gov/ngmdbproject.

Geologic Map Symbols

A draft standard for geologic map symbology, published in a USGS open-file in 1995, was revised by the NGMDB project and members of the USGS Western Region Publications Group and was circulated for internal review in late 1997. The revised draft is now being prepared as a proposed Federal standard, for consideration by the Federal Geographic Data Committee. We also have negotiated with Environmental Systems Research Institute, Inc., a cooperative plan to develop an Arc/Info and ArcView version of the symbols and patterns; for more information, see http://ncgmp.usgs.gov/ngmdbproject/standards/carto/cartomain.html.

Digital Mapping

The Data Capture Working Group last year coordinated the first workshop on digital mapping techniques for state and federal geologists, cartographers, and managers. Sponsored by the Kansas Geological Survey, the meeting was attended by 70 members of 30 state geological surveys, the USGS, and the Geological Survey of Canada. The proceedings were published (Soller, 1997) and served on-line (http://ncgmp.usgs.gov/pubs/OF97-269intro.html). Copies of the Proceedings may be obtained from Soller or Berg.

Map Publication Requirements

Through the USGS Geologic Division Information Council, one of us (Soller) has developed a proposed USGS Publication Requirements for Digital Map Products. When this document is approved by the USGS, perhaps in late 1998, a less USGS-specific version will be proposed to the AASG through the Map Publication Guidelines Working Group. This Working Group then would work with the AASG and the USGS to craft an acceptable guideline for all maps available through the NGMDB.

Metadata

The Metadata Working Group has developed a report, which provides guidance on the creation and management of well-structured formal metadata for digital maps (see http:// ncgmp.usgs.gov/ngmdbproject/standards/metadata/metaWG.html). The report also contains links to metadata-creation tools and general discussions of metadata concepts (see, for example, "Metadata in Plain Language", at http://geology.usgs.gov/tools/metadata/tools/doc/ctc/). The Working Group welcomes your comments on its report.

Geologic Map Data Model

Following numerous presentations, discussions, and progress reports (for example, Raines and others, 1997), in October, 1997, the Working Group posted to the NGMDB project's Web site for public comment a report describing the proposed standard data model. To permit thorough evaluation of the data model, the concepts and specifications described in that report must be translated into software tools that 1) organize and manage the geologic map information in the data model format, and 2) offer a user-friendly interface for data entry and analysis. The Working Group began building some prototype tools in mid-1997. Through presentations and discussions with potential users, the tools have been refined, and are now available for use. These tools are not intended as "production" tools, but are merely prototypes that will aid in the evaluation of the data model.

The data model and tools were presented for discussion in a special session at the Digital Mapping Techniques '98 workshop in late May, 1998. A number of attendees from the state geological surveys expressed interest in helping to refine the model and develop it into a geoscience-community standard. It was agreed that an extended period of evaluation among the states and USGS would begin as soon as possible.

At a three-day workshop in June, 1998, the first formal review of the data model was conducted. The workshop was attended by 28 members of the USGS, state geological surveys, and the federal and provincial surveys of Canada. An overview of the conceptual model and software tools was followed by a hands-on session and facilitated discussion. Throughout, the importance of discussion and consensus-building was emphasized; the process of developing this standard data model must be an open and inclusive one, because a proposed standard cannot actually function as a standard if it is not widely accepted and used. At this workshop, it was resolved to: 1) proceed with development of the data model and software tools; 2) broaden the participation in its further development; 3) begin the extended period of on-site evaluation at state, provincial, and federal surveys; and 4) work toward adoption of the data model as a national standard.

To facilitate the review and discussion of the data model after the June workshop, a Web conference was developed (see http://geology.usgs.gov/dm/). Discussion topics include: 1) general conceptual issues related to the data model and geologic mapping; 2) specific problems with the data model; 3) development of standard geologic terms; and 4) software tools. This site, and the NGMDB project's Web site, also offer access to the data model report and software tools. All interested parties in the state geological surveys, the USGS, and elsewhere are invited to evaluate them, and to help us develop the prototype into a community standard that will serve both the scientist and the general public.

GEOLOGIC NAMES LEXICON

In April, 1998, an on-line geologic names lexicon, "GEOLEX", became available at the NGMDB Web site. This lexicon is under construction, and is estimated to be about 65% complete. GEOLEX is a consolidated, revised, and error-corrected database derived from the USGS GNULEX and GEONAMES databases. It is intended to be the comprehensive, authoritative listing of geologic names approved for usage by the USGS, and will be available as a resource for geologic mappers nationwide.

OTHER ASPECTS OF THE NGMDB

Work has begun on a National Paleontologic Database and a set of Web pages to support the Database and to permit searches. A public release is expected in 1999. To provide users with information about current mapping activities, a Geologic Mapping in Progress Database has been developed. This year, its scope and design were proposed to the AASG at their annual meeting in Portland, ME, and a prototype database was built. The database is being expanded to contain information about 1998 mapping activities, and a Web interface to this database is being designed. Public access is expected by early 1999. Progress continues to be made toward various other goals of the NGMDB, including the serving of standardized digital map products over the Internet. The project's Web site will continue to provide current information on these subjects.

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Geologic Maps, Spatial Databases, and Standards

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"May you live in exciting times."
Ancient Chinese blessing and curse

Makers and users of geologic maps live in exciting times. The cartographic world is undergoing a revolution perhaps comparable only to the invention of maps themselves. No longer tied to paper or mylar, spatial data are now most usefully stored in digital form and manipulated by computer and plotter, not cartographer and pen. Geologic maps are not immune to this change. There are many efforts to bring the world of digital cartography, GIS, and spatial databases to the map-making geologist, and vice versa. But how should we do this--what form should digital geologic spatial data take?

Maps and the discipline of mapping, developed by two centuries of practice with paper and sharp pencil, are integral to geology as we know it. As our spatial data become digital, we are obviously concerned that we do not lose the benefits that paper and pencil bring us. Most discussion to date on digitization has been over how to put paper maps into the computer. But we should think further: Digital spatial databases aren't just a faster and cheaper way to produce and deliver geologic maps. As our spatial data become digital, we will change and improve the way we do geology.

In this essay I discuss what a geologic map is, how geologic maps differ from other maps, and what a geologic spatial database is and how it differs from a map. My hope is to encourage clarity on these topics as we discuss standards for digital geologic spatial data. I then propose several years of explicit experimentation before national standards for digital geologic spatial data are adopted. As a contribution towards this discussion and experimentation, I conclude with some suggestions towards better databases.

My qualifications are limited. I have no formal training in cartography, GIS theory, or database design. I am a geologist with nearly two decades of experience mapping in the humbling terrane of northwest Washington (e.g. Tabor and others, 1994; Haugerud and others, 1994). I have the good fortune to have worked closely for much of this time with an excellent mapper and to have been exposed to many of the other wise men and women within the USGS. I have used Arc/Info for several years. A recent project in regional map compilation (Haugerud, 1997) has turned me into a consumer of digital geologic spatial data. And I have been a peripheral participant in two of the ongoing standards-generation efforts (Raines and others, 1997; Fitzgibbon and Wentworth, 1991).

WHAT IS A GEOLOGIC MAP?

"There isn't a unique, correct, geologic map."
—E.H. Brown to field camp students, 1974

"Plot a symbol, some symbol, to show each outcrop that you visit."
—Eric Cheney to field camp students, circa 1985

"A geologic map is an expression of an hypothesis. (Geologists who make blob maps have blobby hypotheses.)"
—E-an Zen, 1986

"Plot as you plod, or you won't know where to go next"
—Rowland Tabor (paraphrased), many times

A geologic map is (1) a record of observations located in space, (2) an expression of an hypothesis about Earth history, and (3) a tool for analysing Earth history. It is NOT a simple, or even an abstract, description of some part of the Earth.

The Map as Record of Observations

First of all, our maps are records of our observations. A bedding attitude here, a sample locality there. But many, even most, of the observations shown on a geologic map are not simple observed facts. How many times have you explained to an assistant why your notes don't mention the red color, or the extensive fracturing, or the (fill in the blank) of some outcrop? We do not simply record what can be seen. Our field "data" are already filtered through a large body of geologic theory. Sometimes our observations are no closer to being facts than the hypotheses we attempt to test with these observations. This is the major reason that advances in structural, stratigraphic, or petrologic theory commonly necessitate remapping of regions. The point is driven home when you discover that you and your colleague, with over five decades field experience between you, cannot agree on the orientation of bedding at the last outcrop.

The Map as Expression of an Hypothesis

Most geologic mappers see only a fraction of a map area, but possess powerful theoretical tools (Steno's Laws, expectations of facies patterns, and so on) that, with an Earth history inferred from these limited observations, allow extrapolation of geologic relations to the rest of the map sheet, even the areas that are covered. A geologic map is commonly more prediction than depiction. The map is an illustration of an inferred Earth history.

The amalgam of observation and inference on a map can be uneasy, as is discovered by the geologist who gets a helicopter ride to an inaccessible ridge only to discover that the foliation attitude plotted by a revered predecessor was wishful thinking. Unfortunately, paper usually does not allow the density and detail of symbolization that would be needed to fully distinguish between what we saw, what we think we saw, and what we think we would have seen if we could have seen.

The Map as Analytic Device

A geologic map is also an analytic device. This is true after it is made~how many classes have we collectively taken, or taught, in which we were asked to unravel some aspect of Earth history from a map? But the making of a map is also an analytical tool. The mapper knows well the ritual: daily plotting of field observations on the office map; inking that which is well-known; erasing; coloring (sometimes tentatively, sometimes with conviction) of areas that have been mapped; erasing; poring over the uncompleted map, field sheets, and air photos; and long hours of discussion if one is fortunate enough to work with a colleague, always asking "What is the stratigraphy? What is the structure? Where do I traverse tomorrow to fill in the map, maximize outcrop, minimize travel costs, and best resolve the major unknowns in the geologic story?" Putting one's observations on mylar at 1:24,000 or 1:100,000 scale turns incomprehensible mountainsides into simple geologic relations that can be held in the hand~doing so is a tool that allows a flea to see elephants. Putting a station in every square inch of the map enforces a completeness to one's analysis. And mapping all the unconsolidated deposits keeps one honest about what bedrock history can be known and what cannot. (And vice versa.)

HOW DO GEOLOGIC MAPS DIFFER FROM OTHER MAPS?

Geologic maps differ from many other maps in important ways: (1) Our maps are commonly of entities that are observed with difficulty. Identification of a municipal boundary, or an interstate highway, is easier than the identification of many (most?) geologic map units. Uncertainties about classification of the mapped object are greater than with other types of maps. Misclassification errors are correspondingly more common. (2) Our maps are more sensitive to scale than other types of maps. The nature of a contact on a political map does not change with map scale: it is commonly defined, and observed, with much greater precision than it is plotted at a wide range of scales. Geologic objects are commonly defined and observed with a resolution that is near the intrinsic resolution of the map~indeed, we choose our map scale or our observation method so that this is true, and we then use symbols to denote whether an object is located as well as or more poorly than can be depicted at that scale (e.g. continuous or dashed contacts). (3) Our maps are more complex. Whereas some cartographic dogma proclaims 'one theme, one map', geologic maps commonly display multiple themes (e.g. lithostratigraphy and topography) so that the user can observe the interplay between themes and use this interplay to make useful inferences. (4) Many geologic maps have text and correlation charts that describe rich and complex relations between the various units shown on the map. (5) A well-made geologic map has benefited from a great deal of thought about its symbolization. Colors, patterns, line-weights, symbol sizes, unit tags, and type fonts are all carefully chosen to reinforce explicitly recognized relations and to hint at others. (6) Because geologic maps are largely inference, their authorship is important.

WHAT IS A GEOLOGIC SPATIAL DATABASE AND HOW DOES IT DIFFER FROM A MAP?

Most of us understand, at some level, that a geologic spatial database is a set of spatial geologic data in the computer that can be queried, whereas a map is a graphic on a piece of paper or a computer screen. Nonetheless, we often use the terms interchangeably, presuming that a digital map is a database. But there are essential differences between databases and maps.

Databases lack cartography. The meanings (attributes) of objects in a database can, and should, be expressed without symbolization. The lack of symbolization, and the corresponding ability to prescribe different symbolization of the data for different purposes, give digital geology much of its power. The price we pay for this power is the need to explicitly describe some of the meanings that are implicit in much present map symbolization. What is most important? What least? What map units are like, or unlike, other map units?

A database has no intrinsic scale. A paper map does. Consequences of this difference include no limit on the richness of attribute information in a database, whereas maps are limited by printing technology and the resolving power of the human eye. If a database is to have a scale, or resolution, it must be specified explicitly. (Raster databases are exceptions: in them, cell size defines resolution.)

Databases commonly lack base maps. Reynolds and others (in U.S. Geological Survey, 1995), following USGS tradition, suggested that any geologic map worthy of the name must have a base, as the location of geologic features is always relative to the location of physiographic or cultural features. Yet any number of digital geologic spatial databases are available without an associated base. Such databases are more compact. Many users want to plot geologic data on a base map of their own choosing. And in many cases an adequate digital representation of the appropriate base map simply hasn't been available.

Databases can be updated more easily than paper maps. Producing, printing, and distributing a paper map is an expensive and time-consuming proposition. This had the effect of stabilizing our geologic understanding: it simply cost too much for advances in knowledge to be quickly and widely disseminated.

Some of these differences became clear to me when I began a project to produce a large composite geologic spatial database and straightforward methods to produce many maps from this database (see Haugerud, 1997). I have one database: it is a collection of computer files that describe the geology of the Pacific Northwest in (1) terms that the software can manipulate and in (2) symbolic abstractions that are similar to those embodied in a traditional geologic map~units and contacts. If I add to this database a geographic outline, a projection, a scale, and a set of rules for generalizing and visualizing the content of the database, I get a map. With a different outline, projection, scale, or set of generalization and visualization rules, I get a different map. The database contains spatial information sufficient to produce many maps. It does so without the symbolization or scale dependence of a map. Each map contains information (scale, symbolization, projection, extent) that is not present or is different from that in the database. There is not a one-to-one relation between database and map.

STANDARDS FOR DIGITAL GEOLOGIC SPATIAL DATA

Executive Order 12906 (establishing the National Spatial Data Infrastructure) and the National Cooperative Geologic Mapping Act effectively mandate a national standard for digital geologic map data. I believe we do not know what this standard should be. There is a large body of knowledge regarding the computerization of other kinds of spatial data, but much of it is irrelevant. Geologic maps and geologic spatial data differ from other maps and spatial data in significant ways. We need many experiments with data structures and archival and retrieval mechanisms because we presently lack the empirical knowledge to prescribe an optimal standard.

But one of the great advantages of digital storage of spatial data is the ease with which such data can be transferred, transformed, and merged with other data sets. This ease is obtained only if data conform to common standards for format and content. We are thus faced with the need to encourage experimentation while creating some measure of standardization, not an easy task.

I suggest that those who would suggest standards offer an interim minimum standard to provide translatability between data systems and a measure of completeness. This has in part been done (see http://ncgmp.usgs.gov/ngmdbproject/standards/dataexch/dataexchinterim.txt). Beyond this, we should wait some period—perhaps five years—during which we support multiple experiments with data models, formats, and transfer standards. At the end of this period, the experiments should be reviewed and one or two best options adopted by the geologic mapping community.

SOME SUGGESTIONS FOR BETTER DATABASES

What should a geologic spatial database look like? I don't know, but in the hope of encouraging open discussion I make a few suggestions here. A common theme among these suggestions is that they are controversial: each is in opposition to recent practice by thoughtful geologists.

I begin with data quality. Quality of our "data" has two aspects, locational accuracy and attribute accuracy. Paper maps have described data quality explicitly (approximate versus exact contacts, queried faults and unit identifications, reliability diagrams) and implicitly (via map scale, map-series, e.g. Open-file versus MI- and GQ-map, and authorship). Limitations of printing technology and the human eye don't allow much more, but I believe that both geologists who make and re-make maps and users of these maps would benefit from further information. Digital media allow us to provide such information.

Data Quality 1: Explicit Statement of Precision (Locational Accuracy) for Each Data Particle

Digital spatial databases lack the intrinsic scale of paper maps. Yet as noted above, the geologic information recorded in the database is scale-sensitive. Some geologists have suggested that labelling digital spatial databases with the scale of the equivalent paper map is sufficient, but I find a scale statement inadequate on five counts:

1. Geologists may know how precisely the contacts on a 1:100,000-scale geologic map are located, but the county planner who uses our database most certainly does not!
2. A contact is attributed as "approximately located" at 1:24,000 scale. Is it precisely located at 1:62,500 scale? At 1:100,000? Are all "approximately located" features equally-well located? No. As the scale at which a database is plotted changes, how should the symbolization of each of the contacts and faults in it change?
3. The precision of our maps is intrinsically heterogenous. Some contacts are diffuse boundaries seen on air photos, some are located to a pin-point 6 paces NNE of a survey mark, and sometimes I straddle a contact but am in heavy timber and don't exactly know where I am. On a paper map (or a database where precision is denoted by a single scale) all precision of location more exact than that accomodated by the working scale is thrown away. Differing precisions less exact than defined by the working scale are not distinguished by our conventional symbology~all are "approximately located."
4. I have spent a decade mapping on 1:24,000-scale base maps for publication at 1:100,000 scale. Doing so is not significantly more expensive than mapping on a 1:100,000 base. Yet if a geologist of the next millenium wants to know where I was more precisely than the circa 100 meters allowed by the publication scale, she will have to repeat my expensive traverses. Is this a responsible use of our mapping funds? I think not, yet as long as we were restricted to paper maps we had no other choice. With the richness allowed by digital storage of spatial data, we can do better.
5. Users of our digital geology will plot it at larger scales and overlay it on more precisely located features. We cannot prevent this. We can provide information for this to be done intelligently. For example:

Database

arc #	LineType	EstimatedPrecision
36	fault	22 [meters]
37	contact, intrusive	100

Plotting instructions

```
Set MapScale = 24000

Set MapUnits = meters
Set MapPrecision = MapScale / 1000
...
Select arcs with EstimatedPrecision
  <= MapPrecision
Plot these arcs as continuous lines
Select arcs with (EstimatedPrecision
  > MapPrecision) and
  (EstimatedPrecision <=
  MapPrecision * 25)
Plot these arcs as dashed lines
Select arcs with EstimatedPrecision >
  MapPrecision * 25
Plot these arcs with question marks
...
```

Data Quality 2: Record Data Lineage as a Proxy for Attribute Accuracy

One could ask for clear distinction between what the geologist saw, what the geologist thought he saw, and what the geologist thought he would have seen if he could have seen. But as noted above, these distinctions are arbitrary divisions along a continuum of confidence in "data." Communicating the position on this continuum of a given element of data is difficult, for we do not have the necessary vocabulary. By this, I mean that we cannot quantify, even crudely, our answers to questions such as *How confident are we that a certain contact exists? How certain are we that it is a fault and not an unconformity? What is the likelihood that the structural-stratigraphic hypothesis embodied in this map is fundamentally flawed? Even if it is fundamentally flawed, the lithologic and structural information on the map may be useful; how useful is it?*

In the absence of the necessary vocabulary, I suggest we record the lineage of each data element as a crude proxy for attribute accuracy. Let me explain: Geologic spatial data on the 1:100,000-scale geologic maps that I know well come from a variety of sources: previous maps, new field work by many geologists and assistants, interpretation of different kinds of imagery (topography, aerial photographs, aeromagnetic maps, etc.), and inference. Our standard working procedure has been to bring all data—structural attitudes, fragments of observed contact or fault, spots of color on a field sheet to record an outcrop confidently assigned to a geologic unit—together on a single sheet of mylar and then ponder them. As we work—extending and finalizing contacts, inferring faults necessary to make sense of the distribution of geologic units, drawing cross-sections—it is useful to know where each datum comes from. Perhaps a particular strike-and-dip observation is at odds with the surrounding structure. If it is my observation, maybe it should be ignored, as at times I confuse dip directions. If it was made by a trusted colleague, maybe it is correct and my understanding of the surrounding structure needs changing.

I hope that some users of our geologic spatial databases also think this hard about the data within them. Such users will appreciate knowing what we, as creators, know about the lineage of the pieces that comprise the database. I suggest that each element (contact segment, polygon label, structural measurement, fossil age call) carry a lineage attribute. Example values for this attribute, from a 30'x60' compilation I am working on, are

attribute value	explanation
`RAH 24K field sheet`	from RA Haugerud field sheet
`WADGER OFR 89-3`	from McGroder et al., 1989, Washington Division of Geology and Earth Resources Open-file Report 1989-3
`RWT 24K field sheet`	from RW Tabor field sheet
`RAH 30m DEM`	interpreted by RA Haugerud from 30m digital elevation model
`RWT 616080B 571-34`	interpreted by RW Tabor from aerial photography, with project, roll, and frame num ber

Short Text Attributes; Limited Numbers of Values

Attributes of lines, points, and polygons that correspond to contacts, faults, and geologic units should be relatively short and should have a limited number of values. Short because a short attribute can always be written to a longer field when merging data into another database; longer attributes may have to be truncated or translated. Text (character) attributes are preferable to binary numeric attributes because they are immediately readable by humans; integers are OK. Attribute length must be a compromise: shorter attributes take less storage space yet longer attributes are more easily remembered and read by people. I suggest line-type attributes no more than 35 characters long and polygon-type attributes of no more than 10 characters.

Storage of long, frequently-repeated attribute values in a related table is one possible solution. Unfortunately, some experience suggests that as a community we are commonly not sufficiently sophisticated to recognize the existence of the related tables.

If the range of permitted values for a polygon-type or line-type is large, you should question whether you are making a <u>geologic</u> database—much of our art lies in simplifying the Earth into a small number of entities (contact, thrust fault, Quaternary alluvium, etc.) If your geologic spatial database for a 7.5' quadrangle has 800 different values for the polygon identifier, perhaps you have made a set of digital field notes~a useful thing to do, but not helpful for those who wish to operate on the database with the rules developed for geologic maps, or merge it with other databases.

Keep Faults with Unit-Polygons

Some GIS practitioners insist that polygon layers should not contain dangling (unjoined) lines, or lines that separate polygons with identical attributes. The presence of such lines becomes an obvious indication that a polygon layer is corrupt. Faults that terminate within a unit and faults that separate polygons of the same unit are thus not allowed in the unit-polygon layer. Several groups have followed this practice and produced databases with faults in a different layer than polygons. Viljoen (1997) presented arguments that this practice speeds cartography and generalization.

Nonetheless, I suggest that all faults be contained within the geologic-unit polygon coverage. (1) Faults are given meaning by the geologic units that they bound (cut). Removing faults from unit polygons destroys any possibility of automating the analysis of faults. (2) If there are reasons to remove faults from a polygon coverage, this is easily done. It is not always easy to restore faults. (3) Updating a dual-coverage database is likely to be incomplete or lead to inconsistencies.

Define Attribute Values and Conventions

One of the interesting things I have learned downloading geologic spatial data off the Web is that many databases are not comprehensible without reference to the equivalent published paper map. Geologic units are not defined! A polygon is attributed as MzTv, but one one has to go to the map library to learn that MzTv means Mesozoic-Tertiary volcanic rocks.

All values of attributes for which the meaning is not readily evident to the non-specialist should be defined. These definitions can take the form of a simple text file, such as

```
...
MzTv  Mesozoic-Tertiary volcanic rocks
      [description]
pTb   Pre-Tertiary ultrabasic rocks
      [description]
...
```

Such text files should be formatted so that they can be read into a database file.

Various conventions need to be specified: are strikes and trends of structural symbols measured from geographic or grid north? Or from theta = 0 at grid azimuth = 90 of the GIS software? Are azimuths reported in the clockwise degrees of the geologist, or the anti-clockwise degrees of the GIS software? In units other than degrees? Are you using the right-hand rule (dip to the right when facing in the strike direction)? If not, how is dip direction specified? What do you mean by foliation? Is "bedding" with or without an independent, at-the-site observation of facing direction? Are precision estimates 1 sigma, alpha95, or something else?

Authorship

A cartographer I know suggests that if you turn someone else's analog map into digital form, your role is akin to that of the "cartographer who spends years on a map and gets mentioned in 8-point type down in the bottom corner." I suggest that a translator, who gets second billing, is a better analog. In either case you are not the author. The user of the resulting geologic spatial database deserves to know who is responsible for the geology and who is responsible for whatever improvement or degradation has been introduced in the process of digitization. Both pieces of information should be readily evident from even the most cursory catalog listing.

For previously published maps, I suggest a title and authorship statement in the form

Digital version of <PAPER MAPNAME> by <PAPERMAP AUTHORS>, digital transcription by <DIGITAL AUTHORS>

This map previously published by <PAPER MAP PUBLISHER> as <PAPER MAP SERIES NAME/NUMBER>, <PAPERMAP PUBLICATION DATE>

<DIGITAL MAP PUBLISHER>, <DIGITAL MAP SERIES NAME/NUMBER>, <DIGITAL MAP DATE>

Burying authorship of the geology within an accompanying descriptive file, or in a dry metadata statement, is not helpful. New maps may be titled

<GEOLOGY OF QUADRANGLE XYZ> by <GEOLOGISTS>, digitization by <DIGITIZERS>

if agency policy allows. If the geologist and digitizer are the same, it is then appropriate to use

<GEOLOGY OF QUADRANGLE XYZ> by <DIGITALLY-LITERATE GEOLOGIST>

These recommendations pass muster with the librarians with whom I have discussed them and are similar to those of Reynolds and others (in U.S. Geological Survey, 1995).

ACKNOWLEDGMENTS

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Progress Toward Development of a Standard Geologic Map Data Model

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A geologic map data model addresses the concepts inherent in a geologic map, and how the information on such a map (including the map legend and unit descriptions) can be organized in a set of computer files. Whether or not the geologist formally recognizes it, each geologic map they produce, in paper or digital format, is supported by a data model. Whenever they gather geologic information, interpret it, and publish a geologic map, they have used a data model to organize their thoughts and information on the map. Attempts to standardize the organization and syntax of these map data models are worthwhile, helping the geoscience community to organize its thinking about what is contained on a geologic map, and increasing the utility of the maps. Scientists and the general public who use a GIS commonly obtain digital maps from various organizations and integrate them to address scientific or societal issues. Unless geologic maps are widely available in a standard format, their integration with other map themes and, therefore, their utility for addressing such issues is limited.

To propose a standard geologic map data model, in 1996 the USGS and the AASG formed the Geologic Map Data Model Working Group. The Working Group is composed of members of the USGS, the State Geological Surveys, and the Geological Survey of Canada. Although initiated by the requirements for a National Geologic Map Database (NGMDB) (see the project's Web site at http://ncgmp.usgs.gov/ngmdbproject/), the Group intended to propose a model that will be applicable, and acceptable, to the broader geoscience community. Following numerous presentations, discussions, and progress reports (for example, Raines and others, 1997), in October, 1997, a report describing the model was posted to the NGMDB project's Web site for public comment.

To permit thorough evaluation of the data model, the concepts and specifications described in that report must be translated into software tools that 1) organize and manage the geologic map information in the data model format, and 2) offer a user-friendly interface for data entry and analysis. The Working Group began building some prototype tools in mid-1997. Through presentations and discussions with potential users, the tools have been refined, and are now available for use. These tools are not intended as "production" tools, but are merely prototypes that will aid in the evaluation of the data model.

The data model and tools were presented for discussion in a special session at the Digital Mapping Techniques '98 workshop in late May, 1998. A number of attendees from the State geological surveys expressed interest in helping to refine the model and develop it into a geoscience-community standard. It was agreed that an extended period of evaluation among the States and USGS would begin as soon as possible.

At a three-day workshop in June, 1998, the first formal review of the data model was conducted. The workshop was attended by 28 members of the USGS, State geological surveys, and the Federal and Provincial surveys of Canada. An overview of the conceptual model and software tools was followed by a hands-on session and facilitated discussion. Throughout, the importance of discussion and consensus-building was emphasized; the process of developing this standard data model must be an open and inclusive one, because a proposed standard cannot actually function as a standard if it is not widely accepted and used. At this workshop, it was resolved to: 1) proceed with development of the data model and software tools; 2) broaden the participation in its further development; 3) begin the extended period of on-site evaluation at State, Provincial, and Federal surveys; and 4) work toward adoption of the data model as a standard.

To facilitate the review and discussion of the data model after the June workshop, a Web conference was developed (see http://geology.usgs.gov/dm/). Discussion topics include: 1) general conceptual issues related to the data model and geologic mapping; 2) specific problems with the data model; 3) development of standard geologic terms; and 4) software tools. This site, and the NGMDB project's Web site, also offer access to the data model report and software tools. All interested parties are invited to evaluate them, and to help us develop the prototype into a community standard that will serve both the scientist and general public.

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A Process for Utilizing Database Information to Produce High-Quality Direct-to-Printer Digital Map Files

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Technology today has made the business of cartography more dynamic and demanding than at any time in history. With the wide-scale use of Geographic Information Systems (GIS), digital mapping in real-world coordinates has become a standard tool for compilation, evaluation, analysis, modeling, and production.

The Indiana Geological Survey (IGS) at Indiana University has a full-time staff of five cartographers devoted to the creation of digital base maps, graphics, posters, slides, geologic maps, GIS coverages, and many other products to display geologic information. In the last ten years, methods of ink drawing and negative scribing have been replaced with digitizing boards, computers, scanners, and large-format plotters. With the advent of GIS, maps have become "intelligent"; many times in the past, a map could be out-of-date prior to being printed. By using GIS, we are able to print many products on-demand to represent the most current data; however, traditional methods of offset printing are still used to create lasting documents. Many printing houses have modernized their methods and now accept digital files which go either (1) directly to negative (on an imagesetter) and then are transferred to offset plate or (2) directly to offset plate. This process is known as CTP—Computer-To-Plate process. The IGS cartographers faced the challenge of finding a mechanism to combine digital base maps and GIS data into a digital file to be sent to a high-quality printing service. This paper will focus on one particular project and the methods we used to create the final digital product.

The intended product was an Indiana Geological Survey Special Report. This type of publication is traditionally a high-quality, peer-reviewed, technical study of a broad geographic area; final publication size is 8.5 by 11 inches. In this case, the subject matter was information concerning coal in Indiana. The author provided databases containing all pertinent coal information and ArcView 3.0 project files.

The lead cartographer on the project began by modifying the existing digital base map of Indiana, which was digitized in Universal Transverse Mercator (UTM) coordinates (using AutoCAD Release 13 software) from a mylar copy of the United States Geological Survey (USGS) 1978 base map of Indiana, scale 1:500,000. This modified file was kept in AutoCAD format. The ArcView (Version 3.0) files provided were opened to display the data as queried by the author. Shape files of the displayed themes were created for each figure in the publication. The shape files were then imported into ArcCAD (Release 11.4.1) software and displayed, creating vectors of the polygons, lines, and points. This file was merged with the base map and saved as an ArcCAD (AutoCAD) .DWG file to preserve all original data in UTM coordinates; this enabled the cartographer to recall the data in the event of loss or corruption of any future work files and also because CorelDraw automatically places all vectors in page coordinates. The file was then exported from ArcCAD in Digital Exchange Format (.DXF) and imported into CorelDraw 7.0 where final modifications were made for publication. Layer information from ArcCAD was maintained in CorelDraw which allowed the cartographer to more easily manipulate similar entities. Once all the vectored information was in CorelDraw, polygons and lines were modified; using the CMYK and/or Pantone color palettes, fills were added to polygons. For optimal readability in the final publication scale, line weights, styles, and colors were assigned to line entities; PostScript fonts were used for all text entities. The use of PostScript fonts is important when exporting files to printing houses; most printers use Macintosh technology to drive their devices. All IGS digital information is PC-based, using Windows 95 and NT technology. PostScript fonts will translate from PC to Macintosh platform without problematic font substitution. Proof plots were created to undergo a rigorous in-house checking system; necessary corrections were completed. The final digital files were exported in Encapsulated PostScript (EPS) format; for this particular publication, the EPS files were transmitted to the IGS editor who placed them into a desktop publishing application (PageMaker). Any large-format figures or map plates would go (in EPS format) directly to the printer. For this Special Report, the end product was created in PageMaker; all text and graphic images were integrated and exported in EPS format and sent to the printing house. For a summary of this process, see Figure 1.

It should be noted that other software combinations were tried; the best quality for the final product was achieved using the described method. ArcView has an export function to various vector formats, but the resulting vectors imported into both CorelDraw 7.0 and Adobe Illustrator 7.0 appeared as sharp-angled lines which were unacceptable. By using ArcCAD software, the integrity of the GIS data was maintained in UTM coordinates, but was exportable in smooth, high- quality vectors. Adobe Illustrator did not easily accept the DXF files and had less functionality for our purposes than did CorelDraw. The ArcCAD export in EPS format did not seem to overcome the problems Illustrator had with the import.

The state of modern mapping will probably always be in transition, owing to the rapidly advancing technology of GIS programs, graphics software, and new digital printing processes, such as CTP. The IGS has navigated the passage to all-digital production successfully, by using this method for translating GIS data sets into accurate, high-quality, offset-printed maps.

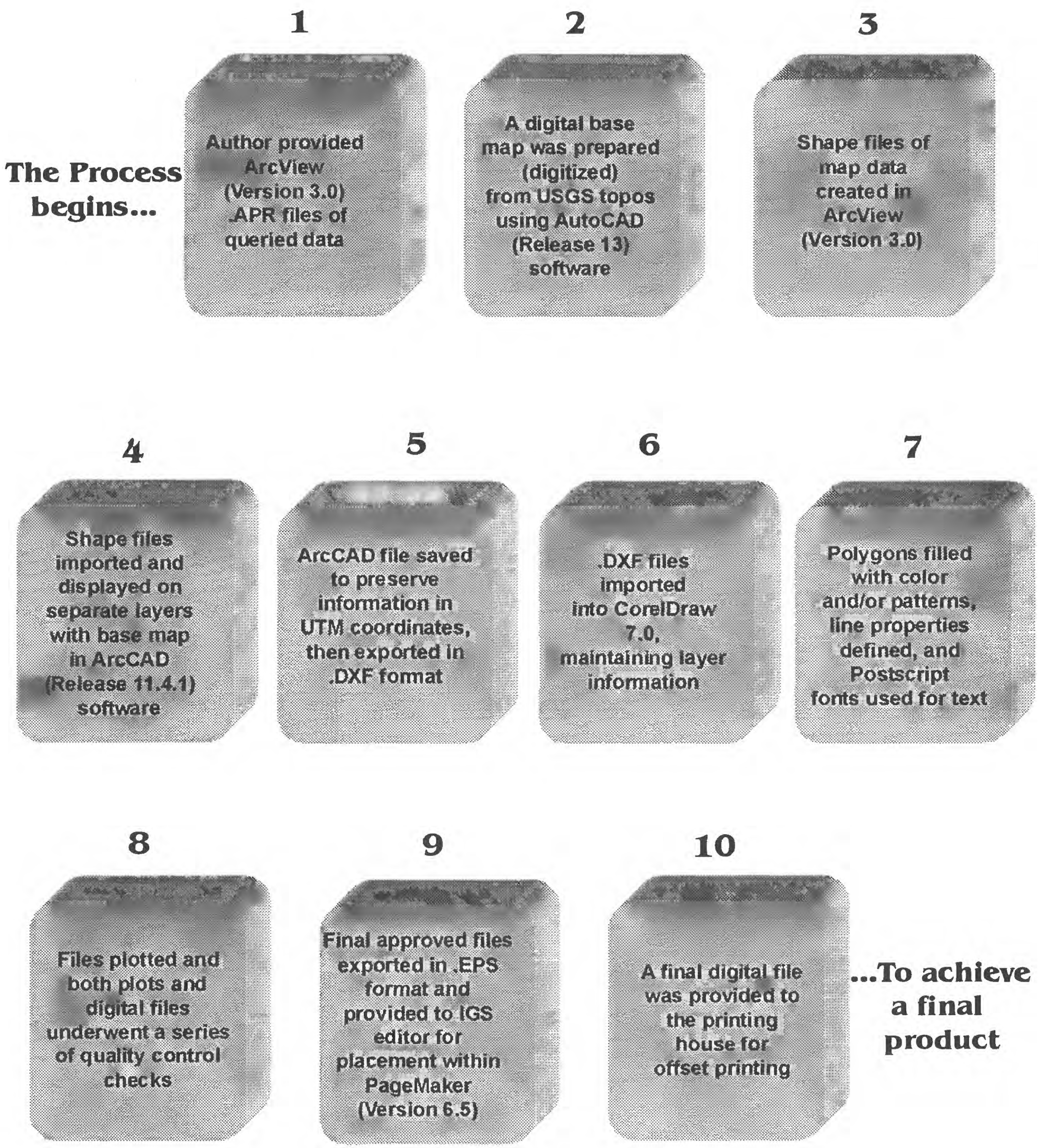

Figure 1. Summary of the process to produce maps for offset printing from GIS coverages.

Streamlining Quadrangle Map Production for On-Demand Publication

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BACKGROUND

New data acquisition and map production methods are being developed and implemented at the Illinois State Geological Survey (ISGS). These changes are in response to the initiation of a comprehensive 1:24,000-scale statewide geologic mapping program. In order to keep pace with rapid mapping progress, two basic data management needs were identified: the efficient acquisition and organization of high quality, accurate data, and time- and cost-effective production of 'on-demand' maps for review, presentation, and public distribution.

On-demand maps are plotted as the need arises rather than being printed in bulk. They have been fully reviewed and published in an ISGS map series. They may be updated as new geologic information becomes available. The graphics files for these maps are archived in a digital library making it easy for the information office to respond to map requests.

DATA CAPTURE

The primary software packages used for GIS data management, analyses, and cartographic production are Arc/Info and ArcView. This software is run on a distributed network of Unix workstations and PCs running WindowsNT (Krumm and others, 1997). Maps are plotted on Hewlett-Packard 750c plotters. Presently, GIS expertise at the ISGS is provided by a core group of ten GIS specialist/geologists, the Geospatial Analysis and Modeling Section (GAMS), plus a number of interns and student assistants.

In the past, mapped geologic data have been submitted for automation according to the methods or mapping 'style' of individual scientists. Mappers and field scientists routinely record type and distribution of geologic features and materials on United States Geological Survey (USGS) topographic maps and in notebooks in the field. Some scientists refine and transfer these raw data onto clean topographic sheets or a mylar (USGS green-line) base. Others provide field maps for digital conversion. Occasionally, reworked (some over-worked) 'pseudo maps' from drawings, images, or even xeroxed copies have been presented for conversion to a digital file. In all cases, the original data were archived at the discretion of the individual scientist.

Data have been hand-digitized using GTCO digitizing boards. Data were primarily input by GAMS members or student interns and assistants. While fully capable of capturing the data in a digital format, GIS staff might be unfamiliar with 1) complex geologic concepts, 2) the geologic characteristics of a particular area, 3) the needs of a particular study, or 4) the mapping notation and style of the individual field scientist. In addition, registration accuracy and efficiency of the individual digitizing the data likely varied from one data-entry session to the next.

Data were registered to the Lambert Conformal Conic projection at quadrangle corners that were extracted from a statewide quadrangle base file or generated using a custom program that automatically creates spatially rectified coverages - digital files that will contain the point, line, or areal data of the selected quadrangle area. RMS error for acceptable registration accuracy was 0.005 or less. After maps were digitized, they were plotted and checked against the original for consistency and completeness. Lines greater than one line width from the original were edited or redigitized. Files were then manually edited or digitally processed to remove redundant arcs, add missed contacts, close polygons, and smooth the final lines. The edited files were then coded according to the unit names assigned by the geologist on a map-by-map basis.

DATA CAPTURE SOLUTIONS

Historically, the majority of GIS users at the ISGS have worked within contract supported enclaves of 'GIS professionals' that were separated from the scientific staff. This resulted in a 'disconnect' between the science of geologic interpretation and the techniques of digital data capture. However, digital awareness is on the rise. GIS software has become easier to use, hardware/software costs are decreasing and personal computers now support robust digital processing. In addition, the Internet has enticed many more people to become computer literate. GIS software and techniques are now becoming a powerful tool for many professional geologists. Increasingly, ISGS field scientists, with support provided by GIS professionals, are entering and editing their own data. This approach to automation of geologic data reduces the number of iterations through which geologic data must pass from the scientists' interpretation to the final data file. Several potential sources of error are thereby minimized.

In view of the rise in digital awareness, the ISGS scientific staff is exploring a number of data entry methods. With ArcView software on the NT platform, geologists enter digital point locations, map unit distribution, and associated field notes using either georeferenced USGS Digital Raster Graphics (DRG) or Digital Line Graph (DLG) data as a base. Tablet registration variation is reduced because data are entered in the georeferenced environment (Universal Transverse Mercator (Zones 15 or 16) or Lambert Conformal Conic) in which they will reside. The ability to zoom in to small areas allows for better control as detailed information is entered. Updates, corrections and interpretative refinements are entered by the scientist 'on the fly'. Test plots may be sent directly from ArcView to a plotter for hardcopy output with the DRG as a base. Finally, geologic units, saved either as areal or line data files, are converted to Arc/Info format and merged into the final geologic database.

The ISGS Quaternary Geology Section is exploring the potential of using MapInfo in conjunction with Arc/Info. MapInfo offers some 'user friendly' options that are not currently available in ArcView. Unfortunately, MapInfo does not support the standard projection of most existing ISGS statewide data sets—Lambert feet.

Geologists have also been entering field notes using the Apple Newton hand-held Personal Digital Assistant. Field notes are written to the device which decrypts the handwritten entries. It "learns" to decode the users notes as frequency of use expands. The data are downloaded to a word processor each evening. A GPS link to tie these field notes to a specific location is being pursued.

The ISGS is in the process of acquiring a wide-format, high-resolution optical scanner. In the future, field maps may be scanned and georeferenced. Geologic data may then be digitized from the rectified image, converted from raster to vector format, or used in raster format. In addition to reducing some of the variability of digitizer coordinate registration, this will result in a digital record of the original mapping and field notation. The traditional method that involves digitizing, editing, and coding data from hand-drawn originals will continue as a method to address back-logged map automation and special situations.

DATA STRUCTURE

It is more efficient to manage and explain a single, consistent file structure than to manage and explain data developed for the particular needs of a specific project, as has been done previously. This fact became obvious in the course of data acquisition for two separate projects. The ISGS automated published geologic maps from twenty-four contiguous southern Illinois quadrangles. Mapped by fourteen different geologists with different mapping styles and methods of geologic interpretation, the data were difficult to join into a single, area-wide data set. At about the same time, ISGS personnel digitized stack unit geology for the fifteen quadrangles of Henry County (with Whiteside and Rock Island counties to be added later). These counties were mapped by a single individual. Not surprisingly, it was far easier to supervise map automation of the Henry County areas, and ultimately join them into a seamless data set.

Creating a seamless, universal data structure required development of an adjustable, standardized data model that would accomodate various types and styles of mapping. The new data structure maintains all unit names, definitions, abbreviations, and descriptive notations found on the individual maps, in a standardized format and sequence. It also includes a twelve-digit numeric code that can be parsed for basic geologic information as the data are read.

One of these extracted code segments of basic information is a four-digit geologic unit designation developed by Tom Buschbach in the 1970's and later updated by David Gross. The original coding system was based on the Pleistocene Stratigraphy of Illinois (Willman and Frye, 1970) and The Handbook of Illinois Stratigraphy (Willman and others, 1975). Age was tacitly implied by numeric sequence, younger units having smaller numbers. In the early 1980's, the ISGS Coal Section began using and customizing the four-digit coding system to automate their production of Coal Resource Maps.

Further mapping studies and evaluation of new data by other ISGS staff have reduced the efficacy of the original four-digit code. In particular, reclassification of surficial units in northeastern and central Illinois (Hansel and Johnson, 1996) and the previously mentioned bedrock mapping in southern Illinois have altered earlier stratigraphic nomenclature and/or generated new geologic units. Adding spaces to the original four-digit code provides room for change as ISGS staff continue to update and expand geologic interpretation.

Consistent numeric attribution provides coherent access to both old and new data sets. Coincidentally, it facilitates database development, map production, and data distribution. Existing geologic databases are available on-line at the Illinois Natural Resources Geospatial Data Clearinghouse (http://www.isgs.uiuc.edu/nsdihome/ISGSindex.html). The developing geologic databases will ultimately be used to produce interactive maps on the Internet. Seamless digital data from each comprehensive quadrangle mapping project may also be written to CDs that will include free viewing software such as Arc Explorer.

MAP PRODUCTION

In the past, ISGS maps were produced by two different methods. Illinois Geologic Quadrangle (IGQ) maps were produced using traditional methods by the Publications, Graphic Arts and Photography Section. The graphics for these select maps were manually drafted and sent out for plate preparation and printing. Maps expected to have a smaller audience were produced digitally by the Geospatial Analysis and Modeling Section. Some of these digital maps became ISGS-Open File publications, others were printed in the Illinois Map series. Still others, considered poster-type maps because of their limited distribution, were never published. All geologic maps are now produced using digital methods and software - mainly some combination of Arc/Info and CorelDraw. The few that are commercially printed are prepared in digital format.

The geology of approximately fifty-four quadrangles is presently being mapped under various federal and state mapping programs. Mapped for bedrock, Quaternary and/or stack-unit geology, twenty-seven of these quadrangles have geologic data in digital format and are awaiting publication.

In 1996, the Illinois Geologic Mapping Program (IGMaP) was initiated. IGMaP is a comprehensive mapping program involving development of suites of maps through in-depth analysis of the three-dimensional geology of each quadrangle by mapping teams. Basic maps for IGMaP include: the geologic materials at land surface (surficial geology), a three-dimensional portrayal of glacial/post-glacial sediments, the uppermost bedrock geology, a three-dimensional portrayal of bedrock materials, and a digital orthophoto that has been reclassified to a single thematic layer applicable to geologic interpretation. Structural geology, geologic unit isopachs, three-dimensional models, block diagrams, geologic columns, and cross sections may be added to the basic maps. Derivative maps included in all basic map sets are: groundwater resources, flood plains and/or flood prone areas, and aquifer sensitivity. Other derivative maps may be added at the discretion of the mapping team. Examples of these derivative maps might be: parent materials, geotechnical properties, geochemical properties, aggregate resources, coal resources, oil and gas resources, and so on.

Seven quadrangles are being mapped during fiscal year '97-'98 and another seven are scheduled for fiscal '98-'99. The expectation is that seven to fifteen maps for each of fourteen quadrangles will be ready for either review, presentation, or publication on-demand within the next two years in addition to maps produced under the USGS National Cooperative Geologic Mapping Program's STATEMAP component.

The Vincennes and Villa Grove Quadrangles were pilot studies for the new IGMaP initiative. To date, the Villa Grove Project has ten maps in preparation or review, and the Vincennes Project four. One GIS specialist participated in the compilation of data and production of maps for each quadrangle.

Several map publication procedures were defined during data development and production of these maps. Uniformity of appearance among the maps of a set was needed. A design format that could be customized was developed. Arc Macro Language programs (AMLs) for title and authorship, north arrow, scale bar, and location map modules and a general map layout were developed and placed in a general access directory. Both scientists and GIS specialists have adapted these programs to produce maps for the Vincennes and Villa Grove Quadrangles. This standardized format is also available as a CorelDraw template.

It became apparent that a vector-format base, produced in-house, was neither time-efficient nor practical. A USGS DRG was a viable alternative base for the Villa Grove Quadrangle. However, a number of limitations to the use of DRG data were encountered while working with the Vincennes Quadrangle data (Stiff, 1997), including high-relief, urban areas, supplementary contours, and poor raster coding. Vector-format DLG data was an option for some quadrangles (although the text layer is not available at the 1:24,000-scale), but not the Vincennes Quadrangle; topography, hydrology and roads were digitized from the Vincennes DRG on-line. This required a considerable investment of time and resources even without setting the text. Experiments with high-resolution scans of USGS topographic maps provided a viable raster-format base. These black and white scans may be used as a TIF images or converted to grid-format or polygon coverages depending upon plotting requirements for any particular map.

With the advent of IGQ and Illinois Map series geologic maps in digital format, higher levels of visual clarity and cartographic quality were required. Programs that produce the maps may be easily adjusted as new technology and output devices become available. Custom color and line sets were generated to produce accepted geologic symbols. New procedures to track mapping/map production progress for each quadrangle have been established.

THE FUTURE

In a perfect GIS-based cartographic world, all geologic data would be input on site by the investigating geologist who is the best and most accurate source of geologic interpretation at a particular site. These data would be imported into a single database with standardized attribute tables containing unit names, abbreviations, definitions and characteristics. Standardization would embed symbology in a database that would drive user-friendly access programs for digital map production and data delivery via the Internet. The resulting maps would be produced on 600 dpi plotters resulting in 'museum quality' output. We are working toward these goals.

Geologists using Arc/Info and ArcView have begun entering geologic data and producing some of their own maps. Standard attribute sets have been developed but the standard data structure has not been fully implemented survey-wide. There is a trade-off between field science and data accessibility. However, our work has shown that scientists can retain the freedom to map and interpret geology and simultaneously reduce the delay between data discovery and delivery. Production of 'on-demand' digital maps is becoming a viable reality -- too quickly for some, not quickly enough for others. Much remains to be worked out regarding acceptable quality.

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Other members of Geospatial Analysis and Modeling—Robert Krumm, Section Head, Curtis Abert, Chris Goldsmith, James Hester, Chris McGarry, Renee Nagy, Dan Nelson, Matt Riggs and Lisa Smith—provide a valuable resource for Arc/Info, ArcView, AML, three-dimensional modeling, graphics software and imaging, and database management.

In particular, Curtis Abert, the Villa Grove Project's GIS Specialist, expanded the possibilities for imagery on maps, implemented new digital mapping methods, and developed the first Quadrangle Overview and Index Plate, a poster-like presentation of a quadrangle's geologic package.

Thanks also to Curtis Abert, Dan Nelson, Jon Goodwin, and Richard Berg for reviewing this paper.

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Digital 1:100,000-Scale Map Boundary Files for Use with a Geologic Map Database

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ABSTRACT

The National Cooperative Geologic Mapping Program (NCGMP) of the U.S. Geological Survey (USGS) is charged with the establishment of a national digital geological map database for use at a scale of 1:100,000. The NCGMP needed to test the concept of a proposed data model for a geologic map database. The Greater Yellowstone Area (GYA) is a region in which such a geologic database, when integrated with other spatial data sets, would add much to the understanding to the GYA ecosystem. The GYA is an area that is five degrees in longitude and four degrees in latitude that is centered on Yellowstone National Park. The construction of a database from 1:100,000 geologic maps requires that the geographic boundaries of each 1:100,000-scale quadrangle map be accurately known. The USGS National Mapping Division (NMD) Digital Line Graph (DLG) data at 1:100,000 scale have inaccuracies of up to 5 meters that would cause numerous problems if the data were used uncorrected for map boundaries. No one group or agency has a standard set of quadrangle map boundary files or a standard procedure to generate such files that has been proposed as a national standard. The author proposes a 1:100,000-scale map boundary standard that calls for the generation of vertices every 2 seconds of latitude and longitude. This standard results in map boundaries for 30' by 60' 1:100,000-scale maps for the conterminous United States that contain 5400 vertices and are accurate in location to less than one meter.

INTRODUCTION

The Geologic Mapping Act of 1992, re-authorized in 1997, calls for the establishment of standards for digital geologic mapping both for paper plotting and for a computer-readable database. In August 1996, the Digital Geologic Mapping Committee of the Association of American State Geologists (AASG) and the U.S. Geological Survey (USGS), National Geologic Map Database Project (NGMDB) formed several working groups to devise standards and guidelines for various concepts that make up a geologic map in digital form. The NGMDB has a web site at URL:http://ncgmp.usgs.gov/ngmdbproject.

One of the working groups that were established has the responsibility to develop data capture standards. The development of map boundary files might logically be a part of their charter. In addition, the working group for the distribution of digital geologic maps might wish to study this problem as well.

THE NATURE OF THE PROBLEM

The problem of choosing a proper map boundary file grew in importance when I began to compile the first GYA geologic map as a pilot 1:100,000 geologic map database for the NGMDB. The pilot database will be used to supply geologic data for the GYA Science Initiative, a new part of the Integrated Natural Resources Science program

(INATURES) of the USGS. The GYA encompasses an area of five degrees in longitude (108 West to 113 West) and four degrees in latitude (42 North to 46 North). Forty 30' by 60' 1:100,000-scale quadrangle maps represent the GYA.

The NGMDB has a unique opportunity to test the results of the standards efforts on a database that is needed, and that will be integrated with other geospatial data sets for ecosystem management. There is an announced need to have databases that can be clipped along known boundaries (including quadrangle boundaries) for use with other data sets clipped out with the same map boundary. Geologic data in the database will need to be updated by removing out-of-date information and adding back new information.

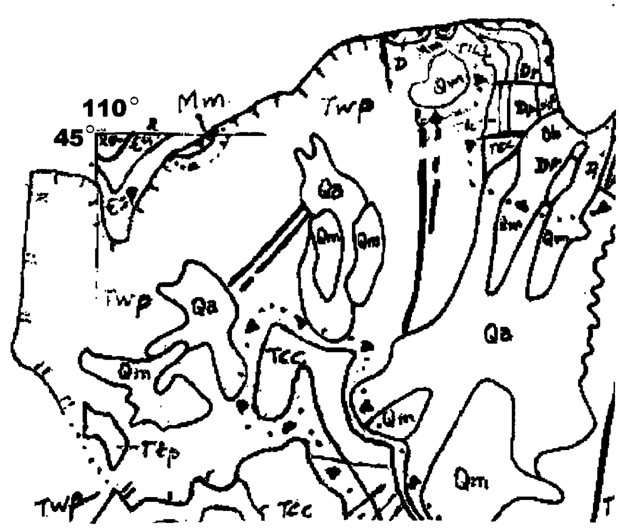

Figure 1. Northwestern corner of geologic map, enlarged from Pierce (1997).

CURRENT DIGITAL MAP BOUNDARY DATA

According to Jack Dangermond (1997) of ESRI (the producers of Arc/Info), accurate federal map digital files for map boundaries and other uses do not exist for the United States. A number of USGS geologic map compilers were asked by the author what files they used for map boundaries. The result of this informal survey indicated that each person has his or her own way of generating a map boundary. However, some state geological surveys within the USGS Central Region have had map boundary files generated by techniques established by other agencies of the state. Other problems have arisen in generating digital boundaries for 1:100,000-scale geologic maps. On one particular 1:100,000-scale published geologic map, one edge of the map is the boundary between two states rather than a line of constant longitude or latitude. Published geologic maps also come with some important geologic information outside the latitude and longitude boundaries of the map. For an example, see Figure 1.

CODY, WY 1:100,000 GEOLOGIC MAP

The Cody, WY 1:100,000-scale geologic map data exists as a film positive that was compiled by W.G. Pierce (1997) for the geologic map of the Cody 1-degree by 2-degree quadrangle. Time constraints preclude the use of larger scale maps as a source for the 1:100,000-scale map. A map boundary file was needed for this map because the data on the film positive included only the corner latitude and longitude tics (Figure 1.)

The most obvious set of digital files for use as boundary file data are the vector data contained in the Digital Line Graph (DLG) data produced by the USGS NMD. GIS specialists in the National Cooperative Geologic Mapping Program (NCGMP) of the Central Region have advised using map boundaries from the DLG files available from the Eros Data Center (EDC) of the NMD, in Sioux Falls, South Dakota. These digital map files are organized into an east and a west half for each 1:100,000 map. So to retrieve all of the DLG data for one layer for the Cody, Wyoming map, one must go to two directories for the data. I chose to get the DLG data called "boundaries," as these files contain, as a general rule a small number of vectors that need to be removed to obtain the boundary of the 1:100,000 map (Figure 2).

When this was done for the Cody, WY sheet and the lines defining the map boundary were assembled, the map corner coordinates were found to be in error from theoretical values by as much as three meters. I have learned that NMD digitizes all maps to an accuracy of 0.001". At a scale of 1:100,000, positions in the digital files are accurate to 2.54 meters. While these values are well within specifications, the values nevertheless meant that geologic data retrieved using these boundary data as a clip polygon can either be in more than one map, or in no map.

Depending upon the tolerances set for building map polygons at this scale, the boundary file may not close to a polygon and discrepancies in node coordinates could require the user to manually close the map boundary polygon. Using a boundary file of this quality along with those from adjoining maps would in all probability generate "sliver polygons" that would complicate building of a map database especially when contributions to the database come from different sources.

If a need might arise to use the 15-minute map unit data as it comes from the 1:100,000-scale DLG files, similar problems could arise. For the Cody DLG data, the corner coordinates of the 15' maps, where all four maps of a 30-minute cell meet, were found to disagree among themselves by as much as 3 meters (Figure 3). Without close checking, it is not possible to tell whether the map corners overlap or whether a sliver polygon belongs to no map.

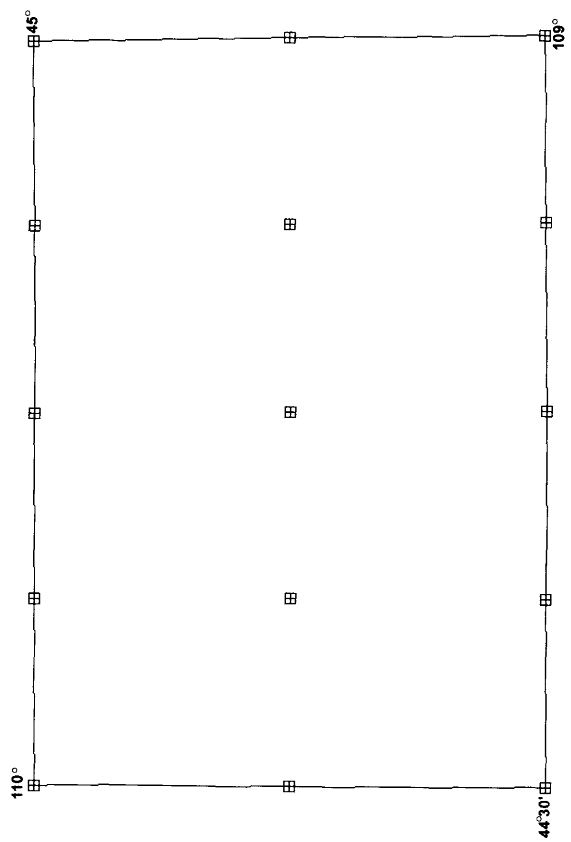

Figure 2. USGS DLG boundary file for Cody, WY. North is to the left.

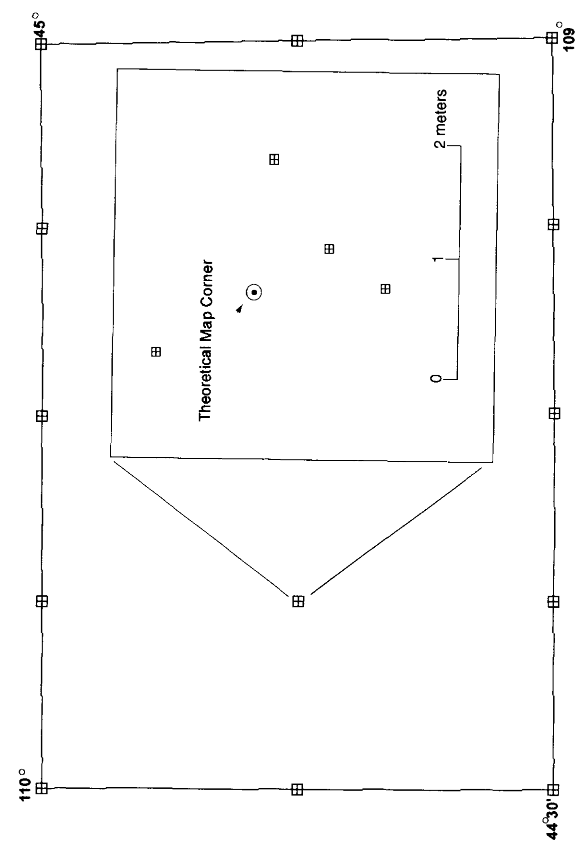

Figure 3. Four interior 15' corners in Cody, WY, DLG data.

ANALYSIS OF DIFFERENT BOUNDARY FILE GENERATION TECHNIQUES

The first step in comparing the DLG 1:100,000-map boundary file for Cody, WY to the theoretical values for coordinates along the boundary was to compute the projection coordinates of the corners of the map. For this purpose, a text file in Arc/Info GENERATE format was created with the closed polygon coordinates in decimal degrees. The data were built into an Arc/Info coverage as a polygon. The coverage was then projected to UTM, Zone 12 coordinates using the PROJECT command in Arc. The coordinates for the four map corners were extracted from the coverage and compared to those from the DLG-derived boundary. When the computed corner coordinates displayed on a CRT screen were compared to the coordinates from the DLG boundary with the Arc DISTANCE command, the difference between the theoretical values and the DLG coordinates was as large as three meters.

COMPUTING A MAP BOUNDARY FILE

A text file was made in Arc/Info GENERATE format that contained vertices every 1 minute, 15 seconds in both latitude and longitude, which gives vertices that coincide with 1:24,000-scale quadrangle corner and tic locations. The generated coverage after projection to UTM Zone 12 was compared graphically to the DLG-derived boundary. Differences as great as 2 meters separated the two boundaries (Figure 4). This particular segment of the DLG boundary file showed a break that was not closed by a CLEAN command with default tolerances set in Arc/Info. Upon further examination, the discrepancy between the two boundaries extended for about 13' of longitude. This means that if data from two Cody sources or data from Carter Mountain, WY, the 1:100,000-scale map immediately south of Cody were to be combined using different boundary files, very long but very thin sliver polygons could be created along the map boundary.

OTHER METHODS FOR BOUNDARY FILE GENERATION

The USGS NMD uses computer-generated boundaries for its new automated mapping process. NMD uses a vertex along a map boundary every 1 minute, 30 seconds regardless of the scale of the map. Other Arc/Info users have a technique that uses the values of the map corners in degrees of latitude and longitude to generate a closed polygon. Then in ARCEDIT the command DENSIFY, with the

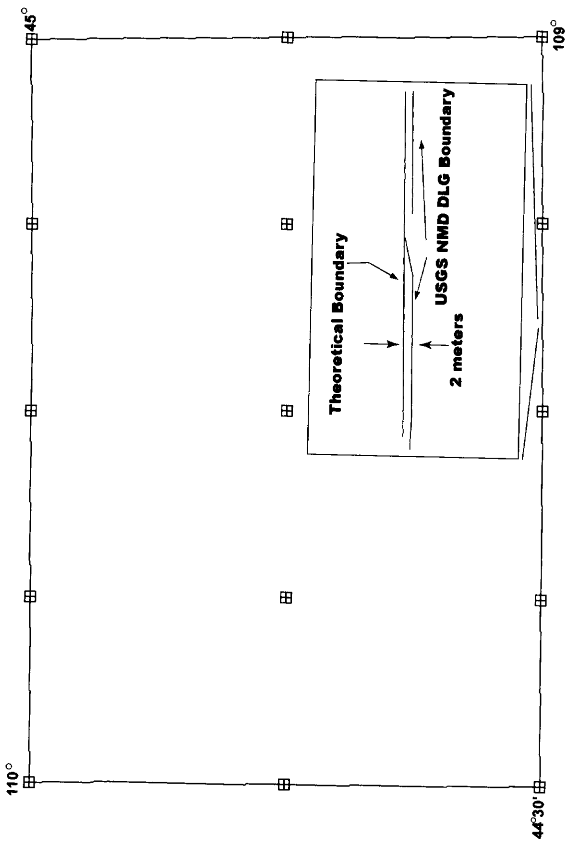

Figure 4. Difference between DLG and theoretical map boundary, Cody, WY.

default grain size, adds vertices along the map boundary every 0.001 degrees, which are about 80 meters apart at 44 degrees north latitude on a line of constant latitude.

A PROPOSAL FOR A STANDARD

The author proposes that map boundary files for 1:100,000-scale geologic maps be generated by inserting vertices every 2 seconds in both latitude and longitude. This would generate 5400 vertices in the boundary file that are about 22 meters apart at 44 degrees north latitude and would be, using single precision, accurate to less than one meter. In addition, this would allow new data from 1:24,000-scale maps to be added in with the map corners and interior tic marks at vertices on the 1:100,000-scale boundary. This proposal is a starting point from which a standard can be developed. The question now is what is the next step to arrive at standard 1:100,000-scale boundary files?

CONCLUSIONS

The author believes that to properly generate a geologic map database at a scale of 1:100,000, a standard set of boundary files needs to be developed. The proposed standard is a strawman meant to provoke discussion.

While this subject might seem trivial in the face of other standards problems, it is representative of the nuts-and-bolts problems that must be addressed by the adoption of reasonable standards that will allow the construction of a national geologic database. These issues need to be resolved quickly to allow use of accurate map boundaries so that work in progress in the geosciences will not have to be revised when standards are adopted. Adoption of reasonable standards for such items as map boundary files will allow the building of geoscience databases from multiple data sets covering the same area and the subsequent extraction of this data from a combined database.

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Visualization of Subsurface Geology from Wireline Logs

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INTRODUCTION

Geologic mapping in three dimensions has become a practical reality for the individual scientist with the evolution of powerful, low cost, high-speed workstations. Vast quantities of subsurface data are stored in wireline logs obtained from wells drilled in the search for petroleum, water, geothermal, and other natural resources. Visualization techniques use the processing power of the computer to merge various transformations of these multidimensional data with the natural interpretive abilities of the human visual system. 'Intelligence amplification' (Schroeder and others, 1998) is clearly manifest as visualization techniques open a window to our view of the subsurface geologic data contained in wireline logs.

This paper will discuss visualization of subsurface geology as achieved by COLORLITH, a software system developed at the Kansas Geological Survey in an effort to provide low-cost, high- resolution, interpretation, and visualization of well log data from a single well or multiple wells. The COLORLITH system is designed for use in the convenient environment of individual workstation technology. As raw data is transformed and presented anew to the scientist, student or lay public, dramatic visual perception occurs of the previously unseen lithologic or petrophysical variations that exist within and between wells in the subsurface. This visualization of well log data, combined with both vertical and horizontal scaling capabilities, facilitates the understanding of geologic problems at scales ranging from facies changes within the producing zones of an oil field to the broad structural framework of a region.

INITIAL CONCEPT

The COLORLITH concept and its initial versions were developed and published in the late 1980's (Collins and Doveton, 1986, 1989). When dealing with data from a single type of log (e.g., gamma ray), the full range of possible readings or measurements from the log is divided into intervals. Each interval is then associated with a specific hue in a color spectrum, or a specific intensity of a single hue (including shades of gray). An image of the data recorded in a well is then generated by a vertical succession of colors or hues corresponding to the succession of log readings with depth in the well. When multiple logs are available from a single well, visualization can take advantage of orthogonal color schemes (RGB, CMY, or HLS). An individual log, or a parameter derived from analysis of multiple logs, is assigned to each of the three colors in the selected scheme. Value intervals from each log or parameter are then linked to intensities of the assigned color, as in the case of a single log. At each recorded log depth, the resulting log image displays a hue derived by mixing the intensities calculated at that depth for the three orthogonal colors. Through careful selection of logs or parameters associated with the three color axes, a direct interpretation of lithology based on displayed colors is possible. The potentials for application of this type of data visualization have been discussed extensively (Collins and Doveton, 1988; Collins, Ross, and Brownrigg, 1995; Doveton, 1994).

Color imaging technology available at the time of its initial development limited the use of COLORLITH to presentation of individual well images at a computer teminal or required the use of very expensive electrostatic plotters for color presentation of regional cross sections. The software was also very computer system specific, running on a large minicomputer. Early versions of COLORLITH were tailored to nonstandard log data formats associated with digital log data available in Kansas at the time. Each of these factors limited general application of the system.

CURRENT CAPABILITIES

In its current version (Collins, 1997a, 1997b), the COLORLITH system is designed to run in UNIX workstation environments. Source code is written in FORTRAN77 and is suitable for compiling and execution on Windows 95 or Windows NT desktop systems. Input log data is expected in the Canadian Log ASCII Standard (LAS) format (Canadian Well Logging Society, 1991). Output from COLORLITH is written as a PostScript file that can be imported to a variety of graphics editors or converted to plot file formats for low-cost, high-resolution, color ink-jet plotters. COLORLITH is specifically designed to analyze and display gamma ray and lithodensity logs. Other logs are handled in a more generalized manner.

Gamma ray logs, treated independently of other log types, can be presented as well images using gray levels or a color spectrum to reflect gamma ray intensity. Figure 1 presents a regional cross section of Permian and Cretaceous formations spanning a geographic distance of 96 miles along Township 16S, from Range 43W in northwest Greeley County to Range 26W in northern Ness County, Kansas. Images for each of the 39 wells are derived from gamma ray logs. The narrow (10-20 ft) light band that begins at an elevation of 1200 feet above sea level in the west (left side of the cross section) and ends at an elevation of about 590 feet in the east corresponds to the Stone Corral Formation at the base of the Nippewalla Group in the Lower Permian. The broader (50-80 ft) light band that begins at an elevation of 3000 feet above sea level in the west and ends at about 2350 feet above sea level in the east corresponds to the Fort Hays Limestone Member of the Niobrara Chalk in the Upper Cretaceous. In this figure, the individual well images have been evenly spaced to emphasize vertical variations in lithology (and provide compact presentation). Alternative spacing options related to distance between wells are available.

Readings taken at each depth on the lithodensity logs are used to derive parameter values for apparent density (RHOmaa) and photoelectric absorption (Umaa). RHOmaa and Umaa parameters are respectively assigned to the red and green axes. Adding readings from the gamma ray log, assigned to the blue axis, creates an enhanced lithology color crossplot (Figure 2). COLORLITH uses the mix of primary color intensities associated with parameters in this orthogonal scheme to generate a color log image reflecting changes in lithology with depth. Figure 3 presents a comparison of two wells for which gray scale gamma ray and color lithology logs have been generated. The gamma ray and lithodensity log data is also displayed in the more conventional graph format. In Figure 3 the relative vertical positions of the two wells have been shifted from a sea level datum to a new datum at the top of the Lower Morrow Limestone. In the same manner, the structural cross-section of Figure 1 could be converted to a stratigraphic cross section.

At present a general routine is used to handle depth-related parameters derived from other analysis packages or data from single log types other than gamma ray. For a single log, the color spectrum or hue intensities are assigned to readings over a range of two standard deviations above or below the mean for that log. When multiple wells are visualized from these log types, the readings are first normalized as described below. Subroutines may be developed in the future to provide custom handling of additional logs commonly found in Kansas, including resistivity and SP data.

NORMALIZING DATA

Quality of regional cross section images derived from well log data can be improved (for purposes of stratigraphic evaluation) if the readings from individual logs are normalized in some manner. Occasionally readings for a log will have compressed or expanded ranges due to circumstances at the time of logging (possibly due to miscalibration). Using typical raw data, images for individual wells frequently appear to have a color shift relative to the images of surrounding wells. Even between separate logging runs on the same well, gamma ray readings may differ by more than 10%. Requirements for determining the precision of wireline logs are rarely included in logging contracts (Griffiths and Bakke, 1990).

In earlier versions of COLORLITH, normalization was based on prior calculations of regional trends in gamma ray intensity along selected geologic formations that persist across the section. This technique required picking the depth interval within each well (subscript j) for a formation with typically high readings (e.g. a dark shale) and a formation with typically low readings (a clean limestone). Average gamma ray readings were calculated for each interval ($avgrl_j$ and $avgrh_j$). Regional trends in average gamma ray readings as a function of location ($tgrl_j$ and $tgrh_j$) were calculated for the two formations. The difference between the low and high average readings and the corresponding trend values ($dgrl_j = tgrl_j - avgrl_j$; $dgrh_j = tgrh_j - avgrh_j$) were calculated. These were the basis for linear scaling, at each depth (subscript i) on the well log, of changes (dgr_{ij}) from the original gamma ray reading

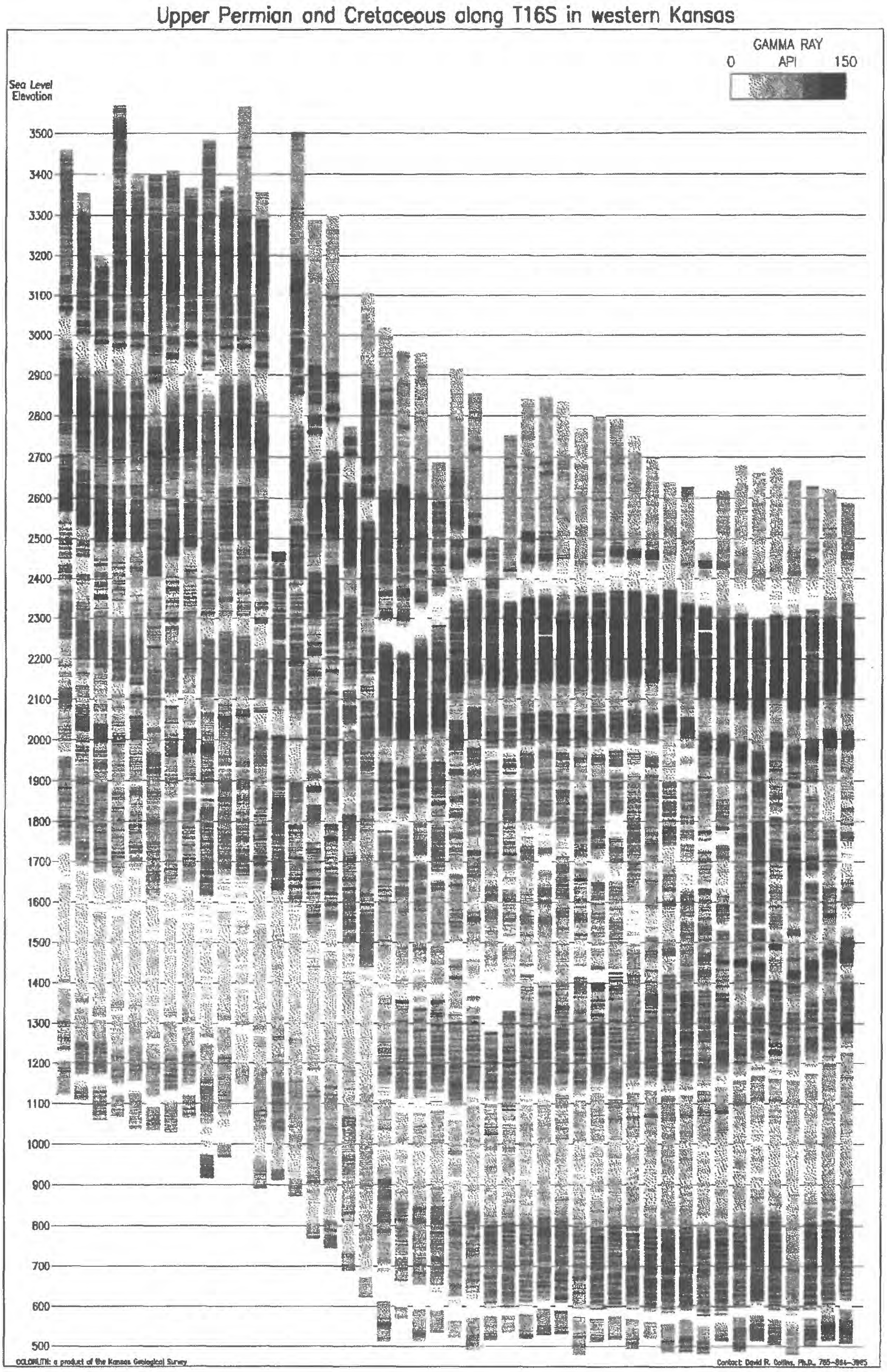

Figure 1. Gray scale images of gamma ray logs from 45 wells for visualization of regional subsurface geology.

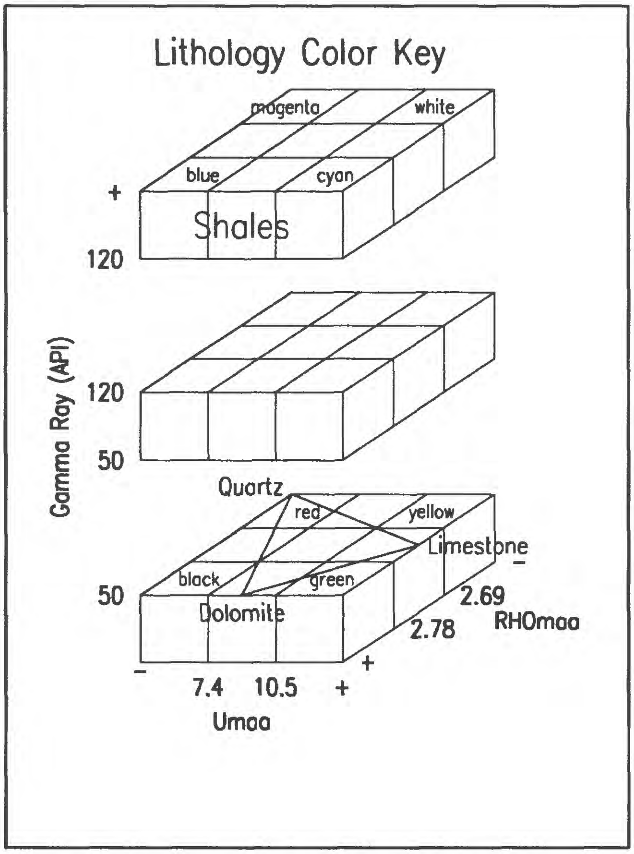

Figure 2. Color cube crossplot of lithology based on parameters derived from lithodensity log data.

(gr_{ij}) using the relationship: (dgr_{ij} - $dgrh_j$) / ($dgrl_j$ - $dgrh_j$) = (gr_{ij} - $avgrh_j$) / ($avgrl_j$ - $avgrh_j$). The resulting normalized gamma ray reading (ngr_{ij}) is then: $ngr_{ij} = gr_{ij} + dgr_{ij}$. The procedure was designed to eliminate locally anomalous logging results while accepting regional variation. Unfortunately, for large numbers of wells this can be a very time consuming and labor intensive process.

COLORLITH now incorporates a simpler process for normalization. In Figure 1, the gamma ray readings from all the wells are normalized in a fully automated procedure before calculating the shade of gray for each depth. The gamma ray log of a selected well (subscript ty) is used as a type log for the cross section. The mean (m_{ty}) and standard deviation (sd_{ty}) of gamma ray readings are calculated over the displayed interval of the type log. Then, for each well (subscript j) in the cross section, the mean (m_j) and standard deviation (sd_j) of the raw gamma readings are calculated over the displayed interval of well j. At each depth interval (subscript i) in well j, the normalized gamma ray reading (ngr_{ij}) is then calculated from the original gamma ray reading (gr_{ij}) by translating the mean to zero (subtracting m_j), scaling from the original standard deviation to the type standard deviation, and translating the mean to the type log mean (adding m_{ty}). The normalization function is expressed as follows: $ngr_{ij} = (gr_{ij} - m_j) X (sd_{ty}/sd_j) + m_{ty}$.

ALTERNATIVE VISUALIZATION TECHNIQUES

The interpretive power of visualization achieved by COLORLITH encouraged a related effort at the Kansas Geological Survey. Well log data from a regional sequence of wells have been converted to the format of seismic trace data (Carr and others, 1995). This permits display and analysis of the data on high-speed workstations using software and hardware designed for optimal handling of the extremely large data volumes associated with seismic exploration. Seismic processing systems are specifically designed to analyze data with high horizontal density but low vertical resolution. Well log data, in contrast, is characterized by very high vertical resolution but low vertical density. Caution is therefore advised when applying various data analysis and transformation capabilities of seismic processing systems to well log data.

Another promising, but untried, technique would utilize 3-D visualization capabilities of computer aided drafting (CAD) systems. Like the previous technique, CAD systems were not originally designed for interpretation of well log data. With CAD systems, well log data would be viewed as vertical columns in 3-D space. Conceptually, there would be no difference between a well drilled in the ground or a support column within a major convention center. The only major obstacle to this application may be limits to the ability of specific CAD systems to handle visualization of columns with patterns of bands on individual columns involving rapidly changing color and band widths. Such systems may view data from a single well as a stack of many cylindrical disks with changing colors and thickness. Once implemented, the geologist could walk through the subsurface just as an architect would walk a client through the virtual reality of a proposed building.

CONCLUSION

Wireline data from well logs adds one or more dimensions of measured physical parameters to the three dimensional measurements of position in space (more specifically, the subsurface). Visualization techniques are well suited to interpretation of data having many dimensions. These techniques involve data transformations and presentations in which new information is repeatedly created and modified to enhance the meaning of the original data. Visualization is an interactive process, that directly engages the scientist and the natural abilities of the human visual system to interpret spatial relationships (Schroeder and others, 1998).

This paper has described COLORLITH; a relatively simple system providing the individual scientist with a variety of options for visualization of well log data. The techniques are very general, based on widely used input data formats, and are easily adapted to other uses.

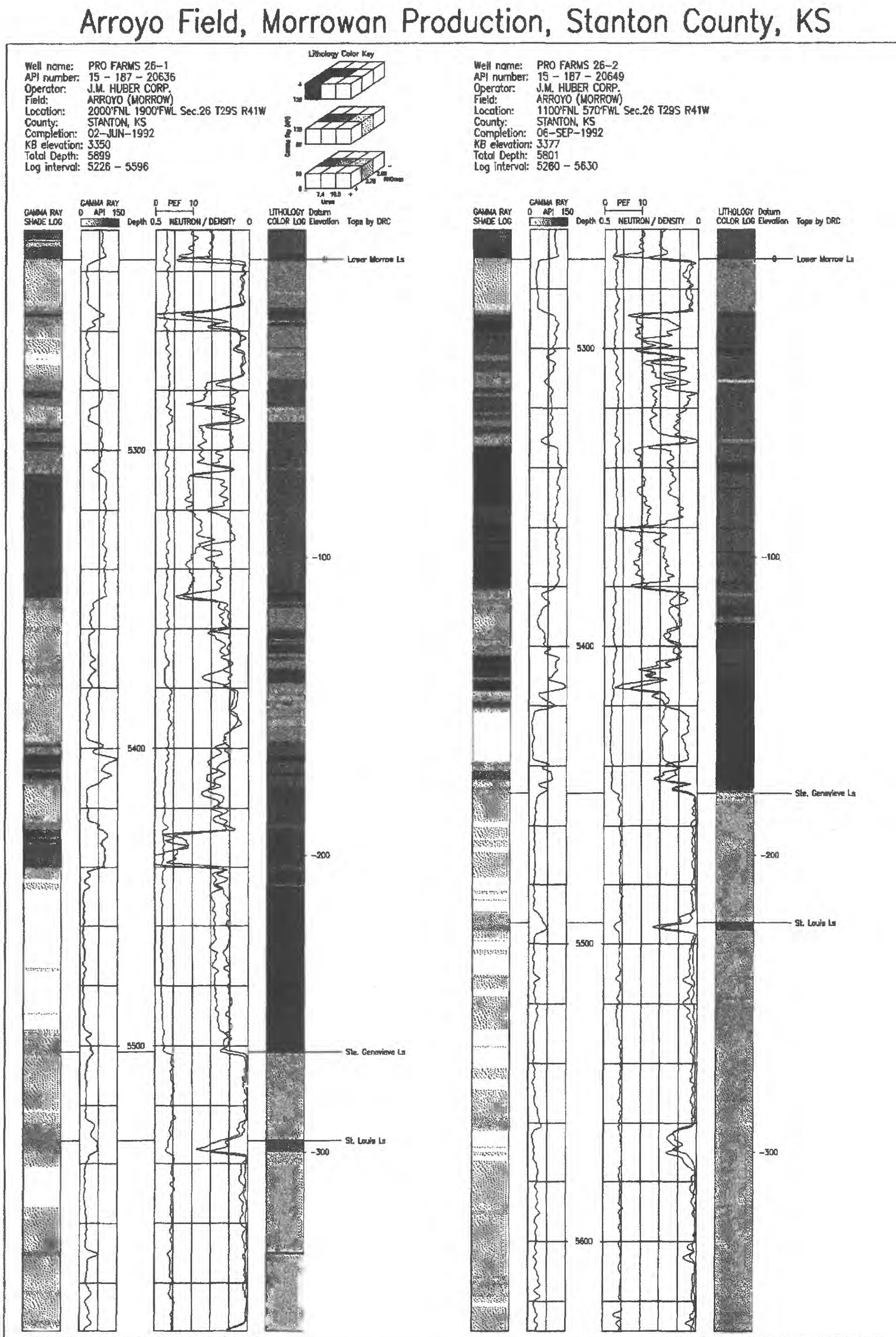

Figure 3. Visualization of subsurface variations in lithology through imaging of gamma ray and litho-density logs (shown in gray scale for publication) from two wells in the Arroyo Field (Morrowan production, Stanton County, KS). Depths are in feet.

Important objectives in the development of COLORLITH have been the focus on effective visualization techniques for the individual workstation while avoiding requirements for high end processing or reproduction technologies. There is significant potential for application of this system in both research and teaching.

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Building Digital Geologic Maps with a Contouring Program

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INTRODUCTION

The rapid development of computer hardware and software in recent years is changing the way geologists work. Geologists are rapidly discovering new ways to solve complex geologic problems and produce specialized products that better meet society's needs, as inexpensive and powerful computer hardware and software become increasingly commonplace. Mapping, a basic geologic tool, is no exception. Geologists are rapidly abandoning traditional mapping techniques in favor of digital techniques. The digital mapping techniques described herein work well when applied to the thin, gently dipping sedimentary rocks that typify Indiana's bedrock geology. Geologists mapping in similar geologic settings should be able to realize the same advantages using these techniques. Geologists mapping stratiform rocks that dip at steep angles should note that the techniques described herein presume that the mapped strata are nearly horizontal so stratigraphic thickness, which is measured normal to bedding, is regarded as equal to vertical thickness here. Geologists mapping igneous intrusions and metamorphic rocks or highly deformed sedimentary rocks where geologic contacts may overlap themselves will not be able to apply these techniques.

The Mineral Resources Section of the Indiana Geological Survey (IGS) is committed to making its data and interpretations available to industry, government, academia, and the general public and sees the abundance of sophisticated computer hardware and software now on the market as an obvious opportunity to better fulfill this commitment. The Mineral Resources Section has successfully completed a pilot project to test the feasibility of constructing geologic maps with a computer contouring program (Surfer 4.0 and 5.03). The pilot study-- an assessment of the mineral resources in Putnam County, Indiana-- used ordinary PC-computers and inexpensive software to economically create, modify, and update maps showing mineral resources and statistical summaries of the resource characteristics. The maps, created with the contouring program, can be exported to the IGS's geographic information system (GIS) (Arc/Info) for GIS applications.

The digital mapping technique described here is unique in that the digital geologic maps are computer-generated interpretations of geological observations stored in a database and are not digitized or scanned/vectorized versions of hand-drawn maps. The advantages of this technique are obvious: it eliminates the necessity of creating hand-drawn maps; the geologic observations and interpretations that underlie any part of any derivative map are easily located in the database; there are never discrepancies between the mapped extent, structure, and shape of a subcropping surface; and a second geologist using the same database and contouring procedures will obtain the same results.

The mapping techniques described here were developed and tested in an IGS-funded study of the mineral resources in Putnam County, Indiana. Putnam County is located about midway between Indianapolis and Terre Haute, and lies on the northeast flank of the Illinois Basin. Putnam County was selected for the pilot study because 1) it is a focus of mineral resource mining and exploration in Indiana; 2) the Mineral Resources Section of the IGS has access to abundant and varied data relating to the mineral resources of Putnam County; and 3) the geology of Putnam County is sufficiently complex to provide a challenging test of the database design and digital mapping techniques.

The pilot study has been completed and the Mineral Resources Section plans to proceed by proposing the development of mineral resource databases, computer-generated maps of mineral resource-bearing sedimentary rock units, computations of resource quantity and quality, and development of mineral resource GIS coverages for selected Indiana 1:100,000 scale quadrangles.

THE DATA

The computer mapping in Putnam County was based on a database developed from public domain geologic data stored in IGS files and at other public agencies. Data sources included the field notes and work maps of IGS geologists, published maps and reports, measured sections, descriptions of exposures in active and abandoned quarries, core descriptions, water well records, soils maps, petroleum exploration well records, and IGS seismic refraction records. Most of the outcrop and subsurface data sites include at least one direct observation of the spatial location of a stratigraphic boundary. Some sites record only indirect evidence such as isolated outcrops, float, or slope breaks. Indirect evidence was included in the database because it helps to establish the presence of a mappable unit at a spatial coordinate. The Putnam County Mineral Resource Database, used to map every mineral resource-bearing rock unit from the surface down to the Rockford Limestone (Mississippian), contains geologic data pertaining to 5,582 locations in and near Putnam County, 20,080 records of stratigraphic units found at those sites, and 20,333 descriptions of the lithologic constituents in those stratigraphic units.

The task of interpreting and computer-mapping sedimentary rock units with public domain data is complicated by variations in spatial and stratigraphic precision. Spatial imprecision occurs where location descriptions--especially vertical control-- are vague. Stratigraphic imprecision occurs where the description of a stratigraphic sequence contains inadequate subdivision and lithologic characterization. These two kinds of imprecision often occur independently. A driller's log, for example, may record a very precise spatial location for a vague and generalized description of a rock sequence. On the other hand, a detailed measured section recorded somewhere in a quarry may lack adequate spatial control. Either kind of data imprecision limits the precision of computer-mapping regardless of data density.

THE DATABASE

The Putnam County Mineral Resources Database is a relational database (Paradox 5.0) comprising three principal tables: the Location, Stratigraphy and Lithology Tables (Figure 1). Other tables in the database perform housekeeping functions such as value checking and storing special data.

The Location Table is the fundamental table in the database. Each record in this database table documents a location where geospatial data was recorded. Variables assign a unique location number, identify the data (source, type, etc.), contain descriptions of geographic location (township, range, section, quadrangle, etc.), and store a state plane coordinate for each data site.

Each record in the Stratigraphy Table documents a stratigraphic unit recorded at a data site. Figure 2 illustrates how stratigraphic unit numbers differentiate multiple units recorded at the same site. Variables in the Stratigraphy Table record the elevation of a unit's upper and lower boundary, allow the geologist to assign stratigraphic names and confidence levels to a unit and its upper and lower boundaries, and provide space to record sample information. Figure 2 illustrates how units in a hypothetical measured section would correspond with records in the Stratigraphy Table and how a conformable contact (Paoli Limestone/Bethel Formation) and an unconformable contact (Bethel Formation/Mansfield Formation) are entered in the Stratigraphy Table. Stratigraphic boundary positions are converted to elevations to make subsurface data, which reads from the surface downward, compatible with measured sections, which record unit thickness from the base of a section upward. Unit thickness is not stored in the database because the thickness of any interval can be computed by subtracting the appropriate upper and lower boundaries.

The Lithology Table stores information about the lithologic composition of stratigraphic units. Each record in this database table documents a lithologic description applied to a unit recorded in the Stratigraphy Table. Lithology numbers are assigned to each lithology to differentiate lithologic descriptions. Unit 99 in the hypothetical core description illustrated in Figure 3, for example, con-

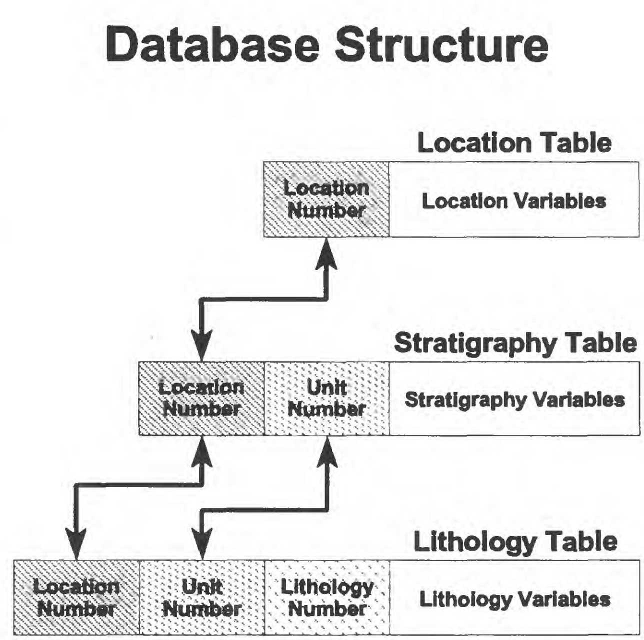
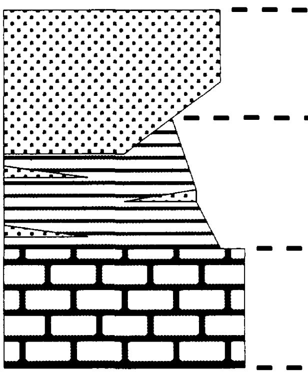


Figure 1. Structure of the Putnam County Mineral Resources Database.

Data Source

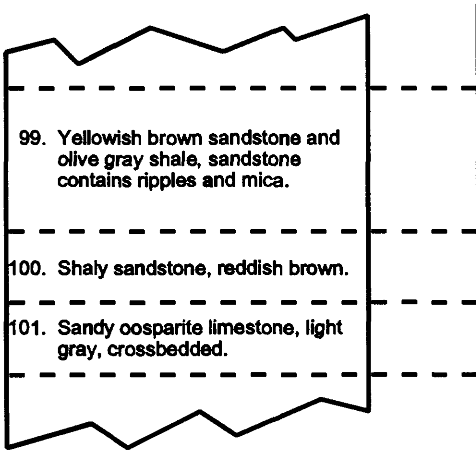


Stratigraphy Table

Location Num.	Unit	Unit Name	Top Name	Qual. (top)	Base Name	Qual. (base)	Top Elev.	Base Elev.	Samples
Loc-111	3	Mansfield Fm.			Mansfield Fm.	1	764.0	749.0	
Loc-111	2	Bethel Fm.			Bethel Fm.		749.0	719.0	
Loc-111	1	Paolli Ls.	Paoli Ls.	1		1	719.0	709.0	

Figure 2. Relationship between stratigraphic units in a geologic record and the Stratigraphy Table.

Data Source



Lithology Table

Location Num.	Unit	Lith. Num.	Lith. Percent	Lith. Modifier	Texture	Lithology	Color	Modifiers
Loc-222	99	1	50			sandstone	yelbrn	rpl mica
Loc-222	99	2	50			shale	olgry	
Loc-222	100	1	100	shaly		sandstone	rdbrn	
Loc-222	101	1	100	sandy	oosparite	limestone	ltgry	xbd

Figure 3. Relationship between lithologic descriptions in a geologic record and the Lithology Table.

sists of two interbedded lithologies-- sandstone and shale. The Lithology Table contains separate records for each of these lithologies.

Lithologic terminology from field notes, measured sections, core descriptions, drillers' logs, and water wells is entered directly into the database or with minor editorial changes. Variations in the detail of lithologic descriptions from different sources are handled by routing the descriptive terminology into three rock classification variables. Every lithologic description, from the simplest to the most detailed, includes an entry in the lithology variable. This variable stores rock names such as "limestone," "shale," or "sandstone," and non-lithologic terms such as "covered" or "core loss." More detailed rock descriptions, like the hypothetical core description illustrated in Figure 3, include terms like "shaly" or "calcareous" that modify the rock name. Unit 100 in Figure 3 illustrates how a lithologic modifier is handled in the database. The combination of common lithologic terms stored in the lithology variable and lithologic modifier variable designate approximate positions in a rock classification tetrahedron similar to the classification of mixed carbonate and siliciclastic sediments proposed by J. Mount (1985, p. 438) so this pair of variables is especially useful for characterizing the lithology of mapped units. The texture variable stores the petrographic terminology included in the most detailed lithologic descriptions. Unit 101 in Figure 3 illustrates how a petrographic term like "oosparite" is entered into the Lithology Table without usurping space reserved for simple rock names and lithologic modifiers. The color variable stores an abbreviated rock color term and the modifiers variable stores all other descriptive terms as space delimited abbreviations. Abbreviations used in the database are from Swanson (1981). The "ripples" and "mica" noted in the description of unit 99 in Figure 3 illustrate how abbreviations of descriptive terms are stored in the modifiers variable. Units that have a specific characteristic, such as "ripples" or "mica," or "brachiopods" are located by initiating a string search in the modifiers variable of the Lithology Table.

This simple database table structure accommodates variations in terminology and level of detail found in public domain rock descriptions and classifies the data so it is possible to retrieve simple or detailed lithologic summaries of mapped rock units and investigate composition trends.

MAPPING PROCEDURES

Geologists make geologic maps by collecting data, interpreting those data, and then drawing a geologic map that fits the data and expresses the interpretation. A geologist making a geologic map with a contouring program collects data (in a database), interprets those data, and creates grid files with the contouring program which are models of the surfaces that bound mappable geologic units. Bounding surfaces are modeled by selecting contouring algorithms, adjusting parameters within the algorithms, combining surfaces, and when necessary adding interpretive data to force the surface to comply with a geologic interpretation. Utilities in the contouring program allow the geologist to derive geologic maps by combining, intersecting, and contouring the gridded models of bounding surfaces.

Conformable contacts are relatively simple surfaces and can be gridded directly when control points are well distributed throughout the map area. Control points for most of the conformable contacts in Putnam County, however, tend to be clustered in the outcrop belt and shallow subsurface making it necessary to extrapolate these surfaces to the edges of the map area. Conformable contacts in Putnam County were extrapolated by retrieving data documenting the interval between the contact and a stratigraphically lower marker surface and extrapolating the isopach of this interval to the edges of the map area. Adding the isopach of the interval to structure on the stratigraphically lower marker surface yields a structure surface which conforms to the data and extrapolates the surface to the edges of the map.

The spatial and stratigraphic noise that affects the vertical positions of boundary surfaces is approximately equal in magnitude to the amplitude of small-scale folding and faulting in Putnam County. Smoothing (matrix smoothing or cubic spline grid extensions) that successfully damps this noise also eliminates the small-scale structural features. The selection of a final map scale for the Putnam County (1:250,000) reflects this limit in the data quality and consequent map detail.

Either the upper or lower bounding surface of a sedimentary rock unit may be complex due to the combined effects of outcrop, subcrop, and depositional irregularity. Such is the case in Putnam County where Mississippian resource-bearing rock units outcrop on the topographic surface, subcrop on the bedrock surface, subcrop on the sub-Pennsylvanian unconformity, and exhibit considerable depositional thickening and thinning.

Building gridded models of complex erosional surfaces generally requires several steps. The gridded model of the sub-Pennsylvanian unconformity in Putnam County, for example, was created by combining modeling that focuses on the trend of the unconformity's upland surface with modeling that focuses on the thalwegs and shape of the southwestward-trending erosional valleys in the unconformity surface.

Deriving a geologic contact from grid file models of bounding surfaces is a simple task with a contouring program. A geologic contact is the intersection between a bounding surface of a rock unit and a truncating surface such as the bedrock surface or an unconformity. A geologic contact line is derived by using grid math (a Surfer utility for defining a functional relationship between two grids with the same dimensions) to compute the difference between the elevation of the truncating surface and the bounding surface of the rock unit. The zero contour on the resultant grid is the contact line.

The thickness of a mapped rock unit is derived by using grid math to compute the difference between the composite upper bounding surface and the composite lower bounding surface of the unit within the mapped extent of the unit. In Putnam County the thickness of every mineral-resource-bearing Mississippian unit is a combination of the isopach thickness of the unit and the erosional effects of the topographic surface, the bedrock surface, and sub-Pennsylvanian unconformity.

The overburden on a mapped rock unit is derived by using grid math to compute the difference between the topographic surface and the upper bounding surface of the rock unit within the mapped extent of the rock unit.

FUTURE WORK

The Mineral Resources Section plans to continue the development of mineral resource databases, construction of computer-generated geologic maps, and mineral resource assessments. Experience gained through the Putnam County pilot study combined with an assessment of the quantity and quality of public domain data indicate that it would be practicable and cost effective to compile mineral resource data at a scale of 1:24,000 and construct computer-generated geologic maps at a scale of 1:100,000 using U.S. Geological Survey 30 X 60 minute quadrangles as the mapping base provided accurate digital elevation models (DEM's) with grid densities of approximately 200 ft or less are available. Each project proposal will include a request for modest external funding and support to supplement IGS resources. In return the IGS will deliver mineral resources databases, computer-generated resource maps, reports summarizing mineral resources, and GIS coverages of resources.

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Use of ArcView GIS for Geologic Surface Modeling— Preliminary Results from Subsurface Mapping in Southwest Florida

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INTRODUCTION

In March 1997, the Florida Geological Survey (FGS) began a regional subsurface geologic mapping project to identify the thickness and extent of several lithostratigraphic and hydrostratigraphic units in a five-county region of southwest Florida. More than 275 irregularly spaced control points for the maps include data from cores, cuttings, or geophysical logs (Figure 1). In addition to generation of structure contour and isopach maps, project goals include geographic information system (GIS) compatibility and 3-D visualization of the multiple subsurface horizons to be mapped. Application of the maps will include protection, regulation, and assessment of ground water and solid earth resources, rules enforcement, and frameworks for ground-water flow and aquifer vulnerability models.

The suite of Environmental Systems Research Institute (ESRI) software products, including Arc/Info and ArcView, are the standard for the Florida Department of Environmental Protection, the parent agency of the FGS. Recent additions and modifications to ArcView have made it more capable of surfacing, contouring, and 3-D functions that were once available only from within the Arc/Info environment. In ArcView GIS (version 3.0a), add-on software, called extensions, can be attached to an ArcView project. The Spatial Analyst extension provides the ability to generate grids and contours with a variety of data-interpolation methods. Three-dimensional visualization and generation of triangulated irregular networks are available through the 3-D Analyst extension. Functionality, compatibility, cost-effectiveness, relative ease of use, and user support are primary reasons for selection of ArcView GIS and these related extensions as the preferred application software for this mapping project.

This paper provides an introduction to surface modeling options available in ArcView GIS and related extensions in the context of contour map generation for the Southwest Florida Subsurface Mapping Project. The primary focus of this paper is to evaluate data interpolation methods readily available from ArcView GIS, with the Spatial Analyst and the 3-D Analyst extensions loaded. Effects of interpolation methods and related user-definable parameters (grid cell size, weights) on map accuracy and realistic surface representation are discussed.

Since the publication of last year's (1997) Digital Mapping Techniques Workshop Proceedings, our mapping database has only recently evolved to the point where an evaluation of contours from surface modeling methods is feasible. Although the database is not in final form, visualization of the effect of anomalous (or problematic) control points is useful toward evaluating various surface modeling scenarios. The structure contour maps presented herein are for illustrative purposes and are not to be considered finalized maps.

The top of the Oligocene Suwannee Limestone is considered representative and suitable to illustrate and evaluate differences in contours derived from various surface model interpolations. This unit is one of the 11 stratigraphic horizons to be eventually mapped. Elevations (relative to mean sea level) of the top of the unit compose the data set. Control points (i.e., data from wells) are, on average, 7 miles apart and the study area covers approximately 2,800 square miles. The Suwannee Limestone gently dips approximately 0.1 degree to the southwest. The surface of this unit is likely punctuated by karst features and is offset by faults within the southwest part of the study area. Although the maps being generated will include delineated faults, well data are not of sufficient density to accurately map karst features within the Suwannee Limestone surface.

BACKGROUND

Project Overview

The Southwest Florida Subsurface Mapping Project is a five-year project cooperative agreement between the FGS and the Southwest Florida Water Management District (SWFWMD). Work 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 completed, this database was used as a screen to select wells that would be appropriate control points for the subsurface mapping project. The mapping phase is presently funded at $80,000 per year and will continue through 2001. During each of the first three years, one-third of the approximately 10,000 square mile study area will be mapped. The fourth year will be used to add recently acquired well data throughout the region, resolve boundary issues, finalize structural interpretation, and review and publish the maps.

Products to be generated include structure contour and isopach maps for Eocene and younger lithostratigraphic units and all regionally extensive aquifer systems. Further details about the project, including database design, data accuracy issues, units to be mapped, and a related cross section project can be found in Arthur (1997). Of the more than 275 control points in the first mapping phase of the project, 74 are deep enough to penetrate the target stratigraphic unit discussed in this paper (Figure 1). The amount of well control increases for maps of shallower stratigraphic units in the regional mapping study.

Hardware

The GIS hardware resources at the FGS include two Pentium II 266 MHz computers, a Sun Microsystems Ultra2 workstation, two HDS x-terminals and an HP Designjet 750C plotter. The PCs are running Microsoft Windows 95, with 64Mb of RAM, 4Mb VRAM, and 3.5Gb hard drives. The Sun workstation is running Sun OS (release 5.5.1) with Solaris 2.5.1, two 167 MHz processors, 128 Mb RAM, and four 2.1Gb hard drives. All computers are on uninterruptible power supply/surge protection units. Images and analysis for this paper, however, were made using only one of the above-mentioned PCs and the plotter.

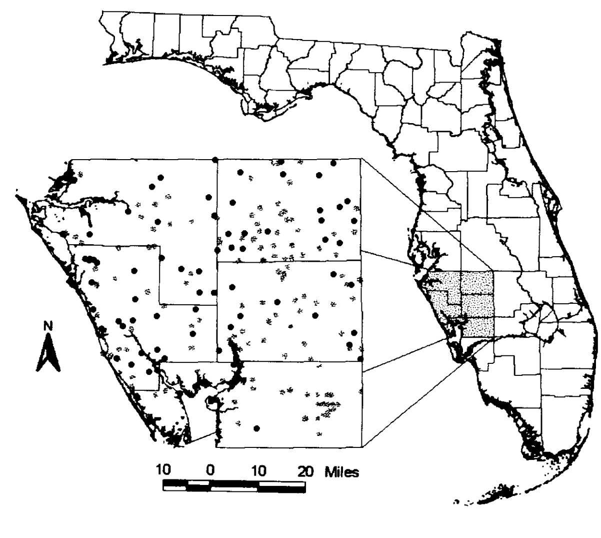

Figure 1. Location map showing borehole control points used for the Southwest Florida subsurface mapping project (black circles). Control data for mapping the top of the Suwannee Limestone are also shown (gray circles).

TIN VERSUS GRID

Tin

The triangulated irregular network (tin) is a surface representation based on randomly or irregularly spaced data points that have x, y, and z coordinates. A typical example of this coordinate system is longitude (x), latitude (y), and an elevation or concentration (z). Non-overlapping, connecting triangles are drawn between all data points where the data points (or control points) are the vertices. In its basic form, tin elevations are calculated based on linear regression between control points; contours are then drawn across the sides of the connected, tilting triangular plates. More advanced algorithms are discussed in Davis (1986) and Houlding (1994).

The tin surface model is available through the 3-D Analyst extension of ArcView GIS. There are very few parameters to set in this extension in order to generate and contour a tin. For the beginner, this is an asset; however, the more advanced user may require more menu-driven control over default values. Through Avenue script, which is a macro language for ArcView, more advanced parameter modification is possible.

Figure 2A shows a tin surface model representing the top of the Suwannee Limestone using the control points shown in Figure 1. The 3-D Analyst was used to create the model (Figure 2A), which is contoured at 25-foot intervals (Figure 2B). The wide distribution of control-point data yields a coarse, angular surface representation that is not desirable for structure contour and isopach maps; the

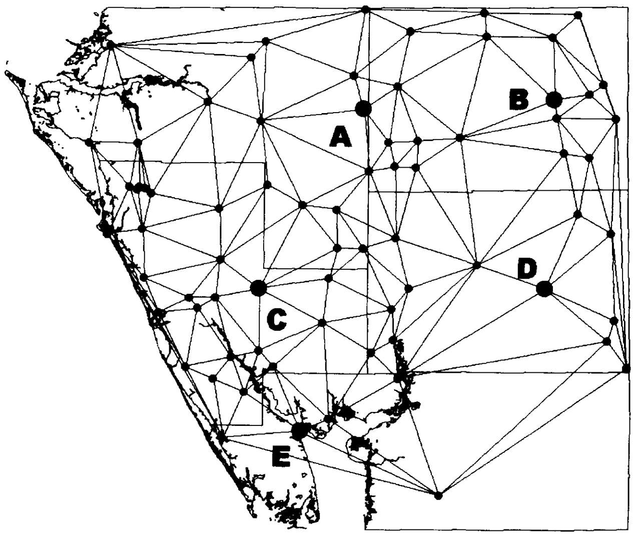

Figure 2A. Triangulated irregular network model based on control points in Figure 1. See Table 1 for reference to points labeled A through E.

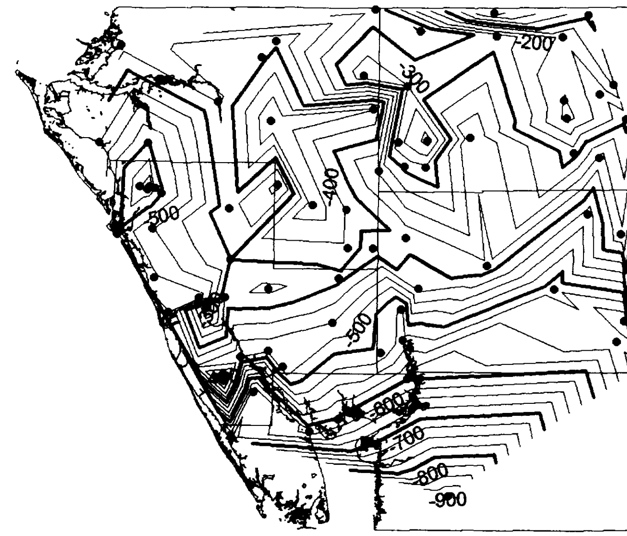

Figure 2B. Contours at 25-foot intervals for the tin model shown in Figure 2A.

angular contours do not accurately reflect the natural geologic environment. Two advantages with tin, however, are that it does not interpolate beyond the distribution of the data, and the map is forced to fit the control points. Tin is well suited for the purpose of generating a more highly resolved structure on which to drape or hang feature layers. One example would be to drape a surface geology coverage on a land surface elevation tin model.

Grid

A grid is comprised of a continuous array of discrete, uniform, square cells that are georeferenced (i.e., known location on the Earth's surface) and contain values that characterize the site. The values for each grid cell, for example, can include elevation, land use, geologic formations, population, or remotely sensed data. Grid cell values are calculated from a mathematical function relating the nearby control points. Usually this function is a form of a spatial average, where the closer control points are weighted more heavily than the more distant ones. Variants of this function include fitting a plane or curved surface to the control data in order to estimate grid cell values by means of regression or projection. Contours are then generated based on the regularly spaced grid cell values.

One disadvantage with grid-based contours is that control point data may not exactly fit the contours, because the contours are based on the calculated cell values that are one step removed from the control data. In contrast, contours from a tin surface model are based on the irregularly spaced control data. The advantage of grid interpolations is that complex surface model algorithms are better suited for a continuous array of evenly spaced data rather than an irregular spatial distribution.

Two grid interpolation functions, spline and inverse distance weighted (IDW), are available in pull down menus within the 3-D Analyst and the Spatial Analyst. The Spatial Analyst provides much more user control and spatial analysis tools than the 3-D Analyst. Additional interpolators available through both of these ArcView GIS extensions include kriging and trend. Note, however, that these two techniques are presently available only through Avenue scripts. For purposes herein, only the "menu-driven" options, spline and IDW, are discussed. As the mapping project database becomes more finalized and we become more proficient in writing Avenue scripts, we plan to evaluate kriging and trend interpolation methods for structure contour and isopach mapping within the ArcView GIS environment.

The inset below, slightly modified from the ArcView GIS Help screen (ESRI, 1990-1996), describes IDW and spline functions and variables:

> **IDW** - This interpolator assumes that each input [or control] point has a local influence that diminishes with distance. It weights the points closer to the processing cell greater than those farther away. A specified number of points [i.e., **nearest neighbor**], or optionally all points within a specified radius [i.e., **fixed radius**], can be used to determine the output value for each location. ... The power parameter in the IDW interpolation controls the significance of the surrounding points upon the interpolated value. A higher power results in less influence from distant points.
>
> The **Spline** interpolator is a general purpose interpolation method that fits a minimum-curvature surface to the control points. Conceptually, it is like bending a sheet of rubber to pass through the

points, while minimizing the total curvature of the surface. It fits a mathematical function to a specified number of nearest input points, while passing through the sample points. This method is best for gently varying surfaces such as elevation, water table heights, or pollution concentrations. It is not appropriate if there are large changes in the surface within a short horizontal distance, because it can overshoot estimated values. The **Regularized** method yields a smooth surface. The **Tension** method adjusts the stiffness of the surface according to the character of the modeled phenomenon. When you choose Regularized, the weight parameter defines the weight of the third derivatives of the surface in the curvature minimization expression. If you choose Tension, the **weight parameter** defines the weight of tension. The number of points parameter identifies the number of points per region used for local approximation.

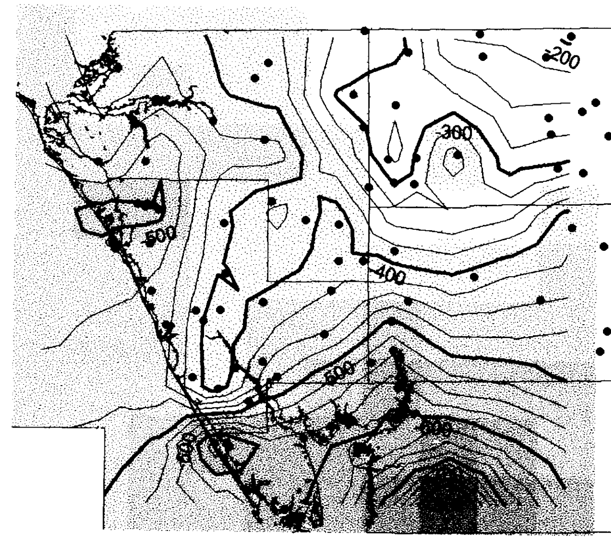

Figure 3. Contours (25-foot intervals) generated from IDW - nearest neighbor grid using a cell size of 7x7 miles; power = 2 (default). The pattern of gray shading shows the grid cell size.

CELL SIZE AND IDW

To illustrate the effect of different grid cell sizes on a surface model, the IDW - nearest neighbor method is used. Three cell sizes are selected: a cell size equal to the average spread of control data (7 miles; Figure 3), half of that distance (3.5 miles; Figure 4), and one order of magnitude less than the average spacing (0.7 mile-; Figure 5). The gray-shaded blocks provide an indication of grid cell size on which the model is based. Comparison of Figures 3, 4 and 5 reveals that a reduction in cell size causes an increase in surface irregularity whereby the surface is heavily controlled by anomalous data points (see especially Figure 5). Grid surface-model accuracy is qualitatively checked by comparing control point data to grid cell values at the same location (Table 1). Based on the cell size comparison using IDW - nearest neighbor, the model more accurately reflects control point data with decreasing cell size (Table 1).

For purposes of discussion and consistency, a cell size of 3.5x3.5 miles is used for subsequent comparative analysis in this paper. This cell size tends to smooth over local perturbations (e.g., possible karst features), while reflecting accurately the semi-regional and regional trends.

Figure 6 shows a surface model based on IDW - fixed radius, where the radius is 10.5 miles (i.e., 1.5 times the average control point spread). Figures 4 and 6 allow comparison of nearest neighbor and fixed radius IDW methods using identical cell sizes. The two methods yield similar, "geologically reasonable," and somewhat accurate surfaces; however, preliminary evaluation suggests that the fixed radius method is slightly more accurate (Table 1).

Table 1. Comparison of selected control-point values (feet MSL) and interpolated values from surface models contoured in Figures 2B [tin], 3 through 5 [IDW(nn - nearest neighbor)], 6 [IDW(fr - fixed radius)], 7 [Spline (tension)], and 8 [Spline (regularized)].

[Point label (PL) refers to labeled control points shown in Figure 2A; "abs" is absolute difference between actual and model values. PL "A" is an anomalous value included to demonstrate how each model handles abrupt surface changes]

PL	Actual value	tin value	IDW (nn)	abs	IDW (nn)	abs	IDW (nn)	abs	IDW (fr)	abs	Spline (tension)	abs	Spline (regularized)	abs
A	-451	-451	-353	98	-376	75	-448	3	-375	76	-465	14	-361	90
B	-223	-223	-247	24	-231	8	-223	0	-229	6	-234	11	-31	8
C	-369	-369	-426	57	-388	19	-370	1	-388	19	-377	8	-394	25
D	-520	-520	-432	88	-494	26	-520	0	-509	11	-511	9	-497	23
E	-615	-615	-585	30	-591	24	-612	3	-597	18	-629	14	-633	18
Cell size (miles)			7.0		3.5		0.7		3.5		3.5		3.5	

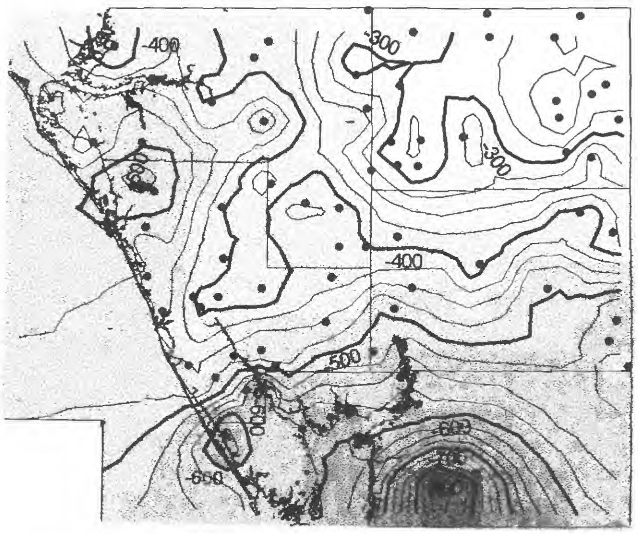

Figure 4. Contours (25-foot intervals) generated from IDW - nearest neighbor grid using a cell size of 3.5x3.5 miles; power = 2 (default). The pattern of gray shading shows the grid cell size.

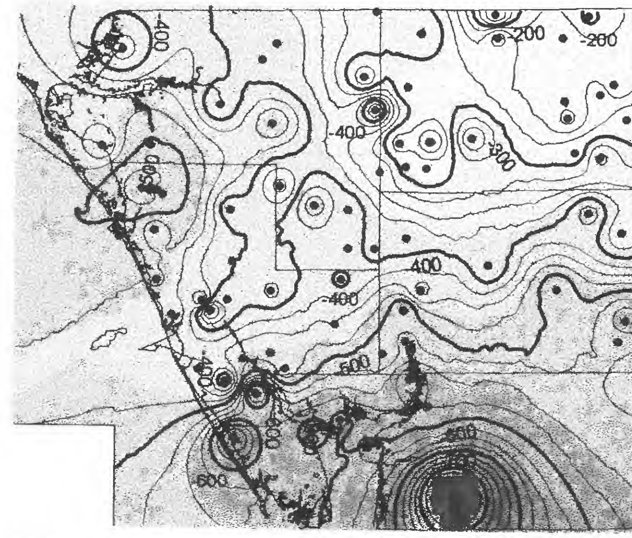

Figure 5. Contours (25-foot intervals) generated from IDW - nearest neighbor grid using a cell size of 0.7x0.7 miles; power = 2 (default). The pattern of gray shading shows the grid cell size.

Note, however, that the fixed radius method of IDW wil not interpolate across the entire map area (Figure 6) because it considers only data within a fixed distance from the grid cell value being calculated, rather than by a fixed number of control points. In other words, depending on the assigned fixed radius value, the method will not calculate a grid (or contour data) across large gaps in data. Both IDW methods yield somewhat pinched, angular contours. Moreover, this interpolation method tends to handle anomalous values as isolated highs and lows. This "bull's-eye" effect, a result of neighboring data influence that diminishes with distance, may be more appropriate for mapping karst features (if one has sufficient data control), or perhaps geophysical- and geochemical-data contouring.

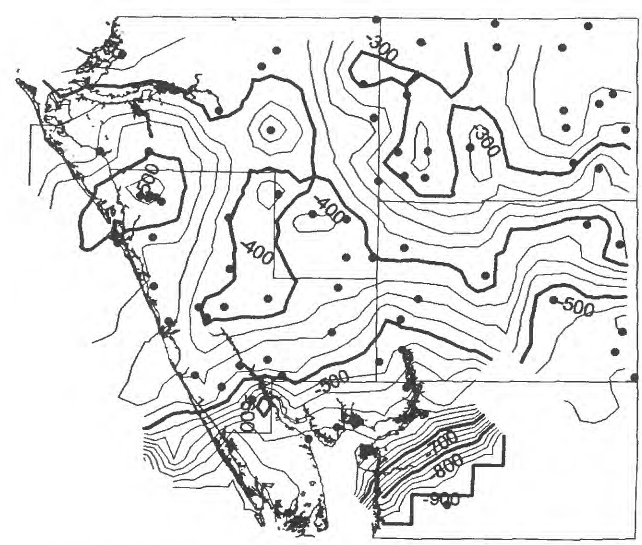

Figure 6. Contours (25-foot intervals) generated from IDW - fixed radius, where radius = 10.5 miles and cell size = 3.5x3.5 miles; power = 2 (default).

SPLINE

A series of spline surface models using the regularized and tension methods were generated by holding constant the grid cell size and number of points in order to evaluate effects of the weight parameter, which is defined above (see inset). With the regularized interpolator, the weight parameter tends to smooth the model surface when values are increased from the program default value of 0.1. This smoothing effect is observed to a lesser extent when weight values are decreased from the default value as well. Weight values less than 0.1 yield the most geologically reasonable interpretation as well as more accurate results.

As the weight parameter is increased using the tension model, the resulting surface becomes more smooth. In our data set, optimum weight values range from 0.001 to 1.0. In our data set and an ESRI data set, weight values <0.001 yield an unreasonable range of cell values and a very inaccurate, implausible surface.

Figures 7 and 8 show contoured surface models generated from the two spline methods, tension and regularized (respectively). The tension method results in a much more irregular surface than the regularized, however the tension yields a more accurate model when comparing grid cell values to the control points (Table 1). Moreover, the anomalous value (point label "A") is more accurately represented by the tension method. Although the tension method in this example creates overshooting (i.e., closed

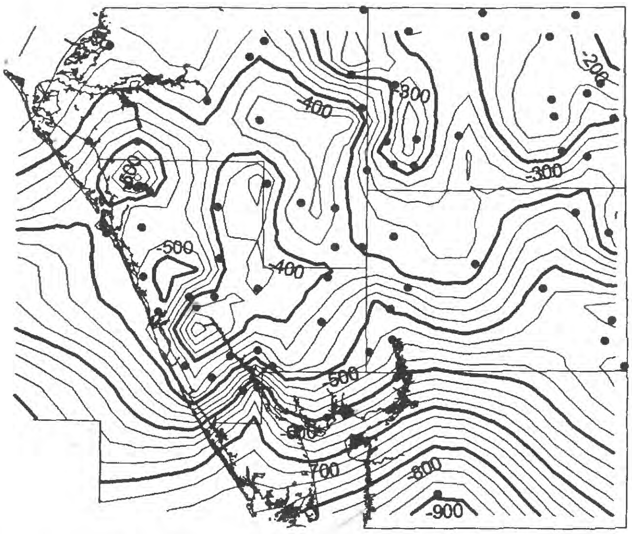

Figure 7. Contours (25-foot intervals) generated from spline - tension, using weight = 0.1, number of points = 12.

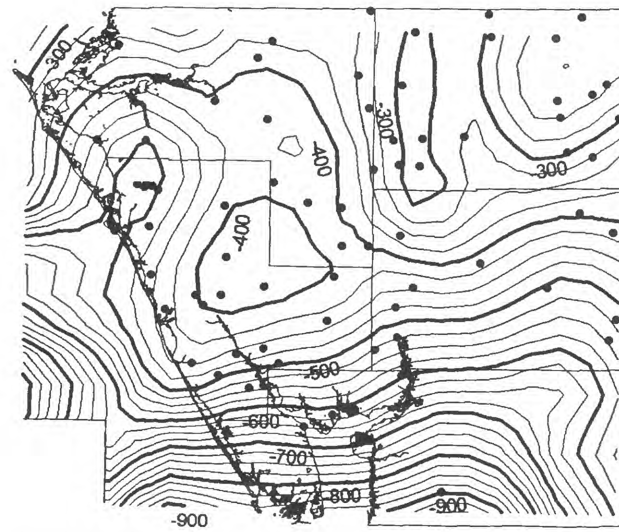

Figure 8. Contours (25-foot intervals) generated from spline - regularized, using weight = 100, number of points = 12.

contours around areas without control point data), this undesirable effect is more pronounced using the regularized method. With the Suwannee Limestone data set, as the weight value is increased to remove the overshooting effect, the spline - regularized method tends to smooth the data beyond acceptable accuracy levels.

SUMMARY

In summary, the contour methods explored in this paper produce results that range from smooth and relatively less accurate to less smooth and more accurate. For purposes of generating a series of structure contour and isopach maps of possibly karstic, faulted stratigraphic units in Florida, selection of a single interpolation method that reflects semi-regional to regional geological trends, yet accurately reflect the control data, becomes problematic. We will continue to explore these methods as our work continues. Based on the present analysis, the spline - tension interpolation method is preferred as it tends to reflect a more accurate, natural geologic surface.

FUTURE PLANS

As our database becomes larger and more refined, and we become more proficient at writing Avenue scripts, we will explore the trend and kriging methods as alternative surface models from which contour maps could be generated. Alternatives such as generating contours from tin surfaces that can then be smoothed will be considered as well. The ability to display and interpret multi-layered spatial data in three dimensions will facilitate aspects of the Southwest Florida Subsurface Mapping Project. These aspects include fault interpretation and lateral continuity of permeable zones within aquifer systems. Initial evaluation of the 3-D Analyst extension indicates that the program will be well suited to this task.

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A Method for Three-Dimensional Mapping

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INTRODUCTION

A cooperative geologic mapping project was conducted by the Illinois State Geological Survey (ISGS) and the United States Geological Survey (USGS) to map the Quaternary deposits in east-central Illinois (Figure 1). This area provides an excellent geologic setting to develop and test new techniques for mapping Quaternary deposits in three dimensions (i.e., mapping the thickness and distribution of geologic materials both at land surface and in the subsurface), because it has diverse Quaternary geology and thick, regional sand and gravel aquifers within a buried bedrock valley system (the Mahomet Bedrock Valley). The Mahomet Sand, which fills the deepest portions of the bedrock valley, is the thickest and most widespread glacial aquifer in the system. In addition, overlying the Mahomet Sand are sand and gravel units intercalated with fine-grained deposits. Where the Mahomet Sand is absent, these aquifers are important sources of water for rural farmsteads, communities, and industries. Decades ago, this bedrock valley commonly had been considered part of the Teays River System, a proposed westward-flowing drainage system formed during preglacial and glacial times, which was thought to extend across Illinois, Indiana, and Ohio, to West Virginia; however, modern evidence suggests that the Mahomet Bedrock Valley is a local drainage system in western Indiana and eastern Illinois that formed during early glaciations through alteration of the preglacial drainage patterns (Kempton and others, 1991).

In past studies, various surface and subsurface mapping techniques have been applied to all or parts of the map area. These include an ISGS statewide stack-unit map (Berg and Kempton, 1988) which shows the succession of geologic materials in their order of occurrence to a depth of 50 feet and a small-scale (1:1,000,000) USGS map of thickness and character of Quaternary deposits (Soller, 1993 and in press). Detailed geographic information system (GIS) mapping techniques (Berg and Abert, 1994, and McLean and others, 1997) also were developed for the region.

GLACIAL GEOLOGY OF THE STUDY AREA

The total glacial drift succession is locally greater than 500 feet thick in the Mahomet Bedrock Valley, whereas the

Figure 1. Location of the map area, east-central Illinois.

bedrock uplands are covered by 50 to 300 feet of glacial sediments (Figure 2). These deposits are a complex sequence of diamictons and sands and gravels associated with multiple glaciations and buried soils associated with interglaciations. [A diamicton is a mixture of clay, silt, sand, gravel, and boulders that, if of glacial origin, is commonly referred to as till; although most of the diamictons in the map area are interpreted as till, we use diamicton, the more general descriptor.] From top to bottom, the sediments are grouped into three major lithostratigraphic units (Figure 3): the interfingering Mason and Wedron Groups and overlying Cahokia Formation alluvium (Wisconsin and Hudson Episodes, respectively), the Glasford Formation (Illinois Episode), and the Banner Formation (pre-Illinois Episode). The Glasford and Banner Formations are, respectively, separated into two and three subunits.

Figure 2. Thickness of glacial sediments, with minor, overlying sediment of non-glacial origin. Dark gray = sediment thickness is 0 to 150'; medium gray = 150 to 250'; light gray = more than 250'. Sediments overlie a bedrock surface of moderate relief; thicker sediments occur in the Mahomet Bedrock Valley and beneath Wedron Group moraines, and somewhat thinner sediments occur on the bedrock uplands. The Mahomet Bedrock Valley is a pre-glacial and early-glacial drainage system in the region (see Kempton and others, 1991). North is to top of map.

The middle Banner Formation subunit is mostly composed of the Mahomet Sand, and is confined to the area of the Mahomet Bedrock Valley, generally trending east-west across the map area, and to the Mackinaw Bedrock Valley to the west. For each of these major sedimentary units and subunits, elevation and thickness maps were developed at 1;250,000-scale for presentation at 1:500,000-scale, as described below. A perspective view of the top of the middle Banner Formation and of the bedrock surface is shown in Figure 4.

MAPPING THE DEPOSITS

Over many years, an extensive ISGS collection of records from wells and borings has been used to interpret age relationships and lithology for geologic mapping and groundwater studies in cooperation with local, State, and Federal partners. A cornerstone of our current effort was identifying a set of "key stratigraphic control points" (Kempton, 1990) from the ISGS collection of subsurface data. From these control points, we built a stratigraphic database. We identified 177 such borehole records, which is about 1.5 per township. These data served as principal control for constructing maps of each stratigraphic unit.

Because of the thick sequence of geologic materials in the region, and the paucity of exposures, subsurface information was a critical part of the geologic mapping project. Subsurface information formed the basis for most geologic

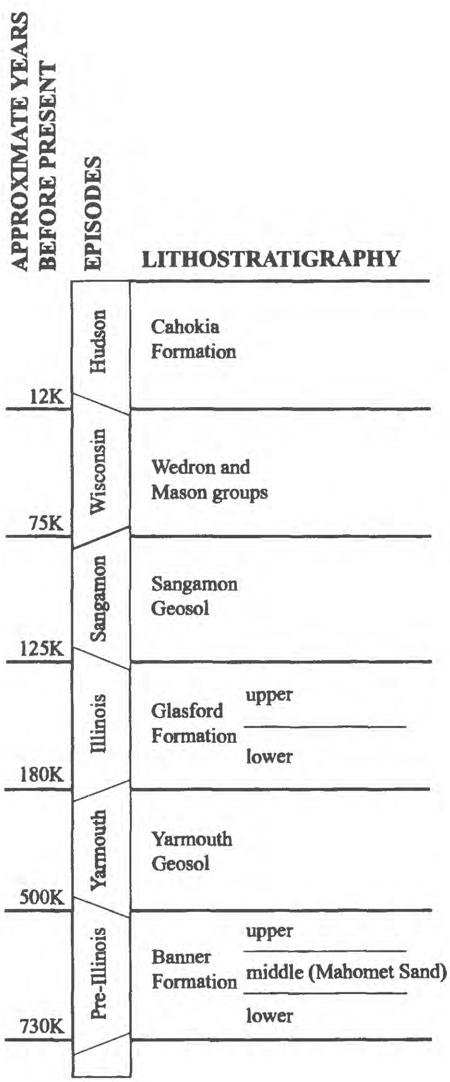

Figure 3. Diagrammatic stratigraphic column of glacigenic sediments in east-central Illinois. The Hudson Episode postdates glaciation. Use of geologic and stratigraphic names and intervals in this report are those accepted by the Illinois State Geological Survey. Years before present is approximate, and is provided only as a general guide.

maps of the region and for the evolution of concepts of the geologic history of the Mahomet Bedrock Valley system and the origin of the sediment cover that incrementally buried it (for example, Horberg, 1953; Kempton and others, 1991; Herzog and others, 1995; and Larson and others, 1997). It was a primary goal of our study to build upon the findings of prior investigations, using newly refined stratigraphic data to produce updated, revised maps that could be used for various computer-aided applications such as ground-water modeling.

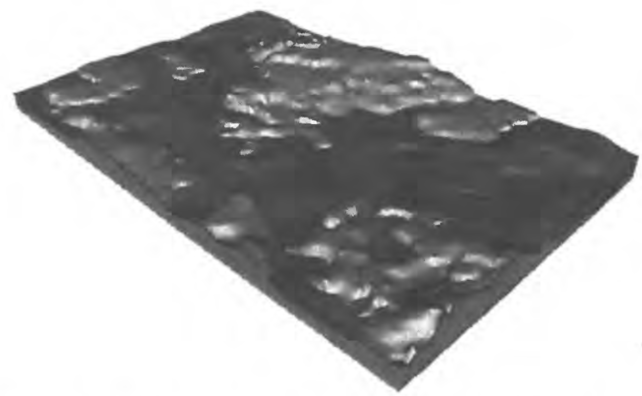

Figure 4. Perspective view of the top of Mahomet Sand (middle Banner Formation) and bedrock surfaces. The Mahomet Sand is the dark surface within Mahomet Bedrock Valley (see Figure 2 for location). This image was developed in EarthVision software, from 2-D grids of stratigraphic horizons created in Arc/Info. North is toward the upper right of the diagram.

Another goal was to produce these maps using digital methods because counties, planning agencies, and other entities increasingly are using GIS to support decisionmaking and planning. Because computer-based mapping of deposits in three dimensions is not yet a common, well-established practice, we developed GIS-based methods to integrate point (key stratigraphic control data) and areal (geologic mapping) data. These methods are only briefly described here, and will be detailed on a forthcoming USGS map (D.R. Soller, S.D. Price, R.C. Berg, and J.P. Kempton, unpublished data) and in a forthcoming publication.

Maps constructed using GIS techniques are in some ways easier to produce than conventional, hand-drawn maps. For example, map revision and generation of color proofs is done more quickly in a GIS. For other needs, however, conventional mapping can be easier and less time-consuming. For example, consider an area with thin, discontinuous units. While creating a hand-drawn set of maps showing elevation of the top of each unit, the geologist will attempt to ensure, visually, that a unit's elevation contour lines do not conflict with those of overlying and underlying units (for example, that the elevation of a lower unit does not surpass an upper unit). In so doing, the geologist produces an internally consistent, three-dimensional geologic model and set of maps for a region.

With GIS techniques, maps are produced that are similar in appearance to hand-drawn maps; to the eye, each elevation map may appear to not conflict with the elevation maps of other stratigraphic units. However, to develop a truly internally consistent set of maps, the maps are processed into a raster (gridded) format, as described below. Then, conflicts in elevation between horizons (and larger conflicts across several horizons) are easy to detect.

Correcting those conflicts is not, however, a trivial undertaking. A significant effort was spent to develop a set of maps which adhered to our models for glacio-fluvial deposition and erosional history.

Creating a Vector Map

For each of six primary stratigraphic units and two minor sand layers, we created three products: a three-dimensional perspective view, an elevation map of the upper surface, and a thickness map. Our mapping of each unit was an iterative process that, through re-examination of stratigraphic data and maps, gradually refined our understanding of the vertical and lateral distribution of each unit. To map a unit, we first plotted the stratigraphic control data, then prepared a hand-contoured map based on the data and an understanding of the regional distribution of the materials and geologic history (for example, the middle Banner Formation had a glacio-fluvial origin and was confined to bedrock valleys). The map was then scanned and a vector map of the linework was created.

Converting to Raster Format

A vector map generally is a faithful rendition of a hand-drawn contour map. For example, each vector, or line, on an elevation map of the upper surface of the middle Banner has an elevation value (for example, the 475' or 500' elevation contour). Areas between contour lines possess a range of elevation (for example, between 475' and 500'), and the elevation at any location on the map (other than on a contour line itself) cannot be more precisely defined. Although such values may be inferred by interpolation, they are not explicitly defined. A raster map, however, depicts information at each of many regularly spaced grid cells. It contains more information than a vector map, because it also provides an estimated or interpolated value between data points and contour lines. Computer-generated cross-sections, 3-D visualizations, and many modeling routines (for example, for ground-water flow) require raster data.

Data on the vector map was processed to a raster format. Although useful for analysis, raster maps can appear somewhat different from vector maps - they tend to show the map information with a blocky or jagged appearance rather than the smoothly drawn boundaries to which we are accustomed. For presentation, we considered creating a smoothed, vector version of each raster map. However, the time and expense involved and, more importantly, our desire to emphasize the analytic uses of digital geologic maps led us to retain the raster maps in this report. To aid visual aesthetics, we chose a small raster grid size (100 meters), thereby minimizing the characteristic blockiness of raster maps. If only the key stratigraphic control data were considered in the gridding, this grid size would be inappropriately small. However, for each unit a general interpretation of depositional and erosional history was developed (a conceptual geologic process model), providing a basis for assumptions about each unit's three-dimensional distribution. Our grid size was selected to maintain the traditional, vector-like appearance of the maps while creating a digital map product that could be adapted to more analytical purposes. For an application such as ground-water modeling, the grid cells may be aggregated to provide a spatial framework more realistic to the needs of that application.

An Internally Consistent Geologic Model and Set of Maps

After each elevation map was rasterized, it was compared to the stratigraphic control data and to the maps of units above and below it. This was the first stage of an iterative process of reevaluating stratigraphic interpretations in the database and refining the maps. In many cases, stratigraphic interpretations were difficult because units of distinctly different ages and different depths can look the same. For example, in a test boring that sampled multiple diamictons, upper Banner Formation diamictons can be misidentified as lower Glasford Formation, especially if intervening soils are not present. If, based on the regional geologic map trend, the elevation of a stratigraphic unit at a particular point was anomalously higher than appropriate, it was reexamined for a potentially better fit with an overlying map unit. In some cases, the lithologic characteristics of the sample were inconclusive and the stratigraphic interval was assigned to the younger age, whereas in other cases the stratigraphy was found to be correct and diagnostic of the lower unit. In the latter case, a shortcoming of the regional mapping is indicated; the anomalously high data point was correct and represented some local relief that was not mappable at our scale. Those map data were retained, and the resulting local "spike" in the map surface indicates a need to gather more information for that area.

Discontinuous units are particularly difficult to map because gridding algorithms compute cell values by interpolation methods. [We used the Arc/Info Topogrid algorithm; for these data, we found that other algorithms supplied in Arc/Info and other software (EarthVision) provided results of somewhat lesser quality.] No algorithm can produce a realistic map where data are absent across areas of relatively high relief. Consider, for example, the middle Banner Formation (Figure 4), which is confined to valleys separated by expanses of upland. A gridding algorithm must compute a value for every cell, including those far removed from data points, and each cell's value depends in some measure on adjacent cells. Unrealistic cell values that greatly departed from values on the vector map were corrected by increasing the density of the elevation data on the vector map (especially in topographically flat areas and near large changes in slope gradients), re-gridding the map, and removing upland-area data from the raster map (because, as noted above, the middle Banner Formation does not occur on the uplands). This method is useful for units whose depositional pattern is predictable. For the basal sands of the Glasford Formation, data are sparse and the unit's distribution is not so predictable. There, we gridded the unit thickness data and computed the elevation of the upper surface by adding unit thickness to the elevation of the underlying unit.

Comparison of maps for each layer revealed potential inconsistencies, such as areas where an older, lower unit was mapped at a higher elevation than the unit above. For example, the initial raster map of the upper Banner Formation was computed without considering the topography of underlying units. Comparison of bedrock and upper Banner elevation maps revealed the control that bedrock topography imposes on the distribution of upper Banner deposits. Revision of contour lines and re-gridding produced a map showing the correct spatial relation -- progressive thinning and then absence of upper Banner Formation, from the valley to the bedrock uplands. Refinement of the map of each stratigraphic unit proceeded in this fashion until an internally-consistent stack of maps was created.

Both data quality and certainty of interpretation varied significantly for each stratigraphic unit. We used the most certain of the units as the starting point to develop the set of maps, relying on them to constrain the mapping of less well-understood units. The top of the Mason and Wedron Groups, which corresponds to land surface, was an obvious starting point. Among the buried units, we had the most confidence in maps of the bedrock surface and the top of the middle Banner Formation, for two reasons. First, the Mahomet Sand aquifer and the bedrock surface were easy for drillers and geologists to identify, relative to the gray-brown diamicton-dominated stratigraphy in the remainder of the section. Second, the fluvial processes that controlled bedrock erosion and deposition of the middle Banner Formation are relatively well understood; fluvial processes leave a relatively predictable pattern of deposits constrained within a network of valleys.

We therefore began our modeling from the top (land surface) and the bottom (bedrock and middle Banner Formation) of the depositional sequence, and worked toward the middle, where interpretations of spatial patterns of buried diamictons and associated sand and gravel were most difficult. For example, the boundary between the upper Banner Formation and lower Glasford Formation was particularly problematic because multiple diamictons of similar appearance commonly occur in both units with scant evidence of paleosols separating them, and in many places, units are missing. Our map of a stratigraphic unit was made internally consistent by comparing it to vertically adjacent, well-defined units. With a complete set of elevation maps generated, maps of unit thickness were then computed by calculating the difference in elevation between the top of the unit and the top of the underlying unit.

When the set of rasterized elevation maps was complete, they were processed with EarthVision software, which includes a three-dimensional visualization tool. Various 3-D perspective views, cross sections, fence diagrams, and vertical and horizontal slices through the deposits were generated for visual analysis. Apparent inconsistencies or errors in stratigraphic unit geometry were evaluated and, if necessary, the maps were revised in Arc/Info before completing the final set of 2-D and 3-D maps and images.

CONCLUSION

An internally consistent, three-dimensional geologic model was developed for a portion of east central Illinois, including the Mahomet Bedrock Valley and surrounding uplands. Based on our experience, and the time needed to generate this model and set of maps, we advise that before a mapping project is begun, the planned and potential uses of the map products be carefully evaluated. Providing an internally consistent, three-dimensional model is essential if there is an analytical use planned, such as development of a ground-water flow model. However, if adequate high-quality data are not available, these maps should not be developed, but more conventional, vector-based methods for preparing maps of each surface should be used to provide a general, visual depiction of the geologic framework.

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Providing Spatial Data and GIS Applications Via the Internet

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INTRODUCTION

Communication of information about local or regional geology and its relationship to human activity is the fundamental justification for virtually every state or national geological survey. Raw data, a measured value or derived attribute of a particular feature or object at a particular place, is rarely the information of concern to our clients. What people want to know is the relationship of the measurements and attributes of one feature to those other features around it. How close is one object with its particular attributes to another object with different attributes? Just as the three keys to success of a business are location, location, and location -- the three keys to the value of geologic data are spatial, spatial, and spatial. This statement of the obvious translates directly to recognition that, in this age of 'Information Super-Highways,' the use of geographic information system (GIS) technologies is essential to the success of our communication efforts.

The Kansas Geological Survey (KGS) recently completed a project to provide the Kansas Department of Agriculture's Division of Water Resources (DWR) with the tools necessary for its clients to have direct access to databases maintained by the DWR on water wells in Kansas. The databases contain very large volumes of data, and the client base ranges from public policy makers to private businesses and individuals. The data exists in digital form, but is relatively inaccessible even to staff within DWR. Annual reports presented dumps of data tables, which contributed little to communication of information about the data. Water table contour maps were occasionally produced with very low distribution or utility compared to their cost of publication.

This paper will describe the successful application of GIS technology by the Kansas Survey to solve the Division of Water Resource's information communication problem. This project is seen as a prototype for providing public access to the information which can be derived from the Survey's digital geologic data, including the Kansas Digital Geologic Map Database, via the Internet.

WATER LEVEL DATA ACQUISITION

Since establishment of an observation well network in 1984, KGS and DWR have been involved in a cooperative annual water level measurement program. About 1380 wells (including stock, irrigation, domestic, and monitoring wells) spread over 47 counties in western and central Kansas are scheduled for annual measurement in January of each year. This year a crew of six people from the KGS successfully measured water levels in 542 of 551 wells visited during a 6 and one-half day field trip.

Each member of the KGS crew was deployed with acquisition software running on a notebook PC interfaced to a GPS unit, along with field notes, maps, a cellular phone and other supplies. The data acquisition software system, WaterWitch, was developed at the KGS. It provides historical data, warning messages for out-of-trend water level measurements or probable errors in well identification, and real-time vehicle tracking and location display (Miller, Davis, and Olea, 1998). The system also helps to enforce completeness in well site documentation. It is clear that this type of data acquisition system is also well suited for collection of field data for mapping surface geology.

DATABASE DESIGN

Various problems, including plugged, damaged, or destroyed wells, occasionally force wells to be dropped from the observation well network. When this occurs, or when geostatistical analysis identifies areas of spatial under-sampling, it is necessary to identify new wells as candidates for inclusion in the observation network.

Databases relating to various subsets from the total of approximately 51,860 water wells in Kansas have historically been maintained by many separate agencies, including: the U.S. and Kansas Geological Surveys, the Kansas Department of Health and Environment, five Groundwater Management Districts, and the DWR. In addition to agency needs to improve communication of information, development of a comprehensive Kansas water well database was undertaken by the KGS in an attempt to make information accessible about all water wells in Kansas for consideration of potential replacement or enhancement wells in the observation network.

The resulting database, called the Water Information Storage and Retrieval system (WIZARD), has been implemented as an ORACLE database on a Solaris 2.5, UNIX operating system. WIZARD consists of numerous tables which focus on different types of information pertaining to each well, such as water quality, water levels, geology, well construction, use, location, and elevation. Unique well identification numbers are included in each table as a common element to link the tables.

DATA ACCESS

At present, listings of water level measurements and well construction data can be obtained by queries through the WIZARD water well search form provided at the KGS web site:
<http://magellan.kgs.ukans.edu/WaterLevels/index.html>. Using this mechanism, data is provided as a listing without visualization of the spatial context of the data. This mode of data access requires a browser at the user end, which connects, via the Internet, to the data provider's web server. The web server then connects, through middleware, to the relational database management system (RDBMS). The middleware establishes the communications protocols between application programs and the appropriate databases. Middleware may be provided by the vendor of the database management system, the vendor of the application program, or by an independent vendor of communications solutions. The choice of middleware depends upon the operating system of the server and the specific RDBMS. The middleware that implements web access to WIZARD through the water well search form consists of code written in ORACLE's SQL*Plus programming language, and is run by the ORACLE Application Server (OAS). In this case, where no attempt is made to visualize spatial relationships, OAS provides an effective database connection, taking maximum advantage of application libraries bundled with the ORACLE RDBMS.

USER — GIS TECHNOLOGY — DATA: PROVIDING LINKS TO SPATIAL INFORMATION

The web services just described for access to raw data can be extended to include visualization of spatial data by the addition of geographic information systems technology. A GIS is inserted, as an intermediate step between the provider's web server and the RDBMS connection software, enhancing the basic middleware. For the water well project at the KGS this was accomplished using ESRI's ArcView GIS.

Queries on attributes of water wells are handled as before, through RDBMS connection software. However, the choice of connection software depends upon the operating system of the workstation running the GIS project to be served. The KGS has successfully served GIS projects running on a UNIX platform with Solaris 2.5 and on PC platforms with Windows NT.

Running ArcView on a UNIX workstation, the Survey chose ORACLE's SQL*Net as its database connection software. This is a practical solution when both the GIS application and the external database (ORACLE) are both running on UNIX systems. SQL*Net handles the communications protocols between ArcView and the ORACLE database. Within ArcView, the UNIX Database Integrator identifies the location of the databases to which the project may be connected.

When the ArcView project is running on a PC, the Kansas Survey uses database connection software obtained from a third party vendor, the Open Database Connectivity (ODBC) driver from Intersolv. The same company also provides a Java version (JDBC), and similar products can be obtained from a variety of vendors.

For spatial queries, water wells are viewed as map features (points in 2-D map space, or lines (the vertical well bore) in 3-D space. Spatial features (points, lines, polygons, or volumes) are represented by boundary coordinate data maintained in a GIS map feature database. This data is typically maintained in tables separate from the attribute data in the RDBMS. Unique identification codes for the spatial map features are used to relate each feature to its own attribute data. Many coverages displaying characteristics of well attributes (such as water levels in a given year or changes in water level over time) and coverages of other map features which provide spatial context for the well information are developed before the project is served to the web.

The complexity of serving a multitude of spatial features to the web as map images requires the addition of one more component to the system, a GIS map server. The map server functions as a connection between the web server and the GIS in much the same way that the database connection software (middleware) operates between the

GIS and the external RDBMS database. The map server establishes the communication protocols between the providers web server and the GIS. It may serve as a network administrator to handle multiple GIS sessions on multiple workstations. Most importantly, the map server provides efficient facilities for browsing, viewing and querying maps. An extension of ArcView, marketed as Internet Map Server (IMS), was used as the map server for the water well project. In IMS, the map browsing, viewing and querying functions are handled by a Java applet. IMS places a minor constraint on potential users since this Java applet requires that the user's browser must be compatible with Java. Microsoft's Internet Explorer would fail this requirement in all but the latest version.

RESULTS

The cooperative effort of the KGS with the DWR to provide spatial data and GIS applications via the Internet was accomplished by the extended system integration outlined in the preceding section. The complete sequence of components from the user to the raw GIS attribute data in an external relational database is shown in Figure 1.

The GIS map server, GIS application software, and database connection software reside on the provider's system. The only requirement at the user end is access to an appropriate web browser. Once a GIS project has been served to the web, a user may access the project via the Internet from any platform (UNIX, PC, or Macintosh). Users do not need to be running any GIS product at their end in order to browse, view and query the served GIS project. This meets a critical objective of the KGS and DWR for systems designed to provide access to public information. The end result should be robust while placing minimal requirements on the user for hardware or software. As presented here, users need no more than the bare minimum of capabilities currently provided on any personal computer sold with Internet access capability.

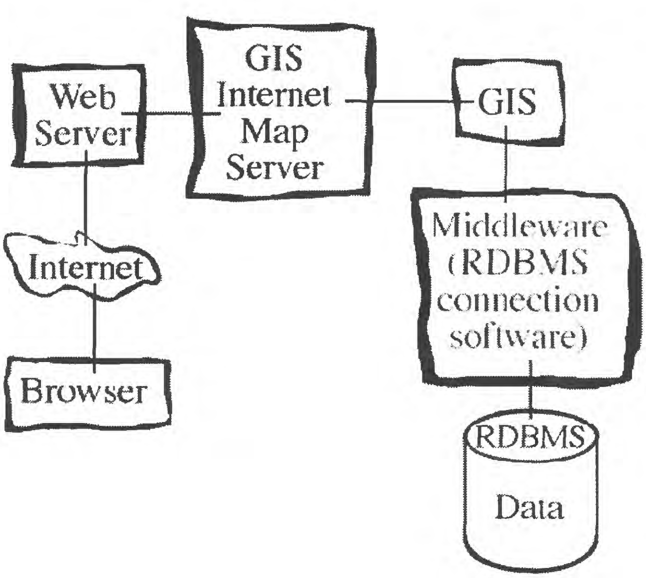

Figure 1. System configuration for providing spatial data and GIS applications via the Internet.

Once connected to the served project, the user is able to carry out all of the basic browse, view, and query functions available with the GIS when viewing an existing project. Via the Internet, the user may view tables providing data on all or selected subsets of wells. More importantly, data may be viewed in the spatial context of selected map features. Figure 2 shows a user's view of nine-year changes of water level in western Kansas observation wells. County boundaries, hydrology, and the extent of the High Plains aquifer are selected as base map information. In Figure 3, the user has zoomed in on an area of the Walnut Creek and Pawnee River valleys and has queried for data on one of the wells. In Figure 4, the user has selected a graphic display of depth to water, measured over ten years, for wells near Great Bend, KS. This type of connection permits real time access to changes in the underlying databases. As updates occur in water level or water quality measurements, the user sees the change immediately, rather than waiting for the next published report. The primary limit on functionality to the user is the inability to create or modify coverages in the GIS.

The resulting systems have been thoroughly tested and found to perform quite well. While the concepts are reasonably simple, it should be emphasized that arrival at a fully integrated, working system does not occur without considerable effort and attention to detail. Extreme care should be taken to insure that the map server and database connection software actually meet the communication protocol needs for the specific releases of the web servers, GIS applications software, and relational databases to be used in the system. In addition, all software must be compatible with the intended operating systems running on the provider's hardware. The presentation of these concepts to the Digital Mapping Techniques '98 workshop, based on this article, may be accessed on the Internet at: <http://www.kgs.ukans.edu/General/Geology/dmt/spatial.html>, where access is also provided to the project described here.

GEOLOGIC INFORMATION SYSTEM PROTOTYPE

Ground-water resource information is only one specialized aspect of geologic information that could be provided in a useful manner via the Internet using the type of system described here. The merits of such systems are not restricted to political boundaries. Live demonstrations of

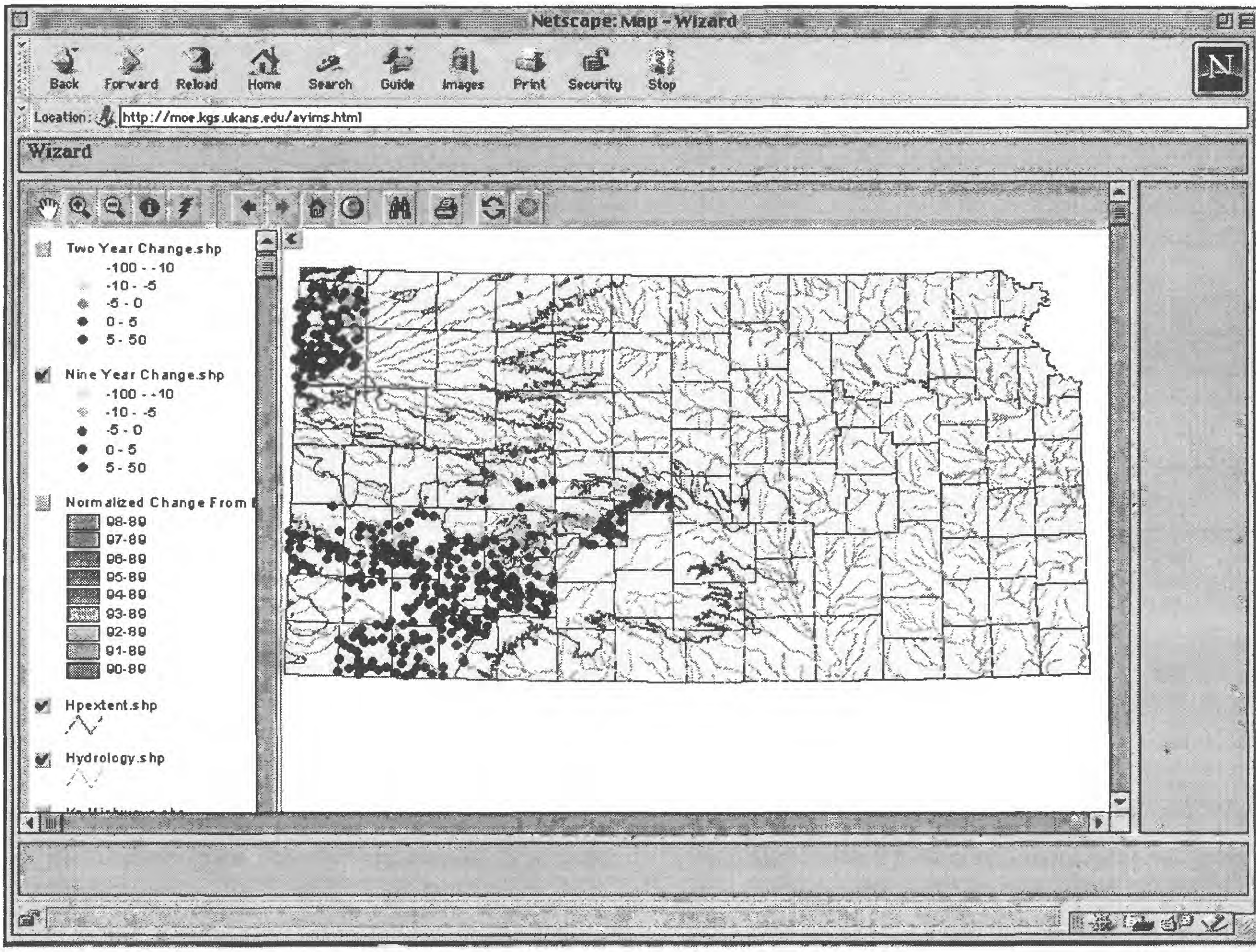

Figure 2. View of nine-year changes of water level in western Kansas observation wells, accessed via the Internet.

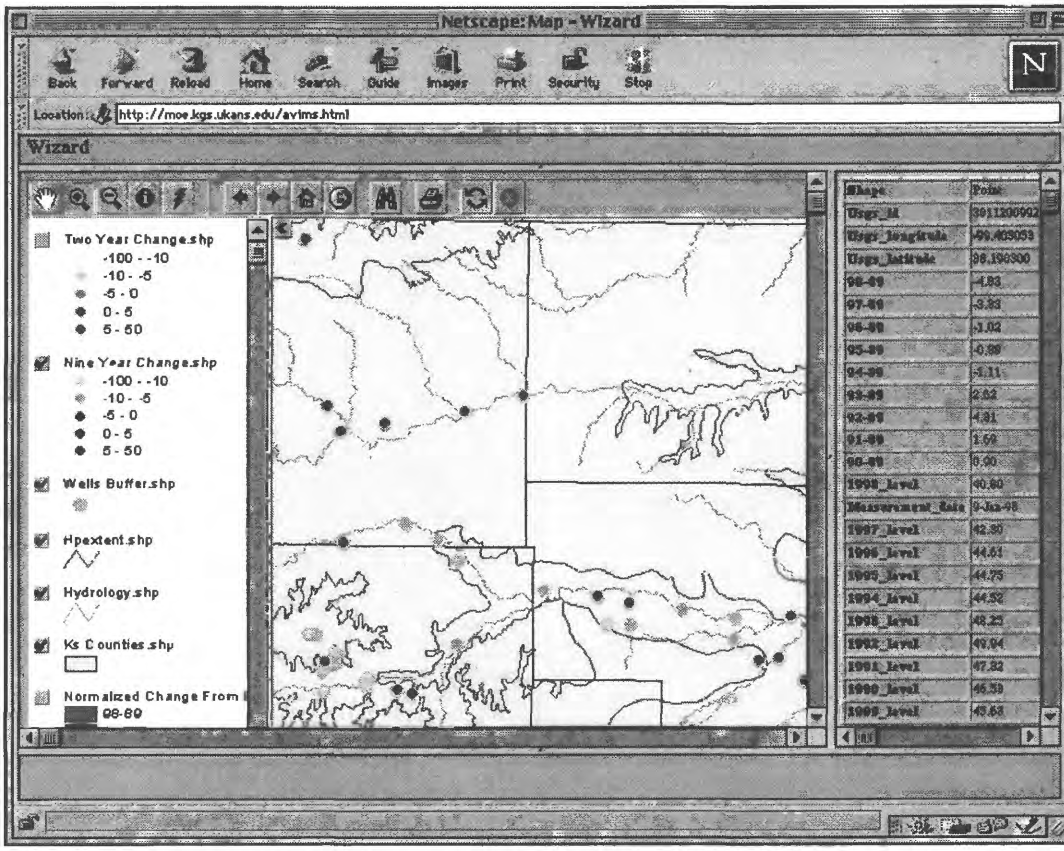

Figure 3. Walnut Creek and Pawnee River valleys, with data table displayed for a queried well.

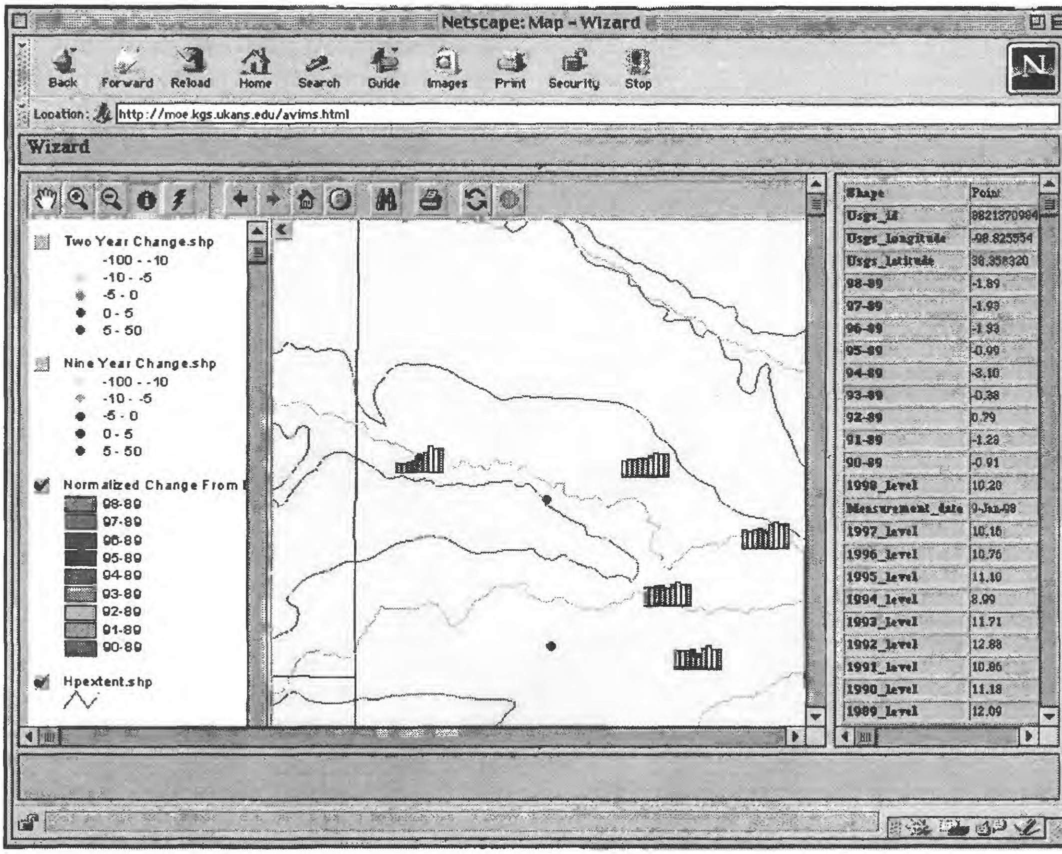

Figure 4. Graphic display of depth to water, measured over ten years, for wells near Great Bend, KS well.

web access to the KGS water well project have recently been provided to companies and government agencies in Austria responsible for collection and distribution of geochemical data for use in development of mining activities and mitigation of possible adverse environmental impacts of mining.

As additional digital county geologic maps are completed in Kansas, this system will be used by the Kansas Geological Survey in a pilot project to provide enhanced access to geologic data. In addition to viewing the basic digital geologic map database, users will be able to identify on the geologic map image the locations of supplemental data, such as measured sections, images of outcrops, regional cross sections derived from well log data, or subsurface structure maps.

CONCLUSION

With appropriate application of available technology, effective service of spatial data and geographic information systems applications on the web can be accomplished with only minimum requirements placed upon potential users of the information system. As access to Internet browsers becomes almost universal, providing complex geologic data to the public through systems that make available the visualization capabilities of geographic information systems is good policy.

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The Illinois Natural Resources Geospatial Data Clearinghouse: A Prototype NSDI Clearinghouse Node in Illinois

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INTRODUCTION

The Illinois Natural Resources Geospatial Data Clearinghouse project is a multi-agency effort, led by the Illinois State Geological Survey (ISGS), to make available on the Internet digital geospatial data and associated documentation (metadata) concerning Illinois natural resources. The project was initiated in September 1996, and the prototype Illinois Clearinghouse began operation on July 1, 1997. The primary goal of this on-going effort is to foster a climate for the cooperative development of a statewide clearinghouse network in Illinois by promoting the advantages of the National Spatial Data Infrastructure (NSDI) via a highly visible, operational prototype. The NSDI is a network of computers and agencies that work to reduce redundant data collection and increase data distribution by cooperatively producing and sharing uniform, searchable metadata catalogs about available geospatial data. The growth of the NSDI is guided by the Federal Geographic Data Committee (FGDC), whose charge is the development of standards, data clearinghouses, local frameworks for data sharing, and cooperative partnerships. Thus far, the Illinois Clearinghouse has received a great deal of attention, and, in the spirit of the NSDI and FGDC, is providing unprecedented access to Illinois digital data. The Illinois Clearinghouse is available at www.isgs.uiuc.edu/nsdihome/ISGSindex.html.

The participants in this project are the ISGS, the Illinois Natural History Survey (INHS), the Illinois State Water Survey (ISWS), the Illinois Waste Management and Research Center (WMRC), collectively known as the Illinois Scientific Surveys, and the Illinois State Museum (ISM), the Office of Mines and Minerals (OMM), and the Office of Realty and Environmental Planning (OREP) of the Illinois Department of Natural Resources (DNR). Each participant has contributed metadata and digital geospatial data to the Illinois Clearinghouse, making data available on topics such as the Public Land Survey System, bedrock and Quaternary geology, wetlands and streams, landfills, fish and wildlife areas, land cover, political boundaries, municipal boundaries, roads, and railroads.

BACKGROUND

The ISGS and several of the other participants have been using Geographic Information System (GIS) technology since 1983 to develop and analyze natural resource information. The system has been used for a wide variety of projects, many in partnership with other government agencies, academia, industry, and citizen groups. Typically, the work has been done using Arc/Info software from Environmental Systems Research Institute, Inc. (ESRI, 1997). One result of these projects has been the accumulation of a large collection of digital geospatial data appropriate for addressing a wide range of natural resource issues.

Until recently, most of these data sets were accessible only to agency staff and a limited number of specialized data consumers. During the last few years, however, decreasing costs of computer hardware and GIS software, increasing Internet connectivity, and the advent of new, user-friendly software have significantly increased the use of GIS technology in the participating agencies and their external customers. This has fostered an unprecedented demand for digital geospatial data. The project partners initially addressed the new demand in two primary ways: by independent direct distribution to end-users, and by cooperative development of a two-volume CD-ROM set of Illinois digital databases (Illinois DNR, 1996). A prototype Illinois Natural Resources Geospatial Data Clearinghouse was the next logical step. The intent was not only to meet existing data distribution needs, but also to provide an operational example of the NSDI clearinghouse system in Illinois that would encourage other agencies to recognize the value of participation in data development and sharing initiatives. The ideal result would be a coordinated statewide clearinghouse system involving the wide variety of organizations that generate, manage and use digital geospatial data. While great progress has been made, such a goal will require several more years of effort. We consider this project the first phase, providing initial impetus and a successful model for subsequent efforts.

The fundamental component of a NSDI clearinghouse is a detailed, searchable metadata database that makes data easily discoverable and accessible. Thus, the primary project objectives were: (1) to adopt a specific format for metadata compliant with the Content Standard for Digital Geospatial Metadata (CSDGM) (FGDC, 1995), (2) to implement the clearinghouse with a robust metadata database and downloadable data available through searching and browsing functions, and (3) to develop Fgdcmeta.aml, a streamlined variant of the Arc/Info metadata collection program Document.aml (ESRI, 1995). The purpose of developing Fgdcmeta.aml was to produce an Arc/Info-based metadata collection program for the efficient generation of metadata files that would conform with existing FGDC metadata preparation, indexing, and server tools.

METADATA TRAINING AND DEVELOPMENT

Methods for metadata collection and dissemination are in the early stages of development. We wished to provide as much metadata as possible on our NSDI node using a flexible approach that could accommodate the evolution of this young discipline. Three major issues were (1) the adoption of a specific metadata format, (2) the amount and type of training to provide, and (3) the metadata tools to choose. The following discussion of these issues is taken in large part from the interim project report (Nelson, 1997).

The CSDGM has been in revision over the past two years and indications are that it will not change drastically. Some metadata elements will be redesignated as "core," "recommended if applicable," and "optional," or something similar, and a standard method of adding "user-defined" metadata elements will be instituted. These changes will give users of the standard more freedom in the way they choose to apply it, while maintaining uniformity and utility. Existing CSDGM-compliant metadata should comply "as is" with the revised standard. Nonetheless, the project partners decided that to formally adopt a specific metadata format based on a soon-to-be-replaced standard would be ill-advised. They informally agreed to produce FGDC-compliant metadata using the set of elements that had previously been identified for use with the Illinois DNR digital data CD-ROM set. This metadata format consists of the Identification Information and Metadata Reference sections of the CSDGM, and substantial parts of other sections as applicable. Although the difference is subtle, proceeding in this manner leaves the participants in a position to better assess and recommend a formal metadata format for Illinois data after the revisions to the CSDGM are complete.

Project staff both received and provided training. They attended a half-day orientation on clearinghouse mission and goals, and how clearinghouse software and data structures utilize properly formatted metadata files for search and presentation. Core project staff attended intensive training classes and have given presentations at several local and regional meetings where the FGDC, clearinghouse and metadata were primary issues. Project partners have participated in several meetings to promote the clearinghouse concept. Most recently, a hands-on metadata training class highlighting the Wisconsin Metadata Primer (Hart and Phillips, 1997) was provided to staff of the Illinois Scientific Surveys.

However, large-scale training of staff not directly involved with the project has been kept to a minimum. The tools and techniques needed by metadata developers are not necessarily those needed by data developers or data users. It was considered prudent to first establish the prototype clearinghouse, assess the results, and refine the product. Then the response of data developers and users could be evaluated to determine the type and scope of training required. Also, the CSDGM is being revised and training of non-project staff was judged not to be an immediate necessity. It was deemed more efficient to wait for the release of the revised metadata standard than to provide training in the current version only to re-tool and retrain for the subsequent version.

Tools for metadata creation were chosen based on the previous experiences of the various participants. Many metadata files were produced prior to the project using tools such as word processing templates, Document.aml, and Xtme (Xt Metadata Editor) (Schweitzer, 1997c). Existing metadata files that were originally produced in this manner for the Illinois DNR digital data CD-ROMs were reformatted using cns (Chew and Spit) (Schweitzer, 1997a) and augmented to comply with clearinghouse requirements. Most of the tools tested were used on a UNIX computer system, but some PC tools were tested also. Limitations experienced with these various approaches led to the development of the Fgdcmeta.aml metadata collection program.

Fgdcmeta.aml was derived using programming code extracted from Document.aml. It was created because Document.aml has some fundamental problems related to text editing processes. In essence, Fgdcmeta.aml uses the core data extraction routines of Document.aml to derive descriptive information from an Arc/Info data set, but employs a much simpler text editing interface for ancillary data entry. Fgdcmeta.aml has proven to be straightforward and efficient in the generation of metadata from Arc/Info data sets for the Illinois project. Several other organizations have also found it useful, including the United States Geological Survey (USGS), the Geological Survey of Alabama, and the Bureau of Land Management (BLM). Unfortunately, and in-depth discussion of the development of Fgdcmeta.aml cannot be presented here. For more information, refer to the article entitled *Arc/Info Solutions to Metadata Problems: Building a Solid NSDI Clearinghouse Node on a Shifting Metadata Landscape* (Nelson and others, 1997). The article and the Fgdcmeta.aml program are available at the Illinois Clearinghouse web site. An independent review of the program (Phillips, 1997) is available at http://badger.state.wi.us/agencies/wlib/sco /metatool/mtools.htm.

Through trial and error, the following metadata generation process was developed: Fgdcmeta.aml is used to gather initial, data-specific information from Arc/Info data sets and produce a CSDGM-compliant template file in ASCII format. The template contains generalized institutional, distribution and contact information, as well as headings and input fields for additional metadata elements that require manual data entry. Any text editor can be used to provide the additional information; Xtme is recommended. The files are then processed with mp (Metadata Parser) (Schweitzer, 1997b) to generate SGML- and HTML-formatted files in preparation for indexing and serving the metadata. Files are indexed using Isite software (CNIDR, 1997) and served on the Internet with the WAIS Z29.50 protocol. The software tools mentioned here (other than Fgdcmeta.aml) are available free of charge at the FGDC web site (http://www.fgdc.gov) for most of the common computer platforms.

RESULTS, IMPACTS, AND CONTINUING EFFORTS

The clearinghouse was brought on-line on July 1, 1997, with over 1,800 downloadable GIS data sets described by over 100 complete metadata documents. An additional 100 documents containing minimal information comprise a metadata working list. The data and metadata are accessible through browse and search functions. Z-server (WAIS) software was brought on-line simultaneously, giving users the ability to search the metadata database either remotely from the primary NSDI gateway or locally by navigating directly to the Illinois Clearinghouse. The downloadable data have since been augmented with a catalog of short abstracts, metadata links, and over 110 GIF images giving graphic portrayals of the data. Links to various other geospatial data applications in state government have been added.

The most significant result for the participating agencies is that we are providing unprecedented access to digital data. Our participation in the NSDI Clearinghouse System gives us a very visible forum through which to further distribute information, data, and methodologies. The technical advantages of a Clearinghouse allow us to easily and significantly increase distribution and to provide most of the data free of charge. From July 1997 to March 1998, the Illinois Clearinghouse had 180,000 hits and 9,450 user sessions, averaging 39 users per day. Metadata documents were accessed over 5,000 times and 15,000 data sets (7.5 gigabytes) were downloaded. The metadata database was searched several hundred times through the Z-server housed at the primary NSDI clearinghouse node at the USGS. Although Internet statistics of this sort are imprecise, they indicate that the Illinois Clearinghouse is receiving a great deal of attention and use. For existing customers, we have provided easier data access and a larger data catalog than previously available. The real impact, however, is for those new customers who, until now, had no idea of the breadth and depth of our digital data holdings.

Also, in some of the participating organizations this effort has provided the impetus to greatly reorganize and enhance existing GIS databases. As a result, data maintenance, update and control policies have been improved, and our geospatial data sets are better prepared to move into the mainstream of traditional digital information systems.

Perhaps the most significant result in terms of the overall NSDI clearinghouse system is that NSDI-node-in-a-box works; the Illinois Clearinghouse is a textbook example. "Node-in-a-box" is a FGDC catch-phrase that is intended to convey the relative ease with which a NSDI clearinghouse can be assembled. The implication is that a great deal of the initial experimental work has been done and that interested parties need only download the required software via the Internet and follow step-by-step instructions. For the Illinois project it was almost that easy. There were, of course, some technical difficulties; every computer system has its unique challenges. Technically adept personnel are essential, and a robust computer network with high-speed Internet connectivity is an absolute requirement. Ultimately, though, thanks to node-in-a-box technology, project staff spent minimal time bringing the metadata indexing and server software up to operational status. This allowed for maximum concentration on the truly important aspects of the project: metadata creation, catalog development, and digital data sharing.

In terms of metadata creation, there is an important and simple lesson to be learned, and it is echoed frequently by novice metadata compilers. The CSDGM is complex. It takes a great deal of time and effort to gain expertise.

Without in-depth study, the meanings of many metadata elements often seem unclear or redundant. The Illinois project was fortunate in this regard because some of the participants had prior metadata experience. Less time had to be spent learning the standard, so more time could be spent implementing it. Nonetheless, a warning to new users of the CSDGM is appropriate: when learning to use the metadata standard, recognize that it is indeed complex, as are most powerful tools. Be prepared, at first, to write and rewrite the same metadata documents reiteratively. After all, few people can ride a bike on the first try, or write the perfect report in the first draft. Repetition is an unavoidable feature of the learning process. It is not unique to metadata creation and, if planned for, should not be a source of frustration. As expertise with metadata increases, so does an understanding of the dynamic nature of metadata and the relationships between individual metadata documents. Such insights often suggest modifications to existing metadata. A constructive way to approach this situation is to institute periodic reviews of data and the associated metadata. This is not only good database maintenance practice, but is also an excellent application of metadata!

The greatest challenge of metadata and clearinghouse implementation is convincing those with no budget for it that it is a worthwhile activity. Many approaches have been suggested to address this issue. In this project the approach was simple: partner with supportive organizations, build the prototype clearinghouse, and use it to promote its own utility. If the data are useful, the demand will be demonstrable and the benefits compelling. In fact, the demand may be too great. One contributor to the Illinois Clearinghouse asked that his metadata be temporarily removed, stating, "I'm getting too many requests for the data, and I'm not quite ready to distribute it!"

The Illinois initiative is now positioned for the next phase. We intend to use the clearinghouse as a self-promotional tool in pursuit of a broader base of institutional support and participation, and new funding for maintenance and expansion. We will continue to build our metadata database and add downloadable digital data sets. We have plans to add 10-30 gigabytes of storage space from which we will serve, free of charge, raw and modified USGS Digital Raster Graphic (DRG) files for every 7.5 minute quadrangle in the state. We also intend to complement digital data with finished cartographic products by creating an on-line browsing gallery of published and openfile maps. Ultimately, we hope the Illinois Natural Resources Geospatial Data Clearinghouse will be the first step toward a cooperative and comprehensive geospatial data framework in Illinois. Such an "Illinois Geospatial Data Framework" would provide uniform map bases and techniques with which spatial data developers and users would build shared solutions to common natural resource and civil planning needs.

ACKNOWLEDGMENTS

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Formal Metadata in the National Geologic Map Database

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Throughout the 1980s and early 1990s, the improving capability of desktop computers to carry out complex analyses has increased the popularity of geographic information systems (GIS). As they became familiar with GIS technology, people at all levels of government, in industry, and in academia have been calling for better access to publicly available geospatial information and more general use of standard terms of reference and of standard formats for the exchange of geospatial data and information. Answering this need is the goal of the National Spatial Data Infrastructure (NSDI), a government-wide coordination effort initiated at the Federal level through Executive Order 12906, which was signed by President Clinton in April of 1994.

A key component of NSDI is the development of a National Geospatial Data Clearinghouse, a general source of information about geospatial data that are available to the public. With the Clearinghouse a user can determine whether geospatial data on a region of interest exist and are appropriate for solving the problem at hand. The Clearinghouse is a distributed network of internet sites providing metadata (information about geospatial data) to users in the same ways. Its success depends on the overall consistency of the metadata that are made available, because users are expected to evaluate metadata from numerous sources in order to determine which data meet their needs.

To promote consistency in metadata, the Federal Geographic Data Committee (FGDC), an interagency council charged with coordinating the Federal implementation of NSDI, has produced the Content Standards for Digital Geospatial Metadata (CSDGM). That document provides standard terms describing elements common to most geospatial data, and encourages people who document geospatial data sets to use these terms. The CSDGM not only describes the terms of reference but also specifies the relationships among those terms. The relationships, many of which are hierarchical, are complex and a formal syntax is provided to specify them.

Because the syntax of the standard is complex and the number of descriptive elements is fairly large (335), creating metadata that conform to the standard is not an easy task. In addition to the problem of assembling the information needed to properly describe the subject data sets, data producers must arrange that information using the terms given in the standard and arrange the terms using the syntactical rules given in the standard. The resulting metadata are formally structured and use standard terms of reference, hence the term "formal metadata" in the title of this report.

The chief advantages of formal metadata are (1) the ability of computer software to process the information meaningfully and (2) the ability of users to locate and recognize within a record the topical components of the information. For these purposes it is important to be able to say with confidence that metadata conform to the structure of the standard. Human review is still required--no software can determine whether metadata are accurate--but human review of the content is easier to do if the syntactical structure is predictable and in accord with the standard.

Our Nation's digital geologic map data form a fundamental part of the its geoscience data infrastructure; making these data more widely known and used is clearly a worthwhile national goal for both the national and state geological surveys. Recognizing the importance of consistent metadata for digital geologic map data, the National Geologic Map Database (NGMDB), a joint project of the USGS and Association of American State Geologists (AASG), formed a Metadata working group to study the implementation of metadata for digital geologic maps. Members of the working group are Peter Schweitzer (USGS, chair), Dan Nelson (Illinois), Greg Herman (New Jersey), Kate Barrett (Wisconsin), and Ron Wahl (USGS). The working group was asked to: (1) look at the Content

Standards for Digital Geospatial Metadata for adequacy; (2) examine implementing metadata in a standard format for geologic maps; (3) establish guidelines as to what the metadata elements mean to a geologist; (4) determine a process for facilitating input from state geological surveys not represented at this (1995) meeting; and (5) format a specific set of fields that must be filled out for the NGMDB map catalog.

The working group's report is online at http://ncgmp.usgs.gov/ngmdbproject/standards/metadata/metaWG.html. Briefly, the working group found: (1) The CSDGM works with a highly diverse range of thematic data; geologic maps fit naturally into this range. Additional metadata elements may be helpful, especially for geologic ages. (2) Technology, training, and work-flow strategies have been developed through discussions within the larger geospatial data community; these apply as well to geologic maps as to any other form of geospatial data. (3) Meaning of metadata to a geologists rarely differs from meaning to anyone else. Terminology used in the standard is not in every case the same as research geologists use, but the concepts apply directly. (4) The geologic mapping community is invited and encouraged to collaborate, communicate, and participate with other geospatial data producers in the NSDI. This Nation needs the wisdom of the geologic mapping community at least as much as it needs that of other scientific and technical disciplines. (5) The catalog schema, as already defined by the NGMDB, is acceptable. Records of the National Geologic Map Catalog are a brief subset of metadata because the emphasis of the Catalog is on all published maps, most of which are printed and not available in digital form. For digital map products metadata must be more detailed because these products are more ready to be used in digital spatial analysis.

The National Spatial Data Clearinghouse has come a long way since its inception in January of 1995. At that time the Clearinghouse consisted of a disparate set of web sites, not searchable by a single protocol or through a single gateway, providing metadata that varied substantially in structure, format, quality, and appearance. Since then, the study of the community, aided in no small way by the financial support and coordination of the FGDC, has developed software tools, training materials, and a more comprehensive understanding of the work-flow issues involved. As a result, the Clearinghouse is now a centrally searchable source of mostly high-quality metadata consistent in structure and format. Much work needs to be done to enhance the usability of the Clearinghouse, but it is now evident that investments made in creating formal metadata are beneficial now and will retain their value well into the future.

Organizations contemplating the task of producing metadata should be aware that many of the questions they ponder have been considered by other organizations, both similar and different from them. It is not a painless process by anyone's measure, and much information and informed opinion is available on the internet. From a business perspective, it makes sense to devote time and energy where the value gained is greatest. The value of metadata depends on: (1) the value of the data to the producers (cost to make and support the product, as well as the benefits, if any, gained by other organizations' use of it); (2) the transience of the workforce, meaning the potential cost to the producing organization if the people who understand how and why the data were produced leave; (3) the goals of the organization overall and its purpose in making the data available; and (4) the quality of the metadata themselves.

METADATA IN PLAIN LANGUAGE

One of the difficulties that hinders implementation of metadata among those who are new to the process is the technical jargon within the CSDGM. The jargon tends to focus the attention of both metadata producers and reviewers on details. Details matter, of course, but it is crucial to ensure that the metadata answer satisfactorily and clearly the broadest questions about a data set that one might have.

With this perspective in mind, I have rephrased most of the CSDGM as a series of plain-language questions arranged in a hierarchy. My intent is to provide managers, novice metadata producers, and metadata reviewers with a general framework within which they can judge fairly the information requested or provided by a metadata record. The hierarchy extends, at the finest level of detail to the element names and structure by which the answers are encoded in a record. That level of detail is not presented here; it is best provided in a hypertext medium. The presentation here is an attempt to specify the information contained in a metadata record in a manner independent of the precise form in which the information will be stored. In the hypertext version these questions lead to specific instructions for encoding the answers in a metadata record. The hypertext version is online at http://geology.usgs.gov/tools/metadata/.

1. What does the data set describe?
    - a. What is the title of the data set?
    - b. What geographic area does the data set cover?
    - c. Does the data set describe conditions during a particular time period?
    - d. Is this a digital map or remote-sensing image, or something different like tabular data?
    - e. How does the data set represent geographic features?
        - (1) How are geographic features stored in the data set?
        - (2) What coordinate system is used to represent geographic features?

f. How does the data set describe geographic features?
   (1) What are the types of features present?
   (2) For each feature, what attributes of these features are described?
   (3) What sort of values does each attribute hold?
   (4) For measured attributes, what are the units of measure, resolution of the measurements, frequency of the measurements in time, and estimated accuracy of the measurements?

2. Who produced the data set?
   a. Who created the data set?
      (1) Formal authors of the published work
      (2) Compilers and editors who converted the work to digital form
      (3) Technical specialists who did some of the processing but aren't listed as formal authors
      (4) Cooperators, collaborators, funding agencies, and other contributors who deserve mention
   b. To whom should users address questions?

3. Why was the data set created?
   a. What were the objectives of the research that resulted in this data set?
   b. What objectives are served by presenting the data in digital form?
   c. How do you recommend that the data be used?
   d. Are you concerned that nonspecialists might misinterpret the data? If so, of what aspects of the data set should they be especially wary?

4. How was the data set created?
   a. Where did the data come from?
      (1) Are the source data original observations made by the authors and their cooperators?
      (2) Were parts of the data previously packaged in a publication or distributed informally?
         (a) Were the source data published?
         (b) Were the source data compiled at a particular scale?
         (c) What time period do the source data represent?
         (d) What information was obtained from each data source?
   b. How were the source data modified?
      (1) How were the data collected, handled, or processed?
      (2) For this activity did you use data from some other source?
      (3) Did this activity generate an intermediate data product that stands on its own?
      (4) When did this processing occur?
      (5) Did someone other than the formal authors do the data processing?

5. How reliable are the data; what problems remain in the data set?
   a. What can you say about the accuracy of the observations?
   b. How accurately are the geographic locations known?
   c. If data vary in depth or height, how accurately is vertical position known?
   d. Where are the gaps in the data? What is missing there?
   e. Do the observations mean the same thing throughout the data set?

6. How can someone get a copy of the data set?
   a. Are there legal restrictions on access or use of the data?
   b. Who distributes the data?
   c. What is the distributor's name or number for this data set?
   d. As a distributor, what legal disclaimers do you want users to read?
   e. How can people download or order the data?
      (1) In what formats are the data available?
      (2) Can users download the data from the network?
      (3) Can users get the data on disk or tape?
      (4) Is there a fee to get the data?
      (5) How long will it take to get the data?
   f. What hardware or software do people need in order to use the data set?
   g. Will these data be available for only a limited time?

7. Who wrote the metadata?

For further information, please consult the information resources available at the web site of the National Geologic Map Database Project, http://ncgmp.usgs.gov/ngmdbproject/.

POSTER SESSIONS

Brief Summaries

Twenty agencies exhibited posters throughout the workshop. These posters provided an excellent focus for technical discussions and support for oral presentations. Depending on the nature of their poster, the authors provided summaries ranging from a brief description to a more formal paper of some length. The brief descriptions are given below, alphabetically by state. In some cases, the poster directly supported an oral presentation in this volume, and no mention is provided here. These brief descriptions are followed by the more lengthy contributions, by Ross (Kansas Geological Survey), Gregson (National Park Service), McCraw and others (New Mexico Bureau of Mines and Mineral Resources), Tremblay and others (Texas Bureau of Economic Geology), and Haugerud and Greenberg (U.S. Geological Survey and University of Washington).

Map Production at the Alaska Division of Geological and Geophysical Surveys Expands with Growing Digital Geologic Database

By Gail Davidson, Gina R.C. Graham, L. Katherine Queen, Alfred G. Sturmann, DeAnne S. Pinney, and Andrew M. McCarthy

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During the past 15 years, the technology of map production at the Alaska Division of Geological and Geophysical Surveys has evolved from hand-scribed peel coats to digital maps and images generated in Arc/Info. As technology changes, the production methods for geologic maps are continually being refined and updated to take advantage of the capabilities of new technologies. Geologic maps currently produced by DGGS are created electronically from a growing digital database. Formerly maps were released as bluelines from inked drawings or as offset-printed Professional Reports. With the rising costs of printing and storage, maps are now produced on demand directly from an electrostatic plotter or in PDF format on the World Wide Web. Continued growth of the geologic database has allowed more efficient production of "classical" geologic maps as well as expanded use of the data for derivative maps. Advances in digital technologies not only allow us to produce "smart maps" but also allow us to better emulate the look and feel of classic cartographic products.

Two project examples are shown. A map series of the Kandik River Basin area in Alaska was produced by combining digitized geologic data with geophysical data gathered using relatively new technologies. A geologic map of the eastern half of the McGrath quadrangle is a compilation of DGGS field work completed over many years and contains both published and unpublished data. Future plans include a meshing of geological and geophysical data to pinpoint areas with high mineral potential to aid in the ongoing search for economically feasible mineral extraction.

Geologic Mapping for Hazards Evaluation and Zonation on the Whittier 7.5' Quadrangle, Los Angeles County, California

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Most of the early areal geologic mapping conducted in the Los Angeles Basin provided the data for interpreting the stratigraphy and complex structure necessary in the search for petroleum. Emphasis of the early mapping was directed toward the uplands where Tertiary marine strata are exposed. Though bedrock types and structure are components for analysis of hazards, data on Quaternary deposits and landslide inventories are also required. Since most hazard analysis is now done on geographic information systems (GIS), the data should be in digital form. The Whittier 7.5' quadrangle was the first map compiled by the California Division of Mines and Geology's (DMG) Regional Geologic Mapping Project specifically for hazards analysis and eventual zonation by the Seismic Hazards Zonation Program. The mapping and compilation of the Whittier quadrangle were supported in part by the U.S. Geological Survey (USGS) through STATEMAP and are part of the Southern California Areal Mapping Project, a cooperative effort between the DMG and the USGS.

Existing geologic mapping was compiled in the Puente Hills, covering about ten percent of the quadrangle. New mapping of the Quaternary deposits covers the rest of the map. The Quaternary units were mapped on the basis of grain size, age, and origin, according to a classification scheme developed for the Southern California Areal Mapping Project. The map is a 1:24,000 scale digital database in Arc/Info.

Idaho Geological Survey Cartographic Update

By Loudon R. Stanford and Jane S. Freed

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The displayed maps show how the Idaho Geological Survey has successfully met its goal of producing full-color, plot-on-demand geologic maps as outlined in our paper presented at the 1997 workshop. The CAD-finished geology is imported into the publication layout program FreeHand where the DRG base map and legend material are laid out. Once complete, the map is sent to the color plotter (2500 HP) as a PostScript file.

AutoCAD with CADMappr continues to be the software of choice for data capture. Geology is digitized by hand on high-accuracy digitizing tablets or by high-resolution scanner with subsequent data conversion and extraction. Ultimately the data sets are exported to Arc/Info where coverages are built. Full metadata come with all released data sets and are easily accessible through links in ArcView.

We would be happy to answer any questions you may have.

Well Data as a Framework for the Third Dimension in a Digital Geologic Map Database

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The history of digital geologic map database development has focused on the capture, management, and visualization of data representing surface or near surface outcrop patterns of local geologic formations. This presentation will focus on efforts to characterize and visualize the regional subsurface stratigraphic framework associated with the surface expression of outcrop patterns. Even when data from only a single well is available within a map area, the visualization techniques presented here are potentially beneficial as a means for making the data and its interpretation more accessible to potential users. The techniques can be used most effectively in regions with extensive exploration drilling in the subsurface, such as mature petroleum plays.

Many states and provinces in North America have extensive collections of well logs in analog form and in some areas digital well log databases have been developed. Increased availability of digital well log data in Kansas has been a positive result of several major research efforts at the Kansas Geological Survey (KGS). Standardization of digital log formats using the Canadian Log ASCII Standards (LAS), and the addition of geographic coordinate locations to well log header record information has simplified technical problems related to display and visualization of well log data within a regional context. Access to this data by the general scientific community is now possible through the KGS home page (http://www.kgs.ukans.edu/kgs.html) on the Internet. A study of the Dakota Formation has provided digital data from gamma ray logs of more than 1500 wells throughout western Kansas. The data from this project covers stratigraphic units from the Quaternary and Cretaceous systems through the Nippewalla Group of the Lower Permian. Log data has been developed in conjunction with the KGS Petroleum Atlas and other KGS database development efforts. More logs will be placed in the on-line databases as they become available. Examples are provided of regional cross sections and single well displays generated from these databases using COLORLITH, a program for log data visualization developed by the author at the KGS.

Coastal Erosion, Chesapeake Bay, Maryland: A Digital Approach

By Lamere Hennessee,[1] Randall T. Kerhin,[1] Jennifer J. Isoldi,[1] Rebecca A. Gast,[1] and Meredith S. Robertson[2]

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Chesapeake Bay is one of Maryland's most significant physical features. Within the state, the total shoreline of the bay and its tidal tributaries is about 6,400 km. Along most of its length, the shoreline is eroding. To quantify shoreline change, the Maryland Geological Survey (MGS) (1) converted the shorelines depicted on historical recent maps and aerial photographs to digital (vector) format and (2) applied a computer program developed by the U.S. Geological Survey to calculate linear rates of erosion along shore-perpendicular transects. These statistics, combined with bank height and stratigraphic information, are used to compute the volume and type of sediment lost. In phase 3, the graphic information (shoreline vectors and shore-perpendicular transects) and tabular information (shore erosion statistics) are linked in a user-friendly, point-and-click electronic atlas—MGS's Coastal Geology Information System (CGIS). Other data sets or layers, such as the physical properties of beach and nearshore sediments, are also included in the atlas. The CGIS can be used to address a variety of coastal issues, for example, (1) determining set-backs for flood insurance or other purposes, particularly in areas at high risk of erosion, (2) calculating a sediment budget for the bay, (3) assessing the effects of shoreline erosion on bay water quality (e.g., turbidity, nutrient loading), and (4) investigating the processes responsible for shoreline erosion.

Digital Geologic Mapping at the Missouri Division of Geology and Land Survey Using ArcView 3 and USGS Digital Raster Graphics

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The Bedrock Geology of the Forsyth Quadrangle, was drawn into ArcView 3 using USGS Digital Raster Graphics (DRG's) as a backdrop. ArcView 3 is a software program that lets you use and query geospatial information. DRG's are scanned, georeferenced images of topographic maps. This pilot project came about as an attempt to fill the need for a digital product, as well as to ease the production of geologic mapping and create a more versatile product.

Both map producers and users benefit from this method of creating geologic maps. Digital Raster Graphic (DRG) images allow the mapper to use the familiar 7.5' topographic quadrangles in a digital form to plot field (or file) data. This gives the mapper the ability to zoom in on the work area to ease plotting which should increase accuracy. The ability to enlarge, or zoom in, also eases map drawing. The ability to overlay themes, or layers, allows the geologist to compare the map with input data during the review process, and having the map in digital form makes editing easier.

Users, who include a variety of people from developers, to city planners, to environmental site assessors, benefit by having a map that is more versatile and easier to use. The maps can be printed at various scales to provide easy-to-read color maps. More importantly, the map can be used as part of a geographic information system (GIS), so that geologic data can be easily compared to other types of data, such as population or land use. Other digital geologic data can be attached to the map, such as scanned or digital well logs, tabular data such as test results, text such as field notes, or drawings such as measured sections of bedrock exposures. A GIS, including digital maps of bedrock and surficial materials and other related basic data, would give the user greater access to geologic information that could be used in applied projects.

This project is the first at the Geological Survey Program where a DRG image of a topographic map was used to digitize data locations while viewing the map on the computer monitor. This type of data collection is popularly called "heads-up digitizing." It has proven to be an easy and accurate method to plot data that has the potential to be useful in many other types of mapping projects. The ultimate goal is to produce an integrated geologic data package that includes a bedrock geologic map, surficial materials map, and detailed stratigraphic data including well logs and measured outcrop sections. This package would be distributed to users who could overlay their own data (e.g. environmental or cultural features). Potential methods of distribution include CD's, DNR network, or even the Internet.

Montana Bureau of Mines and Geology poster

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The results were shown for several mapping efforts by the Montana Bureau of Mines and Geology. The first two provide examples of digital cartography for 1:100,000-scale quadrangles—a geologic map with scanned linework shown in transparent mode, and a geologic map plotted with shaded relief topography. The impacts of geologic mapping in Montana were shown for old and new geologic mapping efforts, and their influence on related programs such as ground-water characterization.

New Jersey Geological Survey posters

Presented by Ron Pristas

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Dover Township Study Area, New Jersey, Well Head Protection Areas

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This map was prepared to assist the New Jersey Departments of Environmental Protection and Health and Senior Services in their evaluation of a possible childhood cancer cluster in parts of Dover Township, Ocean County. Ground water from domestic and public supply wells is the sole source of water for drinking and other domestic uses in the study area. Public community supply wells are shown along with their respective Well Head Protection Areas developed from ground-water modeling. The Parkway Well Field was an area of special concern. Some of the wells there were contaminated by the Reich Farms superfund site. Special coverages were developed from ground-water models to show the potential flow pathlines from the Reich Farm pollution plume if the well field was not pumping.

Identified Potential Beach Replenishment Sand Sources, Onshore and Offshore New Jersey

By Zehdreh Allen-Lafayette, Jane Uptegrove, Jeffrey S. Waldner, David W. Hall, Peter C. Smith, Gail M. Ashley, Robert E. Sheridan, Matthew C. Goss, Frederick L. Muller, and Eugene Keller

This map provides a coast-wide summary of onshore sand and gravel sources, known offshore sand shoals, and borrow areas currently being dredged for beach replenishment. The onshore sources are limited to those within 15 miles of barrier island access (due to import costs). Identification of the offshore sand shoals is from work by Meisburger and Williams (1980, 1992), Smith (1996), Williams and Duane (1974), and Uptegrove and others (1995). Borrow area sites are from the U.S. Army Corps of Engineers, General Design Memorandum, Sections I and II (1989 and 1993, respectively).

The lower right inset summarizes beach erosion data compiled from the New Jersey Beach Profile Network, New Jersey Department of Environmental Protection and Richard Stockton College Coastal Research Center.

Alphanumeric identification labels for onshore and offshore sand sources are keyed to volumetric/materials data tables in an accompanying report, "Characterization of sediments in Federal waters offshore of New Jersey as potential sources of beach replenishment sand, Phase II, Year 2 Final Report," available from the New Jersey Geological Survey.

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Ground-Water Recharge and Aquifer Recharge Potential for Cape May County, New Jersey

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Ground-water recharge is a quantitative methodology for estimating infiltration of water through the soil to the water table, irregardless of the underlying geology. Aquifer recharge potential is a qualitative methodology for indication of areas of varying potential for recharge to underlying aquifers. Ground-water recharge is estimated using a model outlined in the New Jersey Geological Survey Report, GSR-32 "A Method For Evaluating Ground-Water-Recharge Areas in New Jersey." The model was developed a soil-moisture budget. A simple linear equation is used to estimate ground-water: (Rfactor*Cfactor*Bfactor)-Rconstant

A combination of land use and land cover data and soil data is used to provide the rfactor and rconstant. Cfactors (ratio of precipitation over potential evapotranspiration) are retrieved based on municipality. These values combined with the calibration constant provide ground-water recharge estimates for all areas in Cape May of five acres or greater. These estimates are then ranked, based upon volume to produce a five-tier ranking system.

Aquifer recharge potential is produced by combination of the ground-water recharge areas and aquifer rankings. These rankings were produced using well yield data and NJGS profession staff judgment. Aquifer well yield data were collected from NJGS project databases and USGS GWSI entries. The data were analyzed using median, and numeric and geometric averages. The aquifers were then ranked based upon numeric average. Aquifers having insufficient or no well yield data were ranked by a consensus of NJGS hydrogeologic and geologic staff. Combination of the aquifer ranking and ground-water recharge area data produced a 5 by 5 matrix of aquifer and ground-water recharge rankings. This matrix shows the relationship between infiltration and the underlying geology.

Topographic Bitmap Images for Sussex, Somerset, Cumberland, Hunterdon, Warren, Morris, and Passaic Counties, New Jersey

By Maryann C. Scott and Gregory C. Herman

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The New Jersey Geological Survey's Cartographic Section is working with Digital Raster Graphics (DRG) to produce Statewide digital base-map images clipped to county boundaries. We have developed a procedure to scan stable base mylar of United States Geological Survey (USGS) topographic quadrangles and remove foreground image features that extended beyond the county boundary in the Adobe Illustrator program. Next, the image is autocropped to reduce the size of the image in the Vue Print Pro program and saved to the rectangular extends of all positive foreground pixels. Each quadrangle was then geo-registered to the 1983 North American Datum (NAD83) coordinate system in State Plane coordinate feet using the Arc/Info geographic information system. The registration process for each image uses at least four control points located along the image boundary as links to the vector boundary of each clipped tile within its county boundary. The bit map image files use an uncompressed tagged image file format (*.tiff). Each image has a corresponding world-reference file (*.tfw) defining the geo-registration parameters.

As each county base map is complete, it is placed on the New Jersey Geological Survey website. DRG files are reviewed according to standards for New Jersey Geological Survey Open-File products. They are provided at no cost on the Internet as compressed files. The digital bit base-map images are currently available for distribution at the cost of reproduction upon written request to the State Geologist.

North Carolina Geological Survey poster

By Allan Axon

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This poster showed ongoing projects by the North Carolina Geological Survey that are using Arc/Info, ArcView, and MapInfo.

Product Development and Distribution from the Kansas Digital Geologic Map Database

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INTRODUCTION

Increased availability of digital geologic map databases has brought with it a flood of suggestions regarding possible modes of presentation and distribution. Examples are presented here of the responses developed by the Kansas Geological Survey (KGS). Geologic mapping and digital geologic map database development in Kansas targets completion of projects at the county level. In response to constituent needs, geologic maps and map databases are released as county products. Currently, the only exception among standard distribution products is the availability of mylar transparency overlays of surface geology to accompany individual topographic quadrangles.

STATUS OF DIGITAL GEOLOGIC MAP DATABASE DEVELOPMENT

At present, database development has been completed for eleven counties with base maps at 1:24,000. Two additional counties have digital geologic map databases digitized directly from smaller scale, out-of-print maps. Six counties have new field mapping at 1:24,000 scale (and associated database development) in progress or near completion with STATEMAP funding. Similar mapping and database development is underway in eight other counties through KGS funding (two of these county projects have limited support through STATEMAP). New field mapping is planned to begin within 5 years in another eight counties throughout the state. Six counties are priority projects for data compilation at 1:24,000 by interpretation from previously published maps, with completion planned by June 1999. Numerous additional counties (primarily in eastern Kansas) will be targeted for database development through interpretation of previously published maps as the current priority county projects are completed.

Numerous products related to digital county geologic map databases are under development or currently available from the Kansas Geological Survey (KGS). These products include both hard copy and digital formats. Information concerning either published maps or digital geologic data and related products can be obtained through the KGS web site at http://www.kgs.ukans.edu/General/Geology/index.html. A link is provided to the KGS Publications Sales Office.

PRINTED DISTRIBUTION PRODUCTS

The KGS has three standard products developed for printed distribution from its digital county geologic map databases. Geologic maps of individual counties are available at scales of 1:50,000 and 1:100,000. In addition, mylar transparencies are available as overlays for 7.5-minute (1:24,000 scale) topographic maps. These overlays have only the surface geology, within section corners marked to provide local control when positioning the mylar over the paper topographic map. For reference, the quadrangle name and a stratigraphic column are also printed on the mylar. The price of the mylar overlays includes payment for the corresponding 7.5-minute paper topographic map.

DIGITAL DISTRIBUTION PRODUCTS

Through the 'County Geologic Map Index' on the KGS web site, individuals can gain direct access to geologic map images derived from county map databases and to a bibliography of published county maps. For counties with digital geologic map databases, a GIF image of the published map (at half size) can be downloaded directly from the web site. The geologic map images presented for individual counties are also being developed to provide links to more specific images or information related to the geology of that county. Images of outcrops or type sections can be linked to the map location of the photograph or, in the case of type sections, tied to the formation name in the map legend. For instance, when viewing the image of Riley County geology, hot links provide access to images of the following:

1. aerial photography of the topographic structure formed by a kimberlite,
2. a fault exposed in a road cut at the east end of Tuttle Creek Dam,
3. a quarter-mile of road destroyed by mass slumping of water-swollen shales, and
4. a waterfall on Deep Creek at the outcrop of the Elmont Limestone Member.

Such images provide a valuable learning tool for both the general public and the serious student of geology. Information related to subsurface geology can be presented in a similar manner through images of well log data or seismic lines.

Geologic Resources Inventory—Geologic Resources Division, Inventory and Monitoring Program

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Bedrock and surficial geologic maps and information provide the foundation for studies of ground water, geomorphology, soils, and environmental hazards. Geologic maps describe the underlying physical habitat of many natural systems and are an integral component of the geophysical inventories stipulated by the National Park Service (NPS) in its Natural Resources Inventory and Monitoring Guideline (NPS-75). This summary outlines the cooperative endeavor among the NPS Geologic Resources Division (GRD), NPS Inventory and Monitoring (I&M) Program (Natural Resource Information Division - NRID), U.S. Geological Survey (USGS), and individual state geological surveys to implement a systematic, comprehensive inventory of the geologic resources for about 265 NPS units with significant natural resources. The on-going and proposed NPS Geologic Resources Inventory consists of three main phases: 1) a Geologic Resources Bibliography (GeoBib) of literature and maps, 2) an evaluation of existing, needed, and in-progress map coverage and subsequent production of digital products, and 3) a compilation of a geologic report with basic geologic information, hazards and issues, and existing data and studies. New geologic mapping projects may be initiated on case-by-case basis after careful evaluation of park needs, costs, potential cooperators, and funding sources.

STATUS OF GEOLOGIC RESOURCES INVENTORIES

In addition to the existing GeoBib database development and data management planning, GRD and I&M sponsored a Baseline Geologic Data Workshop in Denver in fall of 1997 to get input from NPS, USGS, and state survey personnel and cooperators about basic geologic data needs that could be provided by the I&M Program. At the Denver meeting, Colorado, Utah, and North Carolina were chosen as pilot project states to maximize the cooperation among NPS, USGS, and state surveys. In general, discussions and work have affirmed the existing three-phase approach illustrated in Figure 1.

The GeoBib project is completing the initial phase of data collection for existing geologic resources (maps and literature) in each NPS unit and publishing the data on the NRID Intranet. The bibliography is discussed in more detail in a later section. In addition, index maps of the location of associated geologic maps are being prepared for the parks in Colorado. When map coverage for each park is determined, map products can be evaluated, and potential mapping projects identified and initiated.

Pilot geologic issues/map scoping meetings (Park Teams) are being organized in 1998 to evaluate the resources in Colorado parks and will be followed by pilot projects in Utah and North Carolina in the next fiscal year. Park Teams will identify existing maps for digitizing or conversion to NPS standards. A separate task group is developing a geology-GIS standards document to ensure uniform data quantity and quality for digital geologic maps. A pilot digitization project for Craters of the Moon National Monument will provide additional input for the digital map standards. In addition to evaluating geologic maps for digitization, park scoping meetings will identify new geologic mapping needs. However, the high cost of geologic field mapping and thematic map digitization requires additional long-term planning and exploration of cost-effective programs and partnerships for new projects.

After completion of map inventories, a geologic report of USGS and state geological literature, park, and GRD

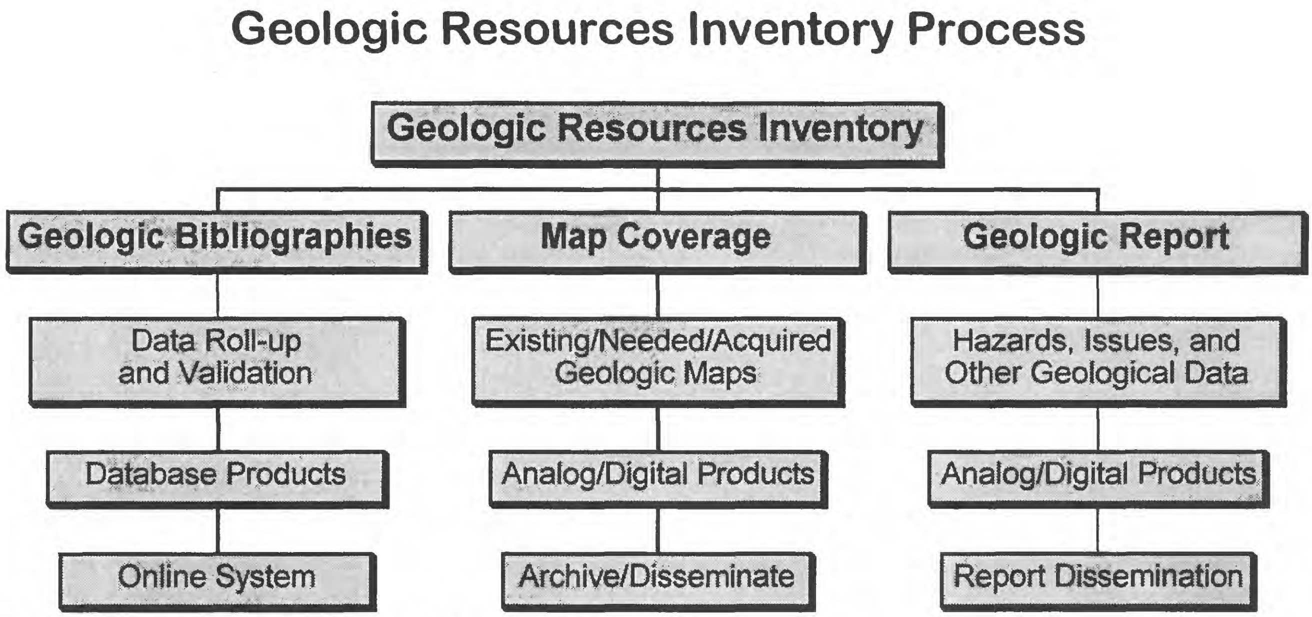

Figure 1. The three themes of the geologic resources inventory process.

data will complete the project for each park. The geologic report content, format, and database are being developed and are outlined in a later section.

RELATIONSHIPS WITH EXISTING DATA STANDARDS AND PROGRAMS

The idealized NPS Level I Inventory goal of bedrock and surficial geologic maps for each park at 1:24,000 scale is compatible with similarly specified scales for base cartography, soils maps, and vegetation maps. However, acceptable geologic map scales must be determined by case-by-case evaluations of existing products, park needs, and mapping costs. USGS and state surveys are digitizing maps for on-going mapping projects, but scales vary and coverage of all NPS areas will probably never be digitized without in-house or contracted work by GRD and the I&M Program.

GEOLOGIC RESOURCE BIBLIOGRAPHIES (Geobib)

The GeoBib project is collecting individual park bibliographies and publishing the data on a secure intranet database system. USGS made bibliographic searches of the Georef and Geoindex databases for each park, which were converted to Procite data files. The Procite data must still be converted for the intranet system, map citations must be edited for duplicate entries, and a list document and index map of associated geologic maps must be prepared. The completed GeoBib database will contain about 100,000 citations of geologic resource literature in an online database.

With GRD and I&M funding, a Colorado State University student was hired to work on the GeoBib database. Bibliographies for 27 parks in the three pilot states were edited for duplicate map citations and used to compile a list of geologic maps for each park. Bibliographies for additional 15 western parks were converted and loaded into the database for editing. After removal of all duplicate map citations, geologic map citation lists will be prepared for each park and used to develop index maps of the footprint of associated geologic maps relative to park boundaries. The map lists and index maps will be converted to word processing documents for transfer to cooperators.

DIGITAL GEOLOGIC MAP COVERAGES

Several agencies are digitizing geologic maps with conventional methods as well as vectorization or heads-up digitizing of scanned images. The I&M task groups will evaluate these methods to allow versatile data acquisition. Scanning and vectorizing of geologic map masters will be tested in a pilot digitizing project of four geologic maps of Craters of the Moon National Monument by the Columbia Cascades Support Office GIS personnel. In addition, as part of this inventory, the I&M Program and GRD plan to obtain conventional digitizing technology and digitize select geologic maps in house. On-going and completed park mapping and digitizing projects will be tracked in the Dataset Catalog system on the NRID Intranet. Digital map products will be archived and distributed on CD-ROM.

BASELINE GEOLOGIC INVENTORY REPORT

The inventory report will contain summaries of the exploration history, geology, unique features, paleontology, disturbed lands issues, geologic data, geologic hazards, and other geology-related issues to describe the basic geologic resources of each park. Several report sections, such as stratigraphic columns and geologic cross section graphics, will incorporate available literature and will be developed with assistance from student employees. Other sections will summarize ongoing NPS programs such as disturbed lands and paleontological inventories. A database system is being developed for the NRID Intranet to provide on-line access for report development and dissemination. An expanded report outline is shown in Figure 2.

In conclusion, the NPS Geologic Resources Inventory is being actively developed with the cooperation of USGS and state geological surveys. However, many opportunities for project collaboration and cooperation exist that have not yet been identified, and effective communication among existing and potential cooperators is a key factor for success of the inventory. Another challenge of inventory planning is the development of digital map standards that are adaptable to diverse geological conditions but still provide quality, uniform products and firm guidance for cooperators and workers. Indeed, the diversity of geologic resources found in the National Park System will provide a continuing challenge for effective project management.

The National Park Service has identified GIS and digital cartographic products as fundamental resource management tools, and the I&M Program and Geological Resources Division are developing an efficient inventory program to expedite the acquisition of digital geologic information for NPS units throughout the country.

NPS Geologic Resources Inventory Report Outline

Executive Summary

History of Geologic Exploration
- For cultural and interpretive information

Geologic Setting
- General summary of park geology

Stratigraphy
- Stratigraphic column (Web and printable graphics)
- Rock unit names, abbreviations, and descriptions (digital geologic map attributes)
- General stratigraphic information will help populate separate NPS Geologic Lexicon
- Cross sections/fence diagrams

Structure
- General description, map(s), and cross sections(s)

Unique Geologic Features (summary and/or map)
- Landforms
- Type localities

Paleontology
- Summary and reference to fossil list in NPSpecies DB

Disturbed Lands
- Summary and reference to AML/GRD data

Geologic Hazards and Issues
- Summary from literature and scoping meetings

Geologic Data
- References
- Links to GeoBib, Geologic Lexicon, NPSpecies, etc.
- Metadata for geology GIS coverage(s)

Other Sections and Topics as needed.

Figure 2. Outline of geologic report.

Combining Arc/Info and Macintosh to Expedite Digital Geologic Map Production for Critical Hydrogeologic Investigations in New Mexico

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INTRODUCTION

Recognizing that modern, accurate hydrogeologic map information provides essential base data for government planning and scientific studies, the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) is now in its sixth year of an aggressive geologic mapping program. Designed to address compelling socioeconomic issues (dwindling water supply and quality, geologic hazards, land-use planning, mineral resources) facing the rapidly growing population in the Middle Rio Grande Valley, 7.5-minute quadrangles are prioritized by the 29-member New Mexico Geologic Mapping Advisory Board, and then funded by the USGS National Cooperative Geologic Mapping Program's (NCGMP) STATEMAP component. For the last four years, NMBMMR has been the most successful state geological survey in the country competing for STATEMAP funds, and by July 1999, we will have mapped 36 7.5-minute quadrangles at either 1:12,000 or 1:24,000.

Unlike many state geological surveys, NMBMMR's digital cartography program evolved slowly through the mid-1990s. Given the rapid rate of STATEMAP quad mapping that developed at this time and the complexity of the geologic coverage, the NMBMMR needed to establish a digital cartographic methodology to develop and distribute high-quality, detailed, multicolor geologic map data to the public as quickly as possible. As a result, a new open-file digital map series (OF-DM) was established in 1997. These OF-DM quads are open-filed for immediate output and consist of a surficial geologic map with explanatory text, unit descriptions, correlation charts, and geologic cross sections.

After attending the Digital Mapping Techniques '97 (DMT '97) conference in Lawrence, KS, we decided to model our digital cartographic production program after that of the Nevada Bureau of Mines and Geology (see Tingley and others, 1997), thereby integrating our Arc/Info-based GIS section with our Macintosh-based Cartography section. This methodology (described below) provided users with digital Arc/Info coverages and/or ink-jet color plots that conformed to our long-established map standards. Combining these platforms allowed us to benefit from the relative elegance of Mac-based graphics programs with the high-end GIS capabilities of Arc/Info. Furthermore, this combined method expedited our overall cartographic production. Months of trial-and-error digitizing and interaction between geologists and technicians were replaced by a single scanned image that could be quickly drafted. In about two weeks, the 1:24,000 Alameda geologic quadrangle went from an inked mylar to a multicolor plotted map sheet, complete with cross sections.

DIGITAL MAPPING METHODOLOGY

After the geologic data are compiled from field mapping, aerial photo interpretation, borehole cuttings, electrical-conductivity log correlations, etc., geologic linework (contacts, structures, and symbology) is inked onto a mylar greenline stable base and scanned at 100% at 400 d.p.i. on an Intergraph Anatech large-format drum scanner. The image is initially pre-scanned and the scanning software, Scansmith, while holding all of the inked linework drops out the greenline base data. The resulting scanned TIFF file is geo-referenced to a projected geographic grid of latitude and longitude in Arc/Info and then exported as an Adobe Illustrator formatted file to a Macintosh Power-PC. After opening the TIFF scan/grid file on a Background layer in Macromedia FreeHand 8.0, the quadrangle neatline and the graticules of latitude, longitude, and UTM are carefully traced from the scanned original onto a map base layer. The process is then repeated for the geologic contacts, essentially eliminating introduced hand-digitizer errors. Each type of contact is drafted onto separate layers as lines composed of smooth Bézier curves (being defined by two end points and two curve handles). This method of line generation is superior to that of Arc/Info, which can only draw straight-line segments between nodes. Complex linework is generated from a minimum number of Bézier curve points (nodes), thereby minimizing map file size. After the contacts are drafted, structures are traced from the scan onto their own layers in the same manner. Additional layers contain strike and dip and other symbols, which are drafted on the horizontal, directly above those on the scan, and then precisely rotated by entering the exact symbol azimuth into the rotation angle dialog box of the Transform panel.

When the linework is complete, contacts and structures that create geologic map unit contacts are "cloned." These lines are then closed into polygons, separated into layers based upon map unit designation, and assigned CMYK color values that correspond to a developed Arc/Info shadeset based upon USGS/NMBMMR cartographic standards. At this stage, each individual layer (attached to the grid) is exported from the Macintosh back to Arc/Info via MAPublisher 3.0, which exports each layer as individual ArcView shapefiles.

The final stage of digital map production for plot-on-demand paper maps, as well as postscript raster output, involves setting type and collar information in Macromedia FreeHand and attaching the topographic base to the geologic quadrangle. In Adobe Photoshop 4.0, the USGS digital raster graphic file for the specific topographic quadrangle is cropped to the neatline, cleaned, and exported as a TIFF file. In Macromedia FreeHand, it is then rendered transparent, screened to 60% black, and attached to the map file by aligning it upon the grid. The quadrangle is then rasterized in Image Alchemy and plotted on an Encad Novajet plotter on demand.

DIGITAL MAPPING AND ENVIRONMENTAL GEOLOGY: SOCIOECONOMIC IMPLICATIONS

The OF-DM quadrangles are selected by the New Mexico Geologic Mapping Advisory Board, consisting of geologists, hydrologists, and planners from federal, state, tribal, and local governments, as well as the private sector. The board bases priorities on socioeconomic importance, which currently revolves around stressed water resources. To date, quads chosen for OF-DM mapping are located in a) the Albuquerque basin, b) the surrounding mountain lowland communities of the East Mountain area to the east of Albuquerque, and c) the Santa Fe area, particularly where rapid development is occurring south of the city.

Albuquerque Basin

Geologic mapping has been concentrated in the Albuquerque basin due to the current concerns over ground-water availability and quality in New Mexico's largest metropolitan area. The USGS is leading an impressive cooperative effort (the Middle Rio Grande Basin Study – MRGBS) among various federal, state, tribal, and municipal agencies to gather and interpret geographic, hydrologic, and geologic data in order to identify, quantify, and better manage the region's water resources. Approximately 20 of our 36 total STATEMAP 7.5-minute quads lie within the MRGBS area. These are complemented by 12 NCGMP FEDMAP quads and 2 NCGMP EDMAP quads. Subsurface (borehole, geophysical) data are incorporated into these STATEMAP quads, thus greatly enhancing their value for MRGBS hydrogeologic modeling and model refinement.

At the northern end of the basin in the Placitas area, NMBMMR is conducting an extensive water resources assessment for Sandoval County. The Placitas 7.5-minute quadrangle (OF-DM 2), mapped at 1:12,000, is the cornerstone underlying these studies. The area extends from the basin across rift-margin faults into the Paleozoic and Proterozoic bedrock of the northern terminus of the Sandia Mountains. Ground water is found in a series of confined and unconfined, compartmentalized aquifers, where faults behave as both barriers and conduits for ground-water flow. In a setting of such geological complexity, OF-DM 2 has provided the framework for a thorough hydrogeochemical and hydrologic sampling and monitoring program designed to evaluate locations and rates of mountain front recharge, delineate aquifer zones, characterize water quality, and assess resource sustainability given current and future development trends.

Finally, basin STATEMAP quadrangles are being utilized by NMBMMR to compile a 1:50,000 map of the greater Albuquerque metropolitan area, depicting both surface and subsurface geology. This compilation will provide a series of critical, accurate Arc/Info coverages for input into the city's GIS database. Given the direct applicability of this digital product for ground-water resource sustainability assessment, it is greatly anticipated by city and regional planners.

Mountain Lowland Communities

In the mountain lowland communities east of the Sandia Mountains and Albuquerque, rapid development of largely upper class subdivisions (complete with approved planned golf courses) has recently caused water demand to exceed the carrying capacity of local aquifers. Landowners in the adjacent Estancia Basin (a closed basin to the east) are currently pumping large volumes of ground water to these East Mountain communities to meet these increasing demands. In April of 1998, county officials placed a moratorium on further subdivision development until ground-water studies of the region can be undertaken.

Not unlike Placitas, the East Mountain area is characterized by complex structural and stratigraphic controls on ground-water flow between mountain recharge areas and adjacent basins and these are poorly understood. A hydrogeologic consultant, who represents the commercial ground-water utilities in the Estancia Basin, has proposed that this recharge flowing off the eastern slope of the mountains flows unimpeded through faults to the Estancia Basin. He states that such a ground-water path exists because these faults are low angle, representative of a decollement that headed in the mountains to the west. If true, this suggests that recharge of deep Estancia Basin production wells may be adequate to prevent ground-water mining; if not, such potential consequential problems of a permanently lowered water table, a decline in water quality, and ground subsidence will likely result. New Mexico Office of the State Engineer (NMOSE) personnel have disagreed with the consultant, claiming that the ground-water flow is strongly influenced by high-angle bedrock structures, and instead flows into the Rio Grande basin along the Tijeras fault zone. The key to this debate involves characterization of the geometry of sedimentary strata and crosscutting faults. Our mapping has shown that the faults are high angle and, in fact, are more impressive in geometric complexity, width, and intensity of brittle fracturing than previously thought. As a result, NMOSE has introduced two of our new OF-DM quadrangles as evidence into the water rights hearings.

Santa Fe Area

Rapid growth is also occurring in and around the capital city of Santa Fe. Although Santa Fe itself relies largely upon surface water for municipal and domestic uses, the growing suburbs are pumping ground water. Development is proceeding at an alarming rate south and west of the city where ground water resources are scarce. In Santa Fe, shallow wells have recently become contaminated and water rationing was implemented in 1996. The city of Santa Fe, the county of Santa Fe, the NMOSE, and private consultants have all realized that they need modern, detailed surface and subsurface geologic data before decisions controlling growth are made. We are currently working on our third and fourth STATEMAP-funded 7.5-minute quadrangle maps in the capital area. In several years we will have covered most of the area of critical concern.

SUMMARY

In the last six years, NMBMMR has been pursuing an aggressive STATEMAP geologic mapping program, averaging over six quads per year at an average cost of $18,240 per quad. Given this rapid rate of mapping, and the fact that these maps were specifically located in areas deemed most socioeconomically critical, where city officials, planners, consultants, and scientists need modern, accurate digital geologic data, we were faced with developing a cartographic production methodology that allowed rapid dissemination of map data while maintaining established map standards. Thanks in part to the interactions of geologists and cartographers at DMT '97, we feel that we have now successfully met this methodological challenge by combining Arc/Info GIS capabilities and accuracy with the amenities of speed, appearance, and simplicity implicit in Macintosh-based graphics.

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Digital Conversion of the Austin West Quadrangle, Texas

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PROJECT GOALS

The Geologic Map of the Austin West Quadrangle is one of a series of digital data bases of geologic maps being produced by the Bureau of Economic Geology (BEG), The University of Texas at Austin. The goal of this effort is to make traditional BEG map products (previously only accessible as paper products) available in a digital geographic information systems (GIS) format. These digital GIS files are designed both for internal research by BEG staff and for use by other public and private entities.

This paper is intended for two audiences. First, it is directed toward experienced GIS analysts who will be using the Austin West files for GIS analysis and who wish to know the technical details about how these files were converted to digital format. This report is also intended for those people who are not experienced in GIS but who may become involved in a similar conversion project. We include a discussion of basic concepts as a possible model for future conversions.

METHODS

The conversion from paper maps to digital GIS format was accomplished using generally accepted cartographic standards. Film positives of original maps were scanned, automatically vectorized, and then coded with attribute information. Arc/Info 7.1 and ArcView 3.0 are the GIS programs used throughout the project to automate and construct tables for the maps. This document serves as the basic metadata summary and describes the methods used during digital conversion.

The files discussed in this report include Arc/Info coverages for geology, faults, points, roads, and cities from the quadrangle map. The digital files are arranged in layers that cover the Austin West Quadrangle, identical to the original map publication. The files are large scale and are best suited for analysis at the local level. The scale of the Austin West Quadrangle Map is 1:24,000. Although the digital GIS files can easily be combined with more precise, larger scale information, it is important to note that interpretation or analysis using these maps should always reference 1:24,000 scale or smaller.

ORIGINAL AUSTIN WEST MAP

The digital files for the Austin West Map are based on the 1:24,000 scale maps printed by the BEG (Rodda and others, 1979). The files reflect the 1979 map publication with no systematic update of features. A companion text by the same authors is available from the BEG that explains the geologic interpretation and provides a complete listing of data sources used in map compilation. To order the original paper map, consult the BEG's Internet site (http://www.utexas.edu/research/beg/).

DIGITAL CONVERSION

A four-step process was used to convert the map data to digital form:

1. **Automation**—A scanned image of the original film positive was vectorized, edited, and processed into arc, polygon, and point formats.
2. **Projection**—Digital files were transformed from digitizer coordinates to real-world coordinates and converted to a cartographic projection.
3. **Tables**—Tables were created to hold label information for polygons, arcs, and points.

4. **Symbology**—A symbol variable was added into the coverage tables and a shading keyfile developed for map plots.

The resulting products include eight digital GIS files and intermediate work files and an ArcView project configured for easy GIS viewing of these data.

Automation

The scanned film positive was automatically vectorized using ArcTools editing software. Line features were coded according to feature type, and polygon features were coded on the basis of their geologic description. Polygons were then labeled using an automated look-up table. All coverages were created using Arc/Info 7.1 in a UNIX operating system environment.

A paper check plot was printed and compared with the original map for accuracy and completeness. Any necessary edits to line placement or labeling were accomplished and noted. Node errors and label errors were corrected during the editing stage of work.

Projection Information

The original base map used to compile the geology data was a U.S. Geological Survey map of the Austin West Quadrangle, the original projection of the printed map is Polyconic. Digitizer coordinates were transformed into Polyconic and reprojected into UTM.

FLY-THROUGH ANIMATION

Fly-throughs are popular media for visualizing many forms of spatial information. The Austin West fly-through uses GIS technology and 3-D visualization to illustrate one of the basic principles of geologic mapping—topographic relief is commonly influenced by underlying geology. Color-coded geologic units (GIS coverage) are graphically combined with computer-derived hill shading and draped over a digital elevation model (DEM). The viewer is then placed in different positions relative to the geologic surface and "flown" over the terrain. The "fly-through" is presented as a tool for investigating spatial relationships between the surface expression of geologic units and topographic relief.

The digitized Austin West Quadrangle provides a thematic overlay for 3-D visualization of geologic-topographic relationships in the rolling Hill Country of central Texas. Meandering through the center of the quadrangle, the Colorado River and its tributaries dissect the Edwards Plateau to the west, providing a suitable setting for this type of terrain model.

The Austin West fly-through has two principal components. In addition to the DEM, an image of the thematic information is created as an overlay for the DEM. The overlay consists of a grid composite that combines a computer-generated hill shade effect with the geologic data. Hill shading enhances the 3-D quality of the surface by illuminating sunlit surfaces and darkening shaded areas. Care must be taken to avoid the loss of geologic information which may be obscured by shadows. The grid composite is then overlaid on top of the DEM to create the final surface.

A suite of GIS modeling programs are used to position the viewer relative to the surface. Once the "flight path" has been determined, multiple parameters must be considered and tested. Through trial and error, parameters such as height above the surface, distance between successive frames, and viewer orientation are determined. Screen captures are recorded as the viewer is moved through the surface to create a series of frames similar to the frames on a roll of video film. When the desired series of screen captures has been recorded, the animation video is assembled and edited. Arc/Info version 7.1.1 supports fly-through animation but has limited editing capabilities.

Future applications of animation and visualization will incorporate virtual reality technology. Virtual reality applications provide more information than a fly-through in that the viewer interacts freely with the data set and is not limited to a predetermined course of investigation. Sophisticated algorithms run on a powerful computer calculate the view model in near realtime as the viewer navigates through the data set. Advanced information technologies provide new models for understanding the complex spatial relationships inherent in geologic mapping.

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Recipes for Digital Cartography: Cooking with DEMs

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INTRODUCTION

For almost all purposes, shaded relief is more effective and efficient than contours for visualizing topography. The cartographic costs—mostly, restriction of the color and pattern palette available for portraying thematic map information—of a shaded-relief base are greatly outweighed by its benefits. Topography and geology are natural cartographic complements; most geologic maps are more informative when produced on a shaded-relief base. Such maps are best produced from digital elevation models (DEMs) and digital thematic map data, using the tools of digital cartography.

Like good cooking, good digital cartography is guided by taste, a knowledge of basic principles and materials, and master recipes that emphasize technique. Here we report principles and recipes that we hope others will find useful for working with DEMs. We assume our readers have some familiarity with Arc/Info and AML (Arc Macro Language). This note is not a primer to the GRID module of Arc/Info. Skill with GRID or a similar tool is necessary for working effectively with DEMs. You can acquire such skill by reading the documentation and experimenting; we are learning GRID this way.

We apologize for how hopelessly ARC-centric we are. We are so ignorant of other GISs that we don't even know to what extent the procedures given here can be adapted to them! (We hope they can be.) We don't mean to recommend Arc/Info as the only software suitable for digital cartography. We use it because it has been available and we have learned how to use it. We are currently working with Arc/Info version 7.1.2, under Solaris 2.5.1 and 2.6, on Sun Ultra hardware. Disk space on our systems is measured in the 10s of gigabytes. We share an HP650C plotter and currently use versions 1.0 and 2.0 of ArcPress. We have not installed any plotters in Arc/Info; we create plot files in ARC and queue these files to the plotter from the UNIX command line.

Bon appetit!

PRINCIPLES

Know Your DEMs

The quality of DEMs distributed by the USGS varies widely. The nominal quality descriptors (Level 1, Level 2, Level 3) do not adequately depict their usability. In general:

- 30-meter Level 2 DEMs, produced and distributed in 7.5' tiles, are gridded from 1:24,000- or 1:25,000-scale contours and are the best generally available DEMs. They are adequate for image-maps at scales of circa 1:100,000 or smaller. The USGS recently began producing 10-meter DEMs by the same technique. These are not more acccurate, but the greater detail provides a smoother image that is acceptable at scales as large as 1:24,000.

- 30-meter Level 1 DEMs were produced by semi-automatic profiling of stereomodels and interpolation—

which commonly leads to furrowed shaded-relief images—or with the Gestalt Photomapper, an early automatic image-correlation engine—which tends to produce irregularly patchy DEMs that map the tree-tops in forested areas. Such DEMs may not be usable for images at scales larger than 1:250,000. Stripes in profiled DEMs are commonly E-W and their visibility can be minimized by illuminating at azimuths near 90 or 270.

- 3-arc-second (circa 90-meter) Level 3 DEMs were derived from 1:250,000-scale contours with a primitive gridding algorithm and have defects that are objectionable when plotted at scales larger than about 1:1,000,000.

Before using any DEM, you should merge it with any adjoining DEMs you will also use, plot a shaded-relief image (recipe 6), and examine it closely. Look especially at large areas of low relief, at DEM boundaries, at shorelines, and at double-line rivers. Boundary mismatches may reflect mismatches in the source contours or may be artifacts of the DEM generation process. Then make histograms of Z values in each DEM (recipe 5) to appreciate some of the systematic errors that may be present.

USGS standards for DEMs *(http://mapping.usgs.gov/www/ti/DEM/standards_dem.html)* U.S. Geological Survey, 1990) contain no specifications for the quality of slope values calculated from DEMs. Slopes are commonly the most important aspect of DEMs for visualization; those who use DEMs for visualization must make their own assessment of the suitability of each DEM for such use.

Avoid Projecting DEMs

To project a DEM is to degrade it. A map should be made in the way that best honors its constituent data. Geology is generally in vector form, and thus easily projectable. Other raster data are generally less voluminous than topography. Thus, project other data into the DEM projection. For large-scale maps of areas within the United States, this means that you are working in UTM coordinates, datum NAD27. The significant exception to this rule is intermediate- or small-scale maps made with high-resolution DEMs, where the DEM is resampled to a significantly larger cell size.

Know Your Output Device

Graphics are device-dependent. As output devices and page-description languages improve this becomes less so, but for now it pays to learn how your output device responds to your instructions, and to customize your plotting procedures for your device.

Our experience is with large-format inkjet plotters. Among the rules we have learned (some the hard way) are:

- Don't change papers in the middle of the exercise. Color range and depth are different for different paper types. Stick with one paper brand. When and if you must change paper, plan on recalibrating your plot colors.
- A graphic that works on an inkjet plotter may not work on an offset press. The plotter has no registration error. Every color is exactly aligned with every other color. Trapping, chokes, and the number of press stations are not issues. Talk with a pre-press expert before designing maps to be printed with more than a couple of vector (lines and type) colors.
- Oversaturation can be dealt with. The HP650 and HP750-series plotters are prone to oversaturation, at least when plotting RTL files. We routinely rasterize with Saturation = 75%, at the cost of some (theoretical) range in color saturation.
- Dots put limits on legibility, shade, and linewidth. Inkjet plotters are dot-oriented. Colors other than the primary colors and their complements (cyan, magenta, yellow, red, blue, green, and black) are approximated by dithering, that is, juxtaposing adjacent dots of plotter ink to produce the illusion of intermediate colors. One-dot-wide lines or text can disappear into a dithered background, and this is especially true if the lines or text are not primary colors or their complements. On a 300 dpi plotter, 0.003" brown lines on a colored background can be nearly invisible.

The number of dots in an ordered dither cell puts a limit on the number of colors the plotter can produce. A random dither only partially avoids this problem. We look forward to acquiring a higher resolution plotter largely for its greater color depth.

Lines are 1, or 2, or n dots wide. Linesizes of 0.003" and 0.005" may be effectively the same width (1 dot) on your 300 dpi rasterizer/plotter. Experiment to find out (try recipe 1), and adjust your plot procedures accordingly.

- If possible, work to the resolution of your rasterizer/plotter. Raster images with greater resolution are merely excess data and a waste of disk space and CPU time. Images with less resolution are a waste of paper, unless those who view such images must stand at a distance from them. Using an ordered dither (ARC's RTL command), the 300 dpi HP650C appears to be a 75 pixel-per-inch device for gray-only images. A 30-meter grid plotted at 1:100,000 scale (3.3 grid cell/mm x 25.4 mm/inch = 84 dpi) has all the detail the plotter can produce. A printing press can reproduce greater detail. So, also, can the 300 dpi plotter with a different rasterizer (ArcPress's random dither)! Experiment.

Empirical Cartography

One of the great delights of GIS is that it makes cartography easy, in the sense that given operations can be repeated with little effort. With this ease of repetition comes the ability to make and remake a map, changing line weights, colors, text fonts, and so on until the map looks right. Plan on making your maps more than once.

Work from Scripts!

The ease of remaking a map is only maximized when you aren't typing long sequences of commands. Always work from scripts! Version-to-version improvements in a map are then accomplished by editing the scripts. Often building a map is a sequence of operations: assembling primary data coverages (by copying or clipping) and massaging intermediate coverages, drawing a graphic to the screen for an initial check on plot quality, and making a paper plot. We typically use three scripts (macros) for this sequence: makemap, drawmap, and plotmap. Makemap assembles and massages the primary data and has no graphics commands. Drawmap comprises graphics commands but does not specify the output device, and thus can be used to draw the map to the screen or to a plot file. Plotmap specifies the output device to be a plotfile and calls drawmap, rasterizes the resulting plotfile, and sends it to the plotter.

Understanding a map to be the product of primary data and a set of scripts (1) allows the map to be easily revised when the primary data are improved, and (2) eases storage space requirements. We try to discard intermediate coverages (unless they contain significant additional manual editing) and plot files, and only retain scripts. Working with scripts has the additional advantage of (3) preserving the cartographic tricks you have learned in written form, where they can easily be recycled by cutting and pasting.

Learn Some Programming Skills

Elementary programming skills will speed your cartography. Learn to use variables wherever possible. Isolate repeated sets of actions as routines or free-standing macros that are called by other parts of your script(s); this will make it much easier to recycle your scripts into the next map. A course in Pascal or another strongly structured programming language may be appropriate, simply to learn these habits of thought.

Have Enough Disk Space

DEMs gobble disk space. Depending on its size, a single map can require up to 0.5 GB of input DEM. You may multiply this by a factor of 5 in the course of constructing the map. Access to 2–3 gigabytes of free disk space is not unreasonable.

Learn the HSV Color Model

For mapping entities that are continuously variable (such as elevation and slope), a simple enumerated shade set may not be adequate to describe the colors on your maps. Color is then more usefully described using an effectively continuous color model (RGB, CMY, or HSV). HSV (Hue, Saturation, Value) is a natural way to describe the colors of topographic surfaces, for the V component can be assigned on the basis of brightness as calculated with the HILLSHADE command in GRID. Recipe 3 makes a hue-saturation color chart.

We know of two caveats to the HSV color model. First, machine (monitor, plotter) saturation is not proportional to human-eye saturation. At a given nominal saturation value, red, green, and blue appear more saturated to the eye than do yellow, cyan, and magenta. For the highest quality work, you may choose to calculate saturation as a (partial) function of hue. Second, ARC may unpredictably (but repeatably) produce undesirable effects when a Value grid contains values of 100. To avoid this, we routinely limit the maximum value to 99, which produces pale-gray collars around our maps. The gray can be masked with a white polygon when it is objectionable.

Think about Symbolization Space

When designing maps, it can be useful to imagine a multi-dimensional space defined by the available range of color (hue, saturation, value), and to reserve certain parts of this space to certain parts of the meaning of the map. A color shaded-relief base map that uses all the available color space will not work well as a backdrop to vector data. The necessary overlap of hue, brightness, and (or) saturation between the backdrop and the overlaid vector data will make the map too busy. A simple solution is to make room (in symbolization space) for overlaid vector data by narrowing the range of saturation and value, perhaps to NewSaturation = OldSaturation/2 and NewValue = 100 - OldValue/2. Then overlay the raster base with vector data plotted in fully saturated colors.

The concept of reserving certain parts of symbolization space for certain categories of meaning can also be applied to text, markers, patterns, and line-types.

RECIPES

Macros are not reproduced here because of space limitations. They are available online at *http://duff.geology.washington.edu/gis/recipes/* or may be obtained with an e-mail request to either author.

We hope these macros will be used, revised, and shared. If you significantly revise one of our macros, please note this in the macro header before you pass it on:

```
/* revised by <YOUR NAME> <YOUR
EMAIL ADDRESS> <DATE>
```

To make the structure of the macros more evident, and to shorten them, almost all error-checking is omitted. Similarly, all macros are designed to be run in the workspace that contains all other elements (input coverages, grids, lookup tables, other macros, and output) of the procedure. Both are questionable practices. Many of the macros will require minor editing before they can be used succesfully; unless a macro is to be called by other macros, we prefer hard-coding input parameters into the macro header to retyping them each time the macro is run.

All macro names are suffixed with .AML; these suffixes are generally omitted here. We work on UNIX systems that are tolerant of long file names. Those less lucky may need to rename some macros and some variables that specify file names within the macros.

1. Test linewidths on your rasterizer/plotter

Ingredients: Macros DRAWTEST, PLOTTEST

DRAWTEST creates a plot with single-stroke text (lines of varying orientations) of many linesizes. Look at the macro to see the use of a simple loop control (&do n = ...&end).

In Arc, type &RUN PLOTTEST. This will start ArcPlot, set DISPLAY 1040, call DRAWTEST, and create a graphic metafile called linetest.gra. Rasterize the plotfile using ArcPress, RTL, or other tool as appropriate, and plot it. Or convert the metafile to Postscript (see recipe 3) and use the plotter's Postscript interpreter to rasterize.

Look at the resulting plot with a hand lens. At what nominal line-sizes does your rasterizer/plotter combination change from one-pixel lines to two-pixel lines? Two-pixel lines to three-pixel lines?

2. A symbolset

Ingredients: IGL font `fnt035`, shadeset rockpat7.shd, macro MAKEINKJETPAT.

Plotter.shd and many of the simple markersets provided with ARC don't work well with an inkjet plotter. Yet geologists need pattern overprints to distinguish units. MAKEINKJETPAT produces the shadeset INKJETPAT.SHD which comprises a set of patterns suitable for overlays on geologic maps. Relevant features are:

- All patterns (except the first, for symbolizing wetlands), are produced in 1-pixel and 2-pixel wide lines on the HP650C
- All patterns (except the first) are produced only in fully saturated colors (black, white, cyan, magenta, yellow, red, green, blue)
- Coding and maintenance are simplified by use of subroutines

Problems with this shadeset include:

- It is dependent on the availability of the appropriate IGL fonts for templates (note that fnt035 MUST be in the workspace in which the pattern is used OR in the directory $ARCHOME/igl63exe)
- Adding a new variation to the patterns (for example, another linesize) can change the numbers of most of the patterns, making existing plotting routines incorrect

Similar procedures work for building a markerset or a lineset. Producing a new font with templates for other patterns is not that difficult; read the on-line documentation.

3. A hue-saturation color chart

Ingredients: Macros MAKEHSV, DRAWHSV, and PLOTHSV.

A hue-saturation color chart is essential for designing colored thematic maps (e.g., geologic maps) with shaded-relief bases. Plotting it can give you a sense of the color depth of your rasterizer/plotter combination. You can also use it to get a sense of the effects of different rasterizers. To make the components of an HSV color chart, type &RUN MAKEHSV at the ARC prompt. Macro DRAWHSV runs from ARCPLOT and draws the HSV chart. To plot the color chart, edit macro PLOTHSV to suit your rasterizer and printing system and type &RUN PLOTHSV at the ARC prompt.

To evaluate the effects of different rasterizers,

(1) plot an RTL file generated with ARC's RTL command

```
Arc: RTL hsv.gra hsv1.rtl # # # # 0
```

(2) plot an RTL file generated with ArcPress

```
Arc: &sys ARCPRESS hsv.gra -
ohsv2.rtl -dHP650C_CMYK -v
```

(note that the -d parameter is for an HP650C with ArcPress 1.0. It will be different for a different plotter and in ArcPress 2.0)

(3) use the internal Postscript rasterizer in your plotter, if it has one, by creating a Postscript file and plotting it.

```
Arc: &sys echo 'compress 0' > com-
press0
```

(This creates a one-line file Postscript parameter file that says "compress 0." If you don't use the compress

0 option, ARC defaults to a compressed Postscript that chokes most Postscript interpreters if the plot file contains a large bitmap.)

```
Arc: POSTSCRIPT hsv.gra hsv.ps #
compress0
```

The hue-saturation chart produced by these macros has value set to 98. This has proven suitable for designing geologic maps on shaded-relief bases where the shading is lightened and restricted as in recipe 9. You may want to try other values. The change is easy to make (line 33 in macro MAKEHSV).

4. Make your own DEM from DLG hypsography

Ingredients: DLGs downloaded from *ftp://edcftp.cr.usgs.gov, macros* IMPORTDLGS, ADDZ, and the ARC TOPOGRID command.

The DLGs (Digital Line Graphs), on-line at the Eros Data Center (*ftp://edcftp.cr.usgs.gov/pub/data/DLG*; see also *http://edcwww.cr.usgs.gov/*), are a great resource. Most of the elements, except annotation, for standard 1:100,000-scale 30'x60' maps for all of the conterminous United States are available through the Internet at no cost.

Good (contour-derived) 30-meter DEMs are not yet available for much of the United States. In their absence, DEMs that may be adequate for use as backdrops to other data can be produced from the 1:100,000-scale hypsography DLGs, which are available for most of the country.

To make such a DEM,

- Download the relevent DLGs from ftp://edcftp.cr.usgs.gov.
- Bring the DLGs into ARC with IMPORTDLGS. This macro makes a list of all gzipped optional-format DLG files in the workspace, and then for each file
  - renames the file so ARC doesn't have to deal with upper-case file names, which don't work in UNIX
  - ungzips, blocks, and imports the file into ARC
  - builds line and point coverages and constructs attribute tables
  - tests for the existence of MAJOR and MINOR attributes up to MAJOR4 and MINOR4. If they are missing, they are added to the attribute tables
  - joins attribute tables to coverage
  - appends the resulting tile-coverage into a compos ite coverage for each map-sheet
- Use ADDZ to create a uniform Z attribute for the DLGs
- Use the ARC TOPOGRID command to create a DEM from the Z-attributed DLG

Note that ADDZ is NOT warranted to work in all situations. We know it fails with some intermediate contours. You should be able to improve the macro. In some cases contours may be misattributed in the DLGs. Check your results, either by making a TOPOGRID DEM and inspecting it (easy, but may take lots of processing time), or by the following scheme, for which we thank Alan Rea (USGS, Oklahoma City):

```
Grid: CONTOURGRID = linegrid (CON-
TOURCOVER, Z, #, #, 30)

Grid: ZGRID = eucallocation (CON-
TOURGRID)

Grid: DIFFGRID = slope(ZGRID, PER-
CENTRISE)

Grid: DESCRIBE DIFFGRID
```

If DIFFGRID has any values greater than contour interval / gridsize, you have a mislabelled contour (or a coarse cell size included two contours in one grid cell.) To identify mislabelled contours, first create the file dgpaint.aml that reads

```
shadeset rainbow
gridshade diffgrid # linear
```

Then, in ARCEDIT,

```
Arcedit: editcover <contourcoverage>
Arcedit: drawenvironment arc
Arcedit: editfeature arc
Arcedit: ap dgpaint.aml
Arcedit: draw
```

TOPOGRID fits splines to the input data, and thus is prone to overshoots and undershoots at the tops and bottoms, respectively, of slopes. To examine your TOPOGRID-derived DEM for the resulting billowy topography, make and plot a shaded-relief image with MAKESR, DRAWSR, and PLOTSR (recipe 6, below). Add the following lines to DRAWSR before the penultimate line:

```
lineset plotter.lin
linesymbol 1
linecolor yellow
arcs <contourcoverage>
```

5. Histograms of DEM Z values

Ingredients: One DEM, macros DEMHIST1, DEMHIST2.

Usage: Grid: &RUN DEMHIST1 <DEM-name>; &RUN DEMHIST2 <DEM-name> <contour interval> <contour units (in DEM Z units)>

A large random sample of elevations from real topography will produce a fairly smooth histogram, excepting big spikes that correspond to lakes and the sea. An ideal DEM should also show an even distribution of Z values, but most DEMs derived from contours show biassing towards contour values.

These macros make histograms of Z values that demonstrate such biassing. DEMHIST1 makes a histogram of values over a range of +/- 100 units from the approximate mean elevation of the input quadrangle. If you know, or can guess, the contour interval of the map from which a DEM was made, use DEMHIST2 which makes a histogram of DZ values, where DZ is the difference from the (vertically) closest contour value.

DEMHIST1 creates an output grid that is not deleted; to run it a second time you must KILL grid <DEM-name>h1. Similarly, DEMHIST2 creates grid <DEM-name>h2.

DEMHIST1 and DEMHIST2 do not specify an output device. Run them from GRID with DISPLAY 9999 3 for the best on-screen graphic. Or specify DISPLAY 1040 and an appropriate pagesize before running each macro.

6. A simple shaded-relief map

Ingredients: One DEM, macros MAKESR, DRAWSR, PLOTSR

Usage: from ARC, &RUN DRAWSR <DEM-name>; &RUN PLOTSR <DEM-name>

MAKESR makes a shaded-relief map that will emphasize the stripey character of profiled DEMs. It maximizes the contrast of the DEM to show fairly subtle changes of slope at all slope angles. The resulting dark, contrasty image is not suitable for a base map; see recipe 7 for that. For a paper version of the shaded-relief map, edit PLOTSR for the mapscale and &RUN it. After you have finished, KILL the intermediate grid <DEM-name>shd.

7. Some shaded-relief variants

Most shaded-relief images are not directly suitable for use as base maps. We routinely lighten and modify the contrast on our images by

```
Grid: &DESCRIBE %shdgrid%
Grid: xxg1 = INT(((%shdgrid% -
%GRD$MEAN%) * %NewStDv% ) /
%GRD$STDV% + %NewMean%)
```

&DESCRIBE %shdgrid% sets the predefined variables GRD$MEAN and GRD$STDV to the mean and standard deviation, respectively, of %shdgrid%. The second statement creates a new grid with the mean brightness shifted to NewMean and scales the standard deviation to NewStDv. To make a Value grid (black = 0, white = 100) for a geology-on-shaded-relief map (below), we typically set NewStDv = 15 and NewMean = 95. One then usually needs to truncate the resulting grid to eliminate too-dark and illegal values:

```
Grid: NewGrid = CON(xxg1 < %min%,
%min%, xxg1 > %max%, %max%, xxg1)
```

For value grids used with the HSV color model to make geologic maps, we typically set Min = 70 and Max = 99. (If you will plot a gray-scale image with the GRIDPAINT command, NewMean, Min, and Max may be in the range 0–255.) Other uses will dictate other values of Min and Max.

Macro DEMSR uses a DEM, coverages of standing-water and glacier outlines, and the the HSV color model to create a color shaded-relief image. It HILLSHADEs the DEM, calculates a value grid from the the result, calculates hue as a function of elevation, and sets saturation to a constant. It then converts the standing water and glacier coverages to grids, calculates hue and saturation grids for water and glacier, and then MERGEs these with the z-derived hue and saturation grids. For more control over the colors created by DEMSR, substitute table-driven SLICEs to calculate hue and saturation from the input DEM.

We have found another variant of color shaded relief useful for comprehending the geomorphology of low-relief areas. Macro EDGES calculates value from slope, with steeper slopes (up to some threshhold) corresponding to higher values (darker areas on the resulting image). EDGES calculates hue as a stepwise function of elevation. The resulting image emphasizes subtle changes in slope in low-slope areas and allows immediate identification of similar (and different) elevations.

8. Geology on shaded relief

Ingredients: Polygon coverage of geology, DEM, look-up table describing colors of geologic units in terms of hue and saturation (start by running macro GEOUNITS), and macro SRGEOL.

The HSV color model is key: shaded-relief provides the V component, and geology (or other map theme) provides the H and S.

To use macro SRGEOL, you first create a lookup table that describes hue and saturation values for each polygon-type in the geology polygon coverage. So,

- Edit macro GEOUNITS so that the polygon-type item is the item in your geology coverage
- Run macro GEOUNITS to create the file <GeoCoverName>.UNITS
- Edit file <GeoCoverName>.UNITS. You are going to transform it from

***.UNITS** to	***.units**
unit	unit,tag,hue,saturation,pattern,unit-name
Ks	Ks,Ks,120,35,0,Cretaceous sedimentary rocks
Jkv	JKv,JKw,150,22,3,Wellman Volcanics
mCg	mCg,m#g,45,44,5,middle Cambrian granite
...	

The important features are the numeric values for hue and saturation. The other items—*tag, pattern*, and *unit-name*—could be omitted. We include them because (a) *tag* gives the freedom to change map-unit labels without having to alter the underlying coverage, (b) *pattern* easily specifies overprint patterns, and (c) *unit-name* makes the resulting file and look-up table easier to read and edit. Rename <GeoCoverName>.UNITS to all lower-case characters.

- Edit values in macro SRGEOL that identify the geologic coverage, the DEM, the illumination angles for shaded-relief, the text-table you have just created, and the name of the polygon-type item in the geologic coverage.
- Run SRGEOL. SRGEOL makes a shaded-image, makes a Value grid, reads the UNITS text-table into an INFO file, creates a SYMbology relate, and creates hue and saturation grids with POLYGRID <geolcover> SYM//hue and POLYGRID <geolcover> SYM//sat

Note that SRGEOL is designed to be run until it fails, the cause of failure corrected and identified, and the macro re-run. The most likely causes of failure are an improperly named or formatted *.UNITS file and incorrect definition of the info file SYM.<map> in routine SymInfo. As you evolve a coloring scheme for a map by making a map, looking at it, and identifying new hue, saturation, and pattern values for the geologic units, you can edit the UNITS text-table, KILL grids <mapname>hg and <mapname>sg, and rerun SRGEOL.

9. Geology on shaded relief under a DRG

Ingredients: HSV grids for a geologic (or other thematic) map, as created with recipe 8; a coextensive DRG; and macro DRGTHEME.

USGS Digital raster graphics (DRGs) are rectified, color-classified intermediate-resolution (circa 300 dpi) scans of standard topographic maps. Our limited experience with them suggests that the classification of pixel colors is too inconsistent for most analytic uses (e.g. separating contours from other features and vectorizing them). However, when plotted at the scale of the source-map, many DRGs make quite acceptable images. Macro DRGTHEME

- turns a DRG into a grid
- creates hue, saturation, and value grids that represent the DRG
- merges these H, S, and V grids with coextensive H, S, and V grids that represent a thematic map. Merging is done on a pixel-by-pixel basis: if a DRG pixel is classified as having a feature color (black, blue, red, brown, etc.), the DRG pixels are used; if the DRG pixel is classified as belonging to an area-fill color (white, green, yellow, light purple, etc.), the thematic-map pixels are used

For the best results, prepare the HSV thematic-map grids at a resolution appropriate to the scale of the final map. 1:24,000-scale maps which use shaded-relief as a component of the thematic map require circa 10-meter DEMs as input.

The resulting maps can have a complexity that strains the resolution and color depth of our 300 dpi HP650C plotter. They are significantly better when rendered on an HP2500C plotter.

10. Synthetic stereopairs

Ingredients: DEM, HSV grids from recipe 7, 8, or 9, and macro STEREO.

With a picture-map and DEM, it is straightforward to drape the picture-map on the DEM to create a perspective image using the SURFACE commands in ArcPlot. With the appropriate pair of viewpoints of the same map-area, one can create a pair of images that have the same geometry as stereoscopic aerial photographs. The resulting images can be viewed with a stereoscope and are an excellent way to teach map reading and communicate map relations.

Macro STEREO automates this process. To run it:

- Obtain map-coordinates for the central point of interest (in ground meters or feet)
- Choose the field-of-view width (in ground meters or feet)
- Edit the initial lines of STEREO to specify the DEM, HSV grids, and central-point coordinates and view-width, and to set PERSPTYPE to PERSPECTIVE (true single-point perspective, similar to photograph geometry) or PANORAMIC (panoramic perspective, corresponding to an anaglyphic image)
- `Arc: &Run STEREO`

If you have developed a macro to plot other elements of a map (contacts, faults, symbols), it is a simple matter to paste it into routine AnImage of macro STEREO. Be sure to precede each plotting command (e.g. ARCS, MARKERS) with SURFACEDRAPE.

Note that ARC plots perspective views rather slowly. Each pixel, including hidden ones, of a view appears to be preserved in the resulting graphics metafile. Subsequent rasterizing is slow and if you must create intermediate Postscript files they are unduly large.

For stereopairs you may wish to have your value grids contain more information than is desirable for a geologic map. This requires that they have a greater range of contrast and be darker overall, e.g. with mean value *circa 80*, standard deviation *circa 30*, and minimum value *circa 50*. See recipe 7.

11. Mapping on a DEM

Many geologic features are commonly mapped from landforms. Faults follow gullies. Quaternary alluvium ends where the valley floor butts up against steep ground. Older alluvium underlies terraces, and so on. When putting geologic maps on a shaded-relief base one quickly notices mismatches between contacts of Quaternary units and the representations of landforms (valley-bottom margins, terrace margins, and so on) with which they should coincide. An obvious step is to map these geologic features directly on an image derived from a DEM.

To do so,

- Make an image by one of the techniques in recipe 6, 7, or 8
- Write a short macro, e.g.
  `gridpaint <SHADEGRID> # # # gray`
  or
  `gridcomposite hsv <HUEGRID> <SATGRID> <VALGRID>`
  to draw this image to the screen. Do not include in the macro any commands that specify page size, map position, or map scale!
- In ARCEDIT, specify your geologic map coverage as the edit coverage, specify your simple plot macro with the AP command, DRAW, and proceed to map (digitize) features visible on the topographic image. As needed, edit your short plot macro to switch to another backdrop with a different illumination angle, or with shading by slope, or with elevation color coding.

ACKNOWLEDGMENTS

Haugerud thanks the Geophysics Program at the University of Washington for friendly and competent system administration, and the USGS National Earthquake Hazard Reduction Program for subsidizing plotting costs. A review by David Soller improved the clarity of our presentation.

REFERENCE

U.S. Geological Survey, 1990, Digital Elevation Models: U.S. Geological Survey, Data Users Guide 5, 51 p.

APPENDIX A

List of Attendees at the Digital Mapping Techniques '98 Workshop

[Grouped by affiliation]

Barry H. Tew, Geological Survey of Alabama

Gail Davidson, Alaska Division of Geological and Geophysical Surveys

Steve Richard, Arizona Geological Survey

Mike Howard, Arkansas Geological Commission
Angela Braden, Arkansas Geological Commission

David L. Wagner, California Division of Mines and Geology

Jonathon D. Arthur, Florida Geological Survey

Jane Freed, Idaho Geological Survey
Loudon R. Stanford, Idaho Geological Survey
Tim Funderburg, Idaho Geological Survey

Curt Abert, Illinois State Geological Survey
Sheena K. Beaverson, Illinois State Geological Survey
Sally Denhart, Illinois State Geological Survey
Chris Goldsmith, Illinois State Geological Survey
David Grimley, Illinois State Geological Survey
David Gross, Illinois State Geological Survey
Ann Hettinger, Illinois State Geological Survey
Jennifer Hines, Illinois State Geological Survey
Kari Kirkham, Illinois State Geological Survey
Chris Korose, Illinois State Geological Survey
Robert J. Krumm, Illinois State Geological Survey
Dave Larson, Illinois State Geological Survey
Alison Lecouris, Illinois State Geological Survey
Donald E. Luman, Illinois State Geological Survey
Jamie McBeth, Illinois State Geological Survey
Christopher McGarry, Illinois State Geological Survey
Don McKay, Illinois State Geological Survey
Mary Mushrush, Illinois State Geological Survey
Renee Nagy, Illinois State Geological Survey
Daniel O. Nelson, Illinois State Geological Survey
Matt Riggs, Illinois State Geological Survey
Joe Schoen, Illinois State Geological Survey
Bill Shilts, Illinois State Geological Survey
Lisa R. Smith, Illinois State Geological Survey

Barbara J. Stiff, Illinois State Geological Survey
Christopher Stohr, Illinois State Geological Survey
Colin Treworgy, Illinois State Geological Survey
Pius Weibel, Illinois State Geological Survey

Gordon Fraser, Indiana Geological Survey
Denver Harper, Indiana Geological Survey
Walter A. Hasenmueller, Indiana Geological Survey
Richard T. Hill, Indiana Geological Survey
Paul N. Irwin, Indiana Geological Survey
Rea W. Kersey, Indiana Geological Survey
Karen Like, Indiana Geological Survey
Ron Smith, Indiana Geological Survey
Kimberly H. Sowder, Indiana Geological Survey

Jim Giglierano, Iowa Geological Survey Bureau
Deb Quade, Iowa Geological Survey Bureau

David R. Collins, Kansas Geological Survey
Jorgina A. Ross, Kansas Geological Survey

Robert Paulsell, Louisiana Geological Survey

Lamere Hennessee, Maryland Geological Survey
Jim Reger, Maryland Geological Survey

Edith Starbuck, Missouri Division of Geology and Land Survey
Cheryl M. Seeger, Missouri Division of Geology and Land Survey

Joel G. Hall, Montana Bureau of Mines and Geology

Joe D. Gregson, National Park Service

Robert Chaney, Nevada Bureau of Mines and Geology

Ron Pristas, New Jersey Geological Survey

Kathryn Glesener, New Mexico Bureau of Mines and Mineral Resources
Michiel R. Heynekamp, 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

Allan Axon, North Carolina Geological Survey

Tom Berg, Ohio Geological Survey
Jim McDonald, Ohio Geological Survey
Edward Mac Swinford, Ohio Geological Survey

Paul Staub, Oregon Department of Geology and Mineral Industries

Bill Kochanov, Pennsylvania Geological Survey
Christine Miles, Pennsylvania Geological Survey
Thomas A. Whitfield, Pennsylvania Geological Survey

Elaine M. Foust, Tennessee Division of Geology

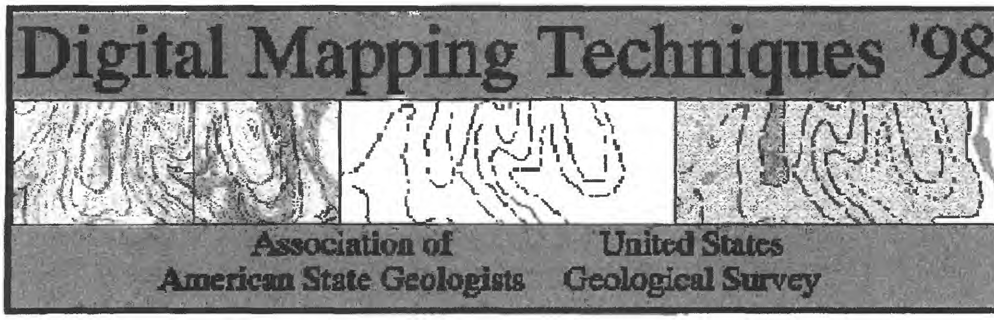
Jordan Hastings, University of Nevada, Reno

Terri Arnold, U.S. Geological Survey
David Fazio, U.S. Geological Survey
Ralph Haugerud, U.S. Geological Survey
Peter T. Lyttle, U.S. Geological Survey
John Nazimek, U.S. Geological Survey
Gary L. Raines, U.S. Geological Survey
Jennifer Sharpe, U.S. Geological Survey
David R. Soller, U.S. Geological Survey
Peter N. Schweitzer, U.S. Geological Survey
Ronald R. Wahl, U.S. Geological Survey

Carl F.T. Harris, Washington Division of Geology and Earth Resources

Chip Hankley, Wisconsin Geological & Natural History Survey
Mindy James, Wisconsin Geological & Natural History Survey
Deborah Patterson, Wisconsin Geological & Natural History Survey

APPENDIX B
Workshop Web Site



Hosted by the Illinois State Geological Survey
May 27th - 30th, 1998
Champaign, Illinois

The Workshop on Digital Mapping Techniques (DMT '98) is an Invitation-Only event designed to bring together those workers at state and federal agencies that are creating digital geologic maps in the United States. Topics will focus on methods of data-capture and digital map production. Please forward your poster abstracts and finalized paper drafts to Dave Soller, by June 15, 1998.

- Paper registration form
- Online registration instructions
- Recommended Lodging
- Conference Site Information

- Guidelines for Paper Submissions
- Poster Specifications
- Schedule of Events
- Conference Attendees
- Highlights

[Champaign-Urbana Maps | UIUC Campus Map | C-U Convention & Visitors Bureau]

[AASG | USGS | ISGS]

Illinois State Geological Survey
Digital Mapping Techniques Conference

Special thanks to the Kansas Geological Survey for the design of the DMT logos and the preliminary layout of these web pages. Visit the DMT '97 Web Page!

Please forward your comments or suggestions to beavrsn@isgs.uiuc.edu
This page last updated 06/01/98

APPENDIX C

List of Addresses, Telephone Numbers, and URLs for Software and Hardware Suppliers

[Information contained herein was provided mostly by the authors of the various articles and has not been checked by the editor for accuracy]

Adobe Illustrator, Photoshop and PageMaker - Adobe Systems Inc., 345 Park Ave., San Jose, CA 95110-2704, (408) 536-6000, http://www.adobe.com

Anatech Scanner and Scansmith Scanning Software - Intergraph Corp. Corporate Headquarters, Huntsville, Al 35894-0001, (256) 730-2000, http://www.intergraph.com

Apple Newton hand-held Personal Digital Assistant and Macintosh - Apple Computer Inc., 1 Infinite Loop, Cupertino, CA 95014, (408) 996-1010, http://www.apple.com

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

AutoCAD - Autodesk Inc., 20400 Stevens Creek Blvd., Cupertino, CA 95014-2217, (408) 517-1700, http://www.autodesk.com

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

COLORLITH - Kansas Geological Survey, University of Kansas, 1930 Constant Ave., Lawrence, KS 66047-3726, (785) 864-3965

CorelDraw - Corel Corp., 567 East Timpanogos Parkway, Orem, UT 84097-6209, (801) 765-4010, http://www.corel.com

DataDirect - INTERSOLV Inc., 9420 Key West Ave., Rockville, MD 20850, (301) 838 - 5000, http://www.intersolv.com/datadirect

EarthVision - Dynamic Graphics Inc., 1015 Atlantic Avenue, Alameda, CA., 94501-1154, (510) 522-0700, http://www.dgi.com

ENCAD Novajet Series Plotter - Encad Inc., 11145 Affinity Court #25, San Diego, CA 92131, (619) 547-5919

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

Hewlett Packard DesignJet Series Plotters (various) - Hewlett-Packard Co 8000 Foothills Rd., Roseville, CA 95747, 1-800-PACKARD, http://www.hp.com

HDS X Terminals - Hitachi Data Systems, 750 Central Expressway, P.O. Box 54996, Santa Clara, CA 95056, (408) 970-1000, http://www.hds.com

Image Alchemy - Handmade Software Inc., 48820 Kato Rd., Suite 110, Fremont, CA 94538, 1800-252-0101

INTERSOLV - see DataDirect

Macromedia Freehand - Macromedia Inc., 600 Townsend St., San Francisco, CA 94103, (415) 252-2000

MapPublisher - Avenza Software Inc., 3385 Harvester Rd. Suite 205, Burlington, Ontario, Canada L7N 3N2, http://www.avenza.com

ORACLE - Oracle, Inc., 500 Oracle Parkway, Redwood Shores, CA 94065, (800) ORACLE1, http://www.oracle.com/corporate/sales_offices

Sun, SUNOS and SOLARIS 2.5.1 - Sun Microsystems Inc., 901 San Antonio Rd., Palo Alto, CA 94303, (650) 960-1300, http://access1.sun.com

Surfer 4.0 and 5.03 - Golden Software Inc., 809 14th St., Golden, CO 80401-1866, (303) 279-1021, http://www.golden.com

Windows95 and WindowsNT - Microsoft Corp., One Microsoft Way, Redmond, WA 98052-6399, (425) 882-8080, http://www.microsoft.com

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