The National Geologic Map Database Project: Overview and Progress

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The National Geologic Map Database (NGMDB) project continues to fulfill its mandate. Some of its accomplishments are specific and tangible, and others are more general in nature – for example, the NGMDB contributes to advancements in digital mapping techniques and database design by agencies in the United States and internationally. However, without extensive collaboration from enthusiastic and highly skilled members of the state geological surveys and the Geological Survey of Canada, these accomplishments would not have been possible. Highlights of the past year include:

- the Geoscience Map Catalog now contains bibliographic records for more than 61,000 map products published by more than 270 organizations including the U.S. Geological Survey(USGS), 43 state geological surveys, universities, and scientific societies and organizations,
- the Geologic Map Image Library has evolved from a concept to a prototype Web site that serves high-resolution images of nearly 1,000 geologic maps,
- the project contributed significantly to evolution of the North American standard data model, science language, and data-interchange format, and to the cartographic standard for the U.S. Through discussions with ESRI, this data model may form the basis for their Geology Data Model for Arc Geodatabase. Internationally, NGMDB staff participated in "DIMAS", the map standards committee of the Commission for the Geological Map of the World,
- the seventh annual Digital Mapping Techniques workshop was a success, bringing together 90 technical experts from 36 agencies, and
- the third phase of the project – the design and implementation of an online, vector-map database – was reoriented mid-year, and began to focus on data input tools and standardized science language.

INTRODUCTION

This project provides an unusual if not unique opportunity to foster better relations and technical collaboration among all geological surveys in the nation. Given the nature of the issue – the creation and management of geoscience map information in digital format during a period of rapid technological evolution – collaboration is critically important. Perhaps more significant, these are changing times for all geological surveys – funding and staff seem to become more scarce each year – and through collaboration we can share our intellectual and computing resources and not "reinvent the wheel" within each agency.

Before describing the NGMDB components and progress, we wish to highlight the various mechanisms by which we define and accomplish our goals. Because advice, guidance, and technical collaboration are an integral part of this project, we discuss the project plan at numerous venues throughout the year. These include geoscience and related professional society meetings, the Digital Mapping Techniques workshop, and site visits to state geological surveys. Advice gathered at these venues serves to refine and, in some cases, to redirect the project's goals. Comments from users, generally via our Web feedback form, also provide us with valuable perspectives, and have prompted us to make numerous modifications, especially to our Web interface design.

Because the NGMDB's scope is so broad, its success relies on the many people and agencies that participate in its activities. Members of the committees and small working groups that advise and contribute to the project's goals are listed in Appendix A. These committees are an important mechanism for coordinating with each agency, and they deserve noting:

- Digital Geologic Mapping Committee of the Association of American State Geologists (AASG) – charged with representing all state geological surveys in the NGMDB project, and with providing authoritative guidance to the project.
- Technical Advisory Committee – provides technical vision and guidance to the NGMDB, especially on the project's Phase Three.
- Map Symbol Standards Committee – oversees the completion, and then the maintenance, of the Geologic Map Symbolization Standard, which will become a Federal standard endorsed by the Federal Geographic Data Committee.
- AASG/USGS Data Capture Working Group – coordinates the annual Digital Mapping Techniques workshop, and provides through an email listserver a forum for exchange of technical information.
- AASG/USGS Metadata Working Group – summarized issues related to creating metadata, and identified useful software tools.
- AASG/USGS Data Information Exchange Working Group – created technical guidance for map publication guidelines.
- AASG/USGS Data Model Working Group – defined a draft version of a standard geologic map data model.
- North American Data Model Steering Committee – succeeded the Data Model Working Group, and is developing a standard data model, science language, and data-interchange format for the North American geoscience community.
- NGDMB contact-persons – within each state geological survey, several people work with us on various project databases and activities.

BACKGROUND

The National Geologic Mapping Act of 1992 and its reauthorizations in 1997 and 1999 (PL106-148) require a National Geologic Map Database to be built by the USGS in cooperation with the AASG. This database is intended to serve as a "national archive" of standardized geoscience information for addressing societal issues and improving our base of scientific knowledge. The Mapping Act anticipates a broad spectrum of users including private citizens, professional geologists, engineers, land-use planners, and government officials. The Act requires the NGMDB to include these geoscience themes: geology, geophysics, geochemistry, paleontology, and geochronology.

In mid-1995, the general stipulations in the Geologic Mapping Act were addressed in the proposed NGMDB design and implementation plan developed by the USGS and AASG. Summaries of this plan are listed in Appendix B. Because of the mandate's broad scope, we proposed a phased, incremental design for the NGMDB. A phased approach has two benefits: 1) it enables us to identify the nature and quality of existing information and quickly serve it to the public; and 2) it gives us time to build consensus and expertise among the database designers in the state geological surveys and the USGS. Furthermore, it enables us to more effectively consider and respond to evolving technology and user needs. These phases, and our progress, are shown in figure 1.

In the first and most fundamental phase of the project, we are building a set of easy-to-use reference databases; for example, a comprehensive, searchable map catalog of all geoscience maps in the United States, whether in paper or digital format. The second phase of the project focuses on the development of standards and guidelines needed to improve the utility of digital maps. The third phase proposes to, in the long term, develop an online database of vector-based geologic map information at various scales and resolution.

In late 1995, work began on Phase One. The formation in mid-1996 of several AASG/USGS Standards Working Groups initiated work on Phase Two. The project opened its Web site to the public in January, 1997, as a prototype intended to solicit comments on the Map Catalog. At the Digital Mapping Techniques '98 through '03 workshops, a series of presentations and discussion sessions provided updates on the NGMDB and, specifically, on the activities of the Standards Working Groups. These progress reports are listed in Appendix B. This report summarizes accomplishments since the project's inception, and therefore repeats material from previous reports, but it focuses on activities since mid-2002. Additional and more current information may be found at the NGMDB project-information Web site, at <http://ncgmp.usgs.gov/ngmdbproject>. The searchable databases are available at <http://ngmdb.usgs.gov>.

To submit general comments about project scope and direction, please address the authors directly. For technical comments on the databases or Web page design, please use our Web feedback form; this form is linked from many of our search pages (see "Your comments are welcome", at http://ngmdb.usgs.gov/).

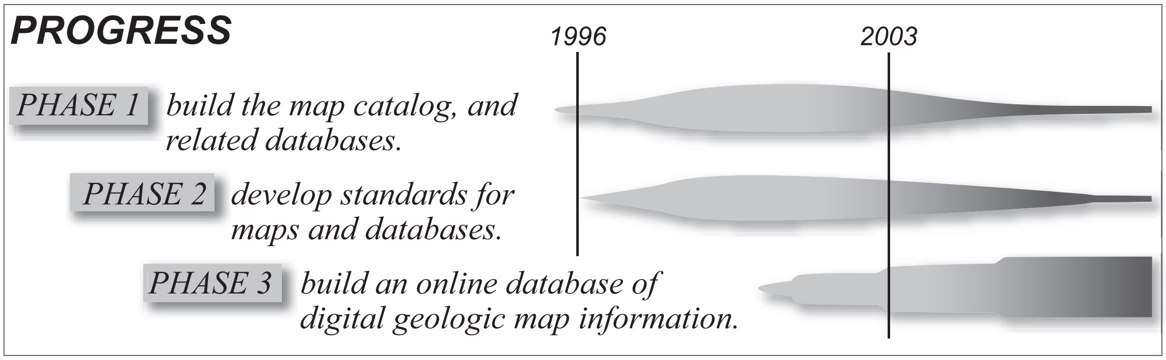


Figure 1. Diagram showing the three NGMDB Phases, and progress toward our goals (for example, documenting in the Geoscience Map Catalog all maps and related products for the United States and its territories and possessions).

PHASE ONE

Through ongoing discussions with private companies, citizens, government officials, and research geologists, it is clear that first and foremost, we need to provide reference databases so that geoscience maps and descriptive information can be found and used. Many people want to better understand the geologic framework beneath their home, business, or town, and so we are building several databases that support general, "data-discovery" questions posed by citizens and researchers alike (fig. 2). These reference databases are: 1) the Geoscience Map Catalog; 2) GEOLEX, the U.S. geologic names lexicon; 3) Geologic Mapping in Progress, which provides information for ongoing National Cooperative Geologic Mapping Program (NCGMP) mapping projects, prior to inclusion of their products in the Map Catalog; and 4) the prototype version of our Geologic Map Image Library – this new initiative is briefly described below, and in other papers in this volume. Plans for the prototype National Paleontology Database also are discussed below.

Figure 3 shows the number of people (actually, the number of unique IP addresses or computers) who have used the NGMDB, per month since it opened to the public in January, 1997. These numbers indicate that the site has become a useful resource. Additional increases in use are expected as the Map Catalog, Geolex, and Image Library become fully populated.

The Geoscience Map Catalog
"I want to know if a map exists for an area, and where I can find it…"

Many organizations produce paper and digital geoscience maps and related products. Discovering whether a product exists for an area, and if so, where it can be purchased or obtained online, can be a time-consuming process. In the past, people found this information by contacting various agencies and institutions, and by conducting extensive library searches. To increase accessibility and use of these paper and digital products, we built the Geoscience Map Catalog as a comprehensive, searchable database of all maps and related products for the United States and its territories and possessions.

The Geoscience Map Catalog contains bibliographic records for more than 61,000 products from at least 270 publishers (see Appendix C or our most current list of publishers at http://ngmsvr.wr.usgs.gov/ngmdb/pub_series.html). Most of these products are from the USGS and 43 state geological surveys. Other publishers include state agencies, federal agencies, scientific societies, park associations, universities, and private companies. Products range from digital maps to books that don't contain maps but describe the geology of an area, and can be formal series products, open-file reports, or unpublished dissertations (fig. 4). Because there are many types of geoscience maps and related products, we categorize them by theme (fig. 5).

The Geoscience Map Catalog provides links to more than 1,300 published, downloadable products of the USGS and the state geological surveys. These links are established only to stable Web pages that provide the official copy-of-record for the publication – in the USGS, links are established only to the Publications Server and the NSDI Clearinghouse node.

Figure 6 shows how the Geoscience Map Catalog can be used to find particular products – upon searching it and identifying the needed product(s), the user is linked to the downloadable data and metadata, to a depository library, or to the appropriate organization for information about how to purchase the product. We address the diverse needs of our user audience through four search options. The easy-to-use Place Name Search is based on the USGS Geographic Names Information System (GNIS); it is designed mostly to address the needs of non-geologists

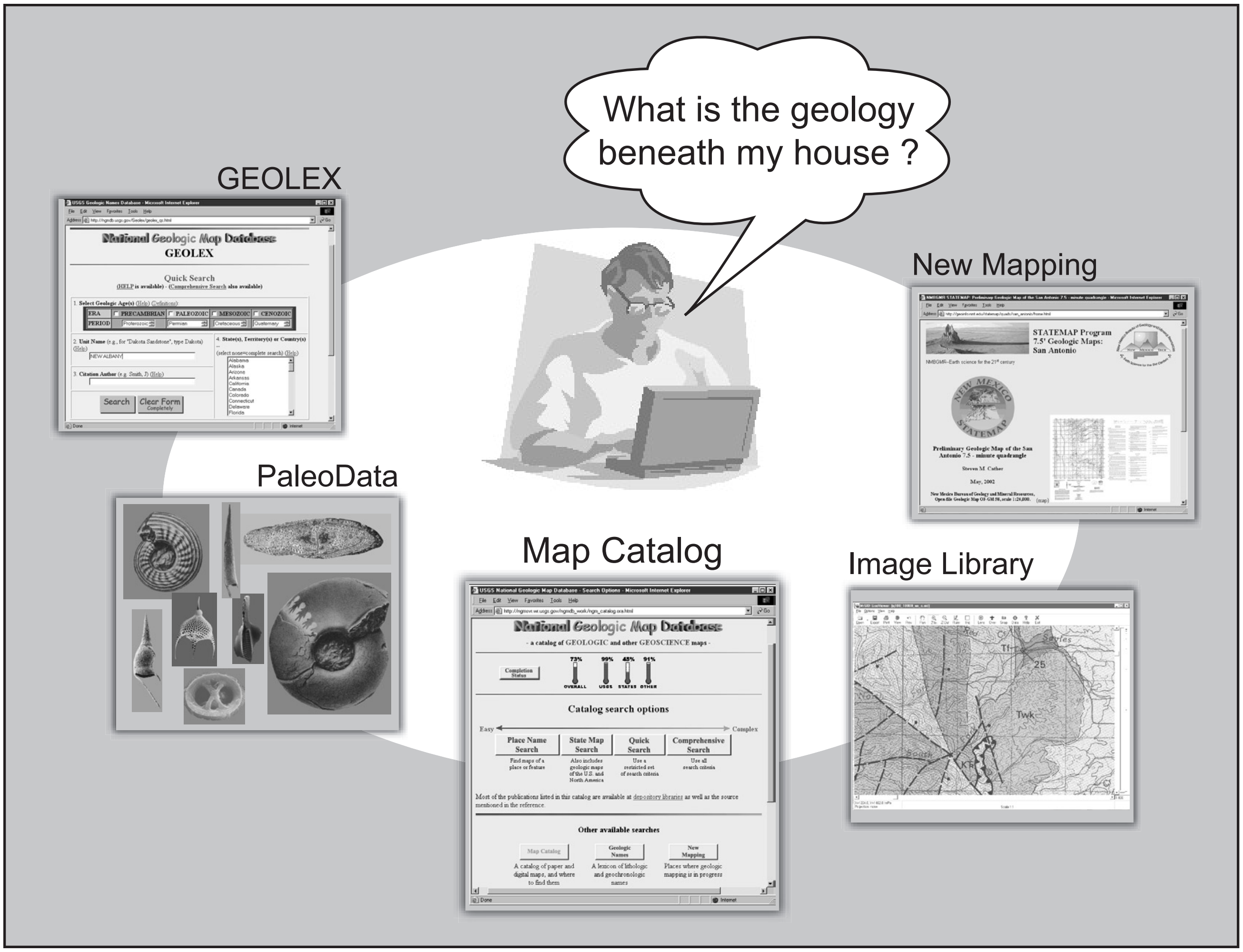


Figure 2. Many people want to know whether the geologic framework and the geoscience characteristics (for example, earthquake hazard, geochemistry) of an area have been studied and published. The reference databases built under NGMDB Phase One provide users with access to that information.

who want to use a simple interface to find information about their home, town, or worksite (fig. 7). In contrast, other choices such as the Comprehensive Search offer more search criteria.

The U.S. Geologic Names Lexicon ("GEOLEX") "I want to know more about the geologic units shown on this map…"

This is the nation's lexicon of geologic nomenclature. GEOLEX contains information for more than 16,000 geologic units in the U.S. (Stamm and others, 2000). It is an excellent resource for finding significant publications that defined and described geologic units mapped in the U.S. These publications can be critically important in field studies, enabling students and mappers to compare these published descriptions with what they see in the field.

GEOLEX includes the content of the four geologic names databases on USGS Digital Data Series DDS-6 (Mac Lachlan and others, 1996). Before incorporating into GEOLEX, those databases were consolidated, revised, and error-corrected. Our work now focuses on:

1. resolving the name conflicts found in the four databases of Mac Lachlan and others (1996). This is done by consulting publications, previous U.S. geologic names lexicons (listed in Appendix A of Stamm and others, 2000), and the records of the U.S. Geologic Names Committee (GNC),
2. using the previous lexicons to incorporate type locality, publication history, geologic age, areal extent, and usage information for many central and western U.S. geologic units listed in Mac Lachlan and others (1996),
3. adding geologic names not recorded in Mac Lachlan and others (1996) but found in the old USGS regional geologic names card catalogs (this is estimated to be 25% of all U.S. names), and

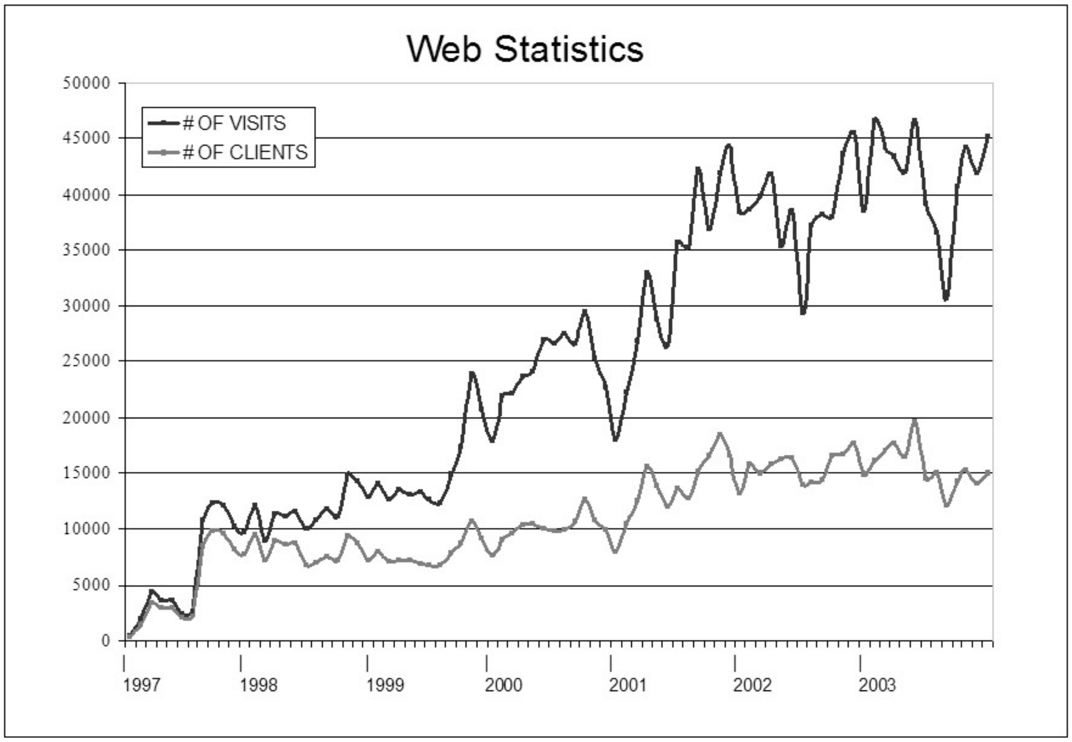


Figure 3. Web usage for the Geoscience Map Catalog, GEOLEX, and Mapping in Progress Databases. This diagram shows that the number of people (actually, the number of unique IP addresses or computers) using the NGMDB has gradually increased as these resource databases become more widely known; this usage trend is punctuated by sharp increases after essentially all USGS maps were entered into the Catalog and after many state geological surveys began to enter map records. The Catalog accounts for about 75-80% of user visits to the NGMDB site.

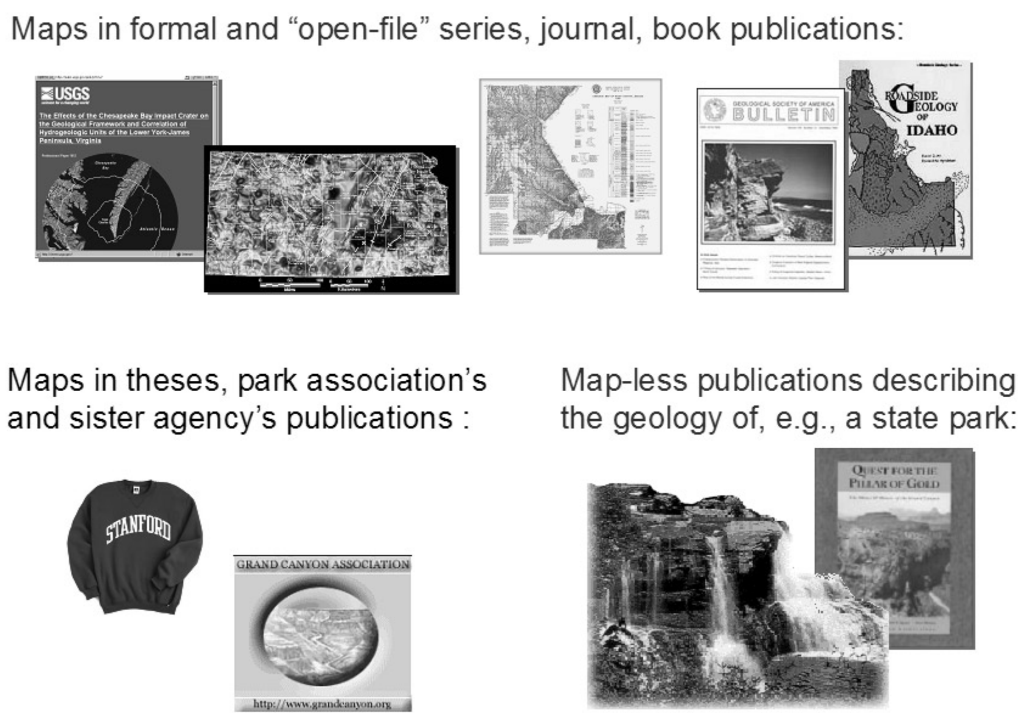


Figure 4. Bibliographic records in the Geoscience Map Catalog are drawn from a diverse group of more than 270 publishers.

GEOLOGY	GEOPHYSICS	MARINE GEOLOGY	RESOURCES	HAZARDS
☐ Bedrock	☐ Magnetics	☐ Geophysics	☐ Metals	☐ Earthquakes
☐ Surficial	☐ Gravity	☐ Coastal	☐ Nonmetals	☐ Volcanoes
☐ Structure Contours	☐ Radiometrics	☐ GLORIA	☐ Petroleum	☐ Landslides
☐ Engineering	☐ Other	☐ Other	☐ Coal	☐ Environmental
☐ Other			☐ Other Energy	☐ Other
			☐ Water	
			☐ Other	
☐ GEOCHRONOLOGY	☐ PALEONTOLOGY	☐ GEOCHEMISTRY		☑ ALL THEMES

Figure 5. A portion of the Geoscience Map Catalog search page, showing the types of products included.

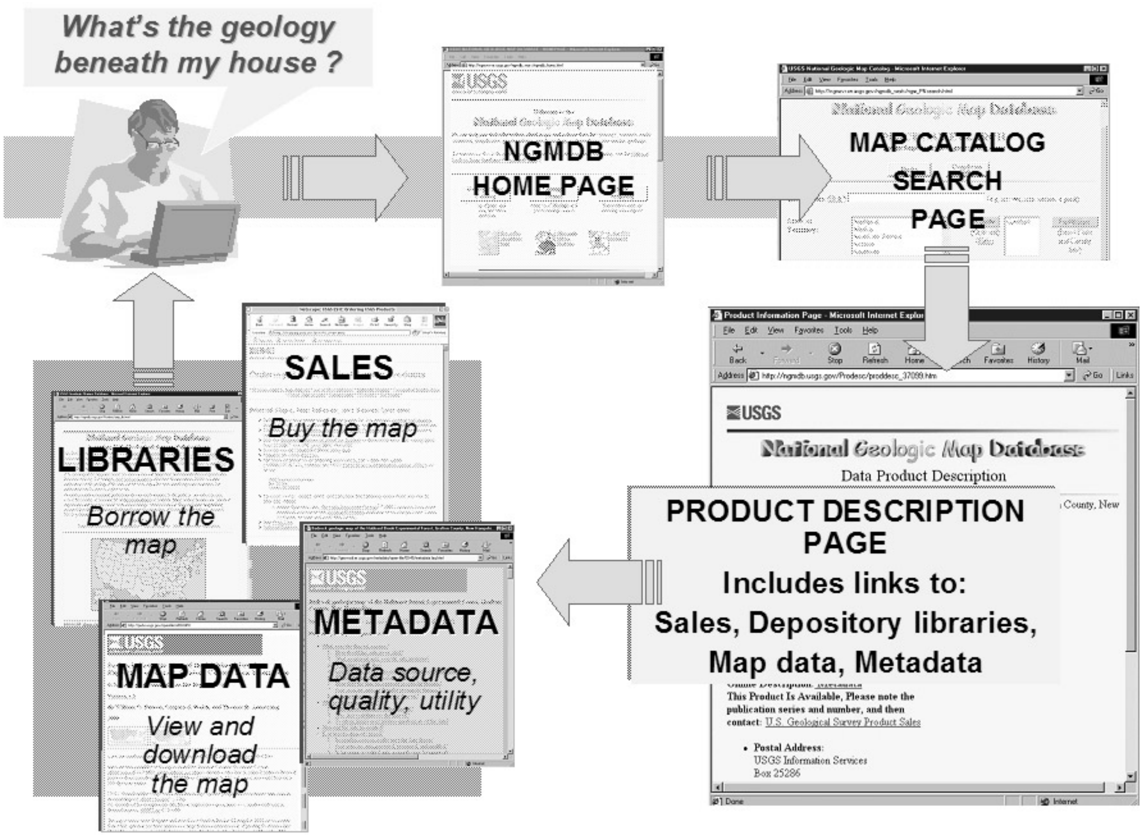


Figure 6. Diagram showing how a user navigates the Geoscience Map Catalog. Interested in knowing something about the geology of an area (such as the land beneath their house), the user queries the Catalog, which returns a hit list of possibly useful maps and related products. The user selects one of these and, from the Product Description Page, obtains further information and can then choose to buy the product, view and download it, inspect the metadata, or find it at a depository library.

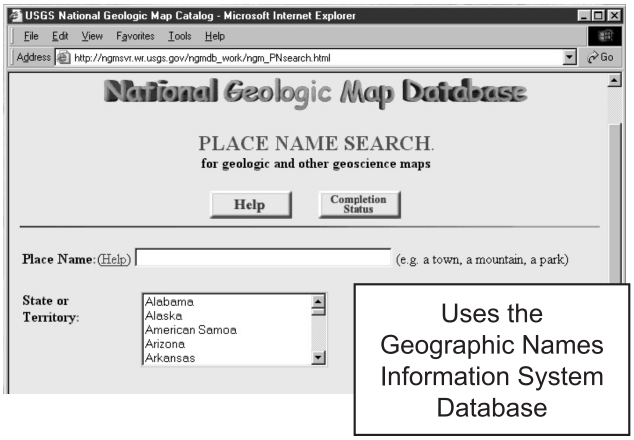


Figure 7. The first page of the Geoscience Map Catalog's Place Name Search.

4. adding geologic names approved by the state geological surveys but not recorded in GEOLEX.

Many state geological surveys have been registering new geologic names with the USGS for decades, and are encouraged to continue this practice. In order to promote standardized geologic nomenclature within the U.S., the GNC is being reconstituted. Formerly a committee that focused on nomenclature issues within the USGS, the new GNC will include members from each state geological survey (fig. 8). When a conflict arises, GNC members from the USGS and those states affected will resolve it, and any changes will be recorded in GEOLEX. Through this mechanism, we anticipate that GEOLEX will serve the entire U.S. geoscience community.

Geologic Mapping in Progress Database
"I see from the Map Catalog that a map hasn't been published for this area – is anyone mapping there now?"

Our Geologic Mapping in Progress Database provides users with information about current mapping activities (mostly at 1:24,000- and 1:100,000-scale, but at 1:63,360- and 1:250,000-scale in Alaska) that is funded by the National Cooperative Geologic Mapping Program. We are re-engineering and repopulating this database, and will be linking it directly to the state geological survey fact sheets and Web sites.

Geologic Map Image Library
"I want to see a picture of this geologic map, online…"

Through discussions with users, and from comments received via our Web feedback form, it became clear that many people are interested in viewing and/or obtaining

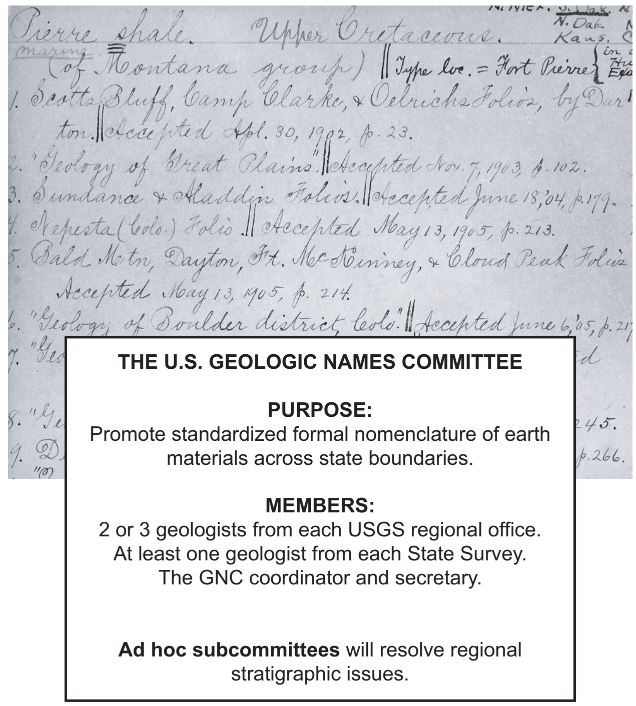


Figure 8. The purpose and membership of the reconstituted Geologic Names Committee. Background image is an index card from the files of the USGS Geologic Names Committee, ca. 1903, showing decisions recorded regarding the use of the Pierre Shale in the USGS Geologic Atlas of the United States folios.

maps "online." Interpretation of the phrase "providing maps online" varies widely—to some people, it implies access to fully attributed, vector-based map databases, whereas to other people, it implies access to map images. Regarding the vector-based map database, we address this large task in Phase Three, below. With the Image Library, we have begun to provide map images to users, as described in two papers in this volume. We hope this new initiative will further strengthen the cooperative relationship between the AASG and USGS.

Paleontology Database
"I want to know if there is any fossil data from this area…"

The NGMDB project has designed and is planning to develop a National Paleontology Database (see Wardlaw and others, 2001). Our general plan is to build prototypes of this database in areas where geologic mapping is underway, so that we can work with mapping projects to design a database useful to science as well as to the public. Plans for a prototype have been delayed somewhat, while we assess ways that the project might interact with the National Science Foundation's CHRONOS project (described in a paper by Wardlaw in this volume).

PHASE TWO

Phase Two focuses on development of standards and guidelines needed to assist the USGS and state geological surveys in efficiently producing digital geologic maps, in a more standardized and common format. Our profession encourages innovation and individual pursuit of science, and so the question may be posed – why do we need these standards? Clearly, standards should not impede science but instead should help us efficiently communicate our science to the public. The need for communication was perhaps best articulated by former USGS Director John Wesley Powell, while planning for the new Geologic Atlas of the United States:

"… the maps are designed not so much for the specialist as for the people, who justly look to the official geologist for a classification, nomenclature, and system of convention so simple and expressive as to render his work immediately [understandable]…" (Powell, 1888).

At that time, and throughout the early 20th century, Powell and others guided the USGS and the Nation's geoscientists toward a set of robust, practical standards for classifying geologic units and materials and representing them on maps. Those standards endured and evolved, and continue as basic guidelines for geologic mapping. Although today we commonly record in the field and laboratory far more complex information than during Powell's era, the necessity to provide it to the public in a standardized format remains unchanged. Newly evolving data formats and display techniques made feasible by computerization challenge us to revisit Powell's vision, and to develop standards and guidelines appropriate to today's technology and science.

In mid-1996, the NGMDB project and the AASG convened a meeting to identify the types of standards and guidelines that would improve the quality and utility of digital maps produced by the nation's geological surveys. From that meeting, Standards Working Groups were formed to address: 1) standard symbolization on geologic maps; 2) standard procedures for creating digital maps; 3) guidelines for publishing digital geologic maps; 4) documentation of methods and information via formal metadata; and 5) standard data structures and science terminology for geologic databases. The working group results will help provide a set of national standards to support public use of standard, seamless geologic map information for the entire country. In essence, Powell's pragmatic vision for the Geologic Atlas of the U.S. has been applied a century later to the National Geologic Map Database.

The tasks assigned to these Standards Working Groups are interrelated, as shown in figure 9 – when in the field, a geologist makes observations and (often, provisionally) draws geologic features on a base map; at that time, the accuracy with which these features are located

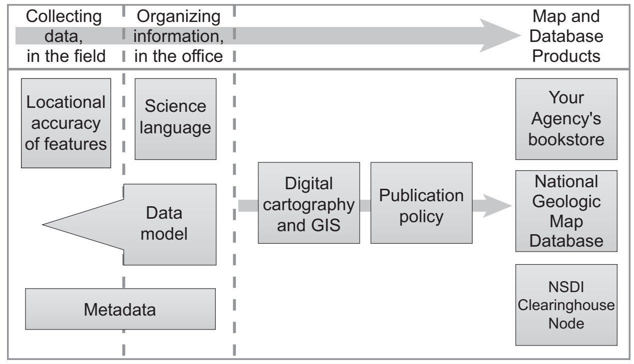


Figure 9. Diagram showing how the standards and guidelines under development by the NGMDB and related groups relate to the process of making a map.

on the map can be estimated. Further, the information may be recorded digitally in the field; if so, it can be structured similar to, or compatible with, the map database's structure (the "data model" in this figure). Returning to the office, the geologist commonly organizes and interprets field observations and prepares for map production – descriptions may be standardized according to an agency or project-level terminology or "science language," the map data may be structured according to the standard data model implemented by the agency, and procedures may be documented with metadata both in the office and when gathering data in the field. The descriptive information then is combined with the feature location information in a GIS, and digital cartography is applied to create a map that is published according to agency policies. Finally, the map is released to the public and accessed through various mechanisms including the NGMDB.

As described below, since 1996 these Working Groups and their successor organizations have made significant progress toward developing some of the necessary standards and guidelines. General information about the Working Groups and details of their activities are available at <http://ncgmp.usgs.gov/ngmdbproject/standards/>. Working Group members are listed in Appendix A.

Internationally, the NGMDB participates in venues that help to develop and refine the U.S. standards. These venues also bring our work to the international community, thereby promoting greater standardization with other countries. Examples include:

1. participation in "DIMAS", the map standards committee of the Commission for the Geological Map of the World (see article in this volume, and http://www.geology.cz/host/dimas.htm), and
2. development of a map database and standards Clearinghouse (http://ncgmp.usgs.gov/intdb/) that is endorsed by the International Union of Geological Sciences' Commission for the Management and Application of Geoscience Information ("CGI", http://www.iugs.org/iugs/science/sci-cnfo.htm) and the

International Association for Mathematical Geology (http://www.iamg.org/).

Geologic Map Symbolization

A draft standard for geologic map line and point symbology and map patterns and colors, published in a USGS Open-File Report in 1995, was reviewed in 1996 by the AASG, USGS, and Federal Geographic Data Committee (FGDC). It was revised by the NGMDB project team and members of the USGS Western Region Publications Group, and in late 1997 was circulated for internal review. The revised draft then was prepared as a proposed federal standard, for consideration by the FGDC. The draft was, in late 1999 through early 2000, considered and approved for public review by the FGDC and its Geologic Data Subcommittee. The document was released for public comment within the period May 19 through September 15, 2000 (see http://ncgmp.usgs.gov/fgdc_gds/mapsymb/ for the document and for information about the review process). This draft standard is described in some detail in Soller and Lindquist (2000). Based on public review comments, in 2002 a new section was added to the draft standard to address uncertainty in locational accuracy of map features. This section was presented for comment (Soller and others, 2002) and revised accordingly. With assistance from a Standing Committee to oversee resolution of review comments and long-term maintenance of the standard, the document is being prepared for submittal to FGDC, for final discussion and adoption as a Federal standard.

Digital Mapping

The Data Capture Working Group has coordinated seven annual "Digital Mapping Techniques" (DMT) workshops for state, federal, and Canadian geologists, cartographers, managers, and industry partners. These informal meetings serve as a forum for discussion and information-sharing, and have been quite successful. They have significantly helped the geoscience community converge on more standardized approaches for digital mapping and GIS analysis, and thus agencies have adopted new, more efficient techniques for digital map preparation, analysis, and production. In support of DMT workshops, an email listserver is maintained to facilitate the exchange of specific technical information.

The most recent DMT workshop, held in Millersville, Pennsylvania, and hosted by the Pennsylvania Geological Survey, was attended by 90 representatives of 36 state, federal, and Canadian agencies and private companies. Workshop proceedings are published (see Appendix B and http://ncgmp.usgs.gov/ngmdbproject/standards/datacapt/). Published copies of the proceedings may be obtained from David Soller or Thomas Berg.

Map Publication Requirements

Through the USGS Geologic Division Information Council, the NGMDB led development of the USGS policy "Publication Requirements for Digital Map Products" (enacted May 24, 1999; see link under Map Publication Guidelines, at http://ncgmp.usgs.gov/ngmdbproject/standards/). A less USGS-specific version of this document was developed by the Data Information Exchange Working Group and presented for technical review at a special session of the Digital Mapping Techniques '99 workshop (Soller and others, 1999a). The revised document (entitled "Proposed Guidelines for Inclusion of Digital Map Products in the National Geologic Map Database") was reviewed by the AASG Digital Geologic Mapping Committee. In 2002, it was unanimously approved via an AASG resolution, and has been incorporated as a guideline for digital map product deliverables to the STATEMAP component of the National Cooperative Geologic Mapping Program (see link under Map Publication Guidelines, at http://ncgmp.usgs.gov/ngmdbproject/standards/).

Among the geological surveys there are many approaches to determining authorship credit and citation format for geologic maps, digital geologic maps, and associated databases. It is prudent for agencies to adopt policies that preserve the relationship of the geologist-authors to their product, the map image, and to identify the appropriate authorship (if any) and/or credit for persons responsible for creating the database files. A summary of this issue and a proposed guideline was discussed at the Digital Mapping Techniques workshop in 2001 (Berquist and Soller, 2001).

Metadata

The Metadata Working Group developed its final report in 1998. The report 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 contains links to metadata-creation tools and general discussions of metadata concepts (see, for example, the metadata-creation tools, "Metadata in Plain Language," and other helpful information at <http://geology.usgs.gov/tools/metadata/>.

Geologic Map Data Model

In early 1999, the Data Model Working Group had concluded its work with release of a draft version of a data model (Johnson and others, 1998). The Group then was succeeded by the North American Data Model Steering Committee (NADMSC, http://geology.usgs.gov/dm/). State and USGS collaborators on the NGMDB continue to participate in this activity, helping to develop, refine, and test the North American Geologic Map Data Model ("NADM") and the standard science language that must accompany it. This work recently has produced a significant accomplishment, the NADM Conceptual Data Model. This model is available for perusal and comment, at <http://geology.usgs.gov/dm/steering/teams/design/NADM-C1.0/NADMC1_0.pdf>. Information about other Committee activities is provided in two papers in this volume: 1) the development of a XML-based interchange format; and 2) the development of standard science language to describe the lithology of earth materials.

To provide templates for building GIS data, ESRI is designing ArcGIS data models for many industries and applications (see http://esri.com/software/arcgisdatamodels/index.html). Through discussions that involved the NGMDB, ESRI plans to structure the ArcGIS data model at least in part on concepts in the NADM Data Model.

PHASE THREE

Over the past few decades, significant advances in computer technology have begun to permit complex spatial information (especially vector-based) to be stored, managed, and analyzed for use by a growing number of geoscientists. At the beginning of the NGMDB project, we judged that computer-based mapping was not a sufficiently mature discipline to permit us to develop an online, vector-based map database. In particular, technology for display and query of complex spatial information on the Web was in its infancy, and hence was not seriously considered by the NGMDB project as a viable means to deliver information to the general public. However, there now exists sufficient digital geologic map data; sufficient convergence on standard data formats, data models, GIS and digital cartographic practices and field data capture techniques; and sufficient technological advances in Internet delivery of spatial information to warrant a research effort for a prototype, online vector-based map database.

Before beginning to design this database, project personnel held numerous discussions with geoscientists and the general public to gauge interest in an online database and to define its scope. Based on these discussions, it was clear that this database should be:

1. built from edge-matched geologic maps at various scales;
2. managed and accessed as a coherent body of map information, not just as a set of discrete map products;
3. updated by mappers and/or a committee, "on the fly" when new information becomes available - it should be a "living" database;
4. standardized, adhering to a standard data model with standard scientific terminology; and
5. available to users via Internet browsers and common GIS tools (such as ArcExplorer).

This database will integrate with other databases developed under the NGMDB project. For example, a user accessing the online, vector-based map database might identify a map unit of interest, and then want to purchase or download the original published map product, or inquire about fossils found within that unit, or learn about the history of the geologic unit. Also, a user might access the Map Catalog and identify a map of interest, and then be linked to the online map database in order to browse and query it.

Prototyping

The NGMDB project has begun a series of prototypes, to advance our understanding of the technical and management challenges to developing the operational system; an introduction is given in Soller and others (2000). In 1999, we outlined some basic requirements for the prototype and tested them using map data for the greater Yellowstone area of Wyoming and Montana (Wahl and others, 2000). The second prototype (Soller and others, 2001) was conducted in cooperation with the Kentucky Geological Survey. In this prototype, we demonstrated in a commercial database system (GE-Smallworld) how the geologic database could be analyzed over the Web in concert with local datasets. The data model for the second prototype is described in Soller and others (2002), and was a significant contributor to the design of the new NADM Conceptual Data Model noted above.

Before proceeding further with plans for the publicly-accessible map database, we need to define a set of standardized terminology for the properties of earth materials (the science language). This science language must be sufficiently robust to accommodate terminology generated through today's field mapping, and terminology found in map unit descriptions on older and on smaller-scale maps, where descriptions tend to be highly generalized. Also, we need to collect enough standardized geologic map data to justify the cost of developing the database. Therefore, in our third prototype we will create map data with a standardized data model and science language, using available mapping in disparate field areas (central Arizona, northern Virginia, Kentucky, southern California, and the Greater Yellowstone Area; see fig. 10). To achieve this, we are writing data-entry software tools supported by science language derived from the NADMSC.

What is a data model, and how does it apply to geologic maps?

A data model provides organization to the descriptive and spatial information that constitute a geologic map.

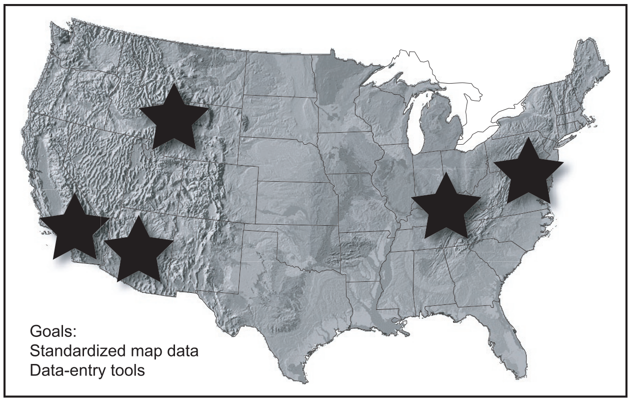


Figure 10. The goals of the current prototype are to: 1) create map data that has a standardized data model and science language, beginning with some national-scale maps and available mapping in disparate field areas shown above, and 2) create data-entry tools that are flexible and readily modified, enabling geologists to enter detailed, more standardized descriptive information.

The relations between a data model, science language, and the geologic map require some explanation. A data model may be highly conceptual, or it may describe the data structure for managing information within a specific hardware/software platform. In either case, it is a central construct because it addresses the database design for geologic maps in GIS format. In figure 11, the data model is simplified to four locations, or "bins", where information can be stored, with each bin containing many database tables and fields:

1. Occurrence – this bin contains the spatial geometry for each geologic feature in a map database. For example, the map unit identifier and the coordinates that define the outline of a map unit are included here.
2. Descriptor – this bin contains the wealth of descriptive information for each feature that occurs in the map database. This can include the full map unit description and simple attributes such as dominant lithology, color, and the nature of bedding.
3. Concept – this bin contains essential reference standards, such as geologic time scale(s) and science language. It also contains concepts and definitions essential for querying the database (for example, the concept that a rock can "intrude" another rock).
4. Symbol – this bin includes cartographic entities for symbolizing the map on-screen and in print form.

Will the U.S. have a single standard data model and science language?

The NGMDB online map database is envisioned as a distributed system that will provide seamless access to, and display of, map data served by many agencies. If all agencies used the same science language and exactly the same data model, and if it were implemented on the same hardware and software platform, a functional system would be relatively easy to build. That, however, is not a realistic scenario. Each agency has a unique history, set of objectives, and budget that will dictate the nature of their map database. (It should be noted that not all geological surveys in the U.S. can now afford to build such a system.) A more realistic approach is to assume a heterogenous computing environment, and to build software that can translate data structure and science language from one agency's system to another (fig. 12). This translation mechanism ensures "interoperability" between systems, and is the most realistic approach for the NGMDB.

To facilitate interoperability among systems, the NGMDB will define and maintain a set of reference standards (for data model, science language, time scale) based in part on those produced by the NADMSC. Interoperability software that enables disparate systems to appear to the user as a single system is being evaluated by groups including the NADMSC, NGMDB, and the National Science Foundation-funded GEON project. We anticipate collaborative research, especially with GEON, on XML-based "wrapper/mediator" technology to address these needs for the NGMDB. Through this technology, agencies should be able to correlate their unique data structure and scientific terminology to the reference standard, and the translator (presumably XML-based) will enable us to display the information to the user in a single view.

Extending the data model to include three-dimensional (3-D) map information

The data model was designed for the typical geologic map, which provides a two-dimensional representation of the geologic framework. On most geologic maps, this framework is expressed generally, in cross-sections and map unit descriptions. The data model can accommodate more detailed and location-specific 3-D information, although it has not yet been applied in this fashion.

Three-dimensional geologic map information can be represented by various methods. The most traditional approach is vector-based stack-unit mapping, where a vertical stack of surface and subsurface geologic units are combined into a two-dimensional (2-D) map unit (fig. 13a). The stack-unit characterizes the vertical variations of physical properties in each 3-D map unit. These maps are readily managed in the data model, like a traditional geologic map (fig. 11).

Map unit descriptions, whether on traditional 2-D geologic maps or vector-based stack-unit maps, apply to the entire unit. As a consequence, if a map unit's texture is described as "generally sandy, although fining to the east," the unit cannot be readily subdivided into areas that are sandy and those that are finer. This can be a limita-

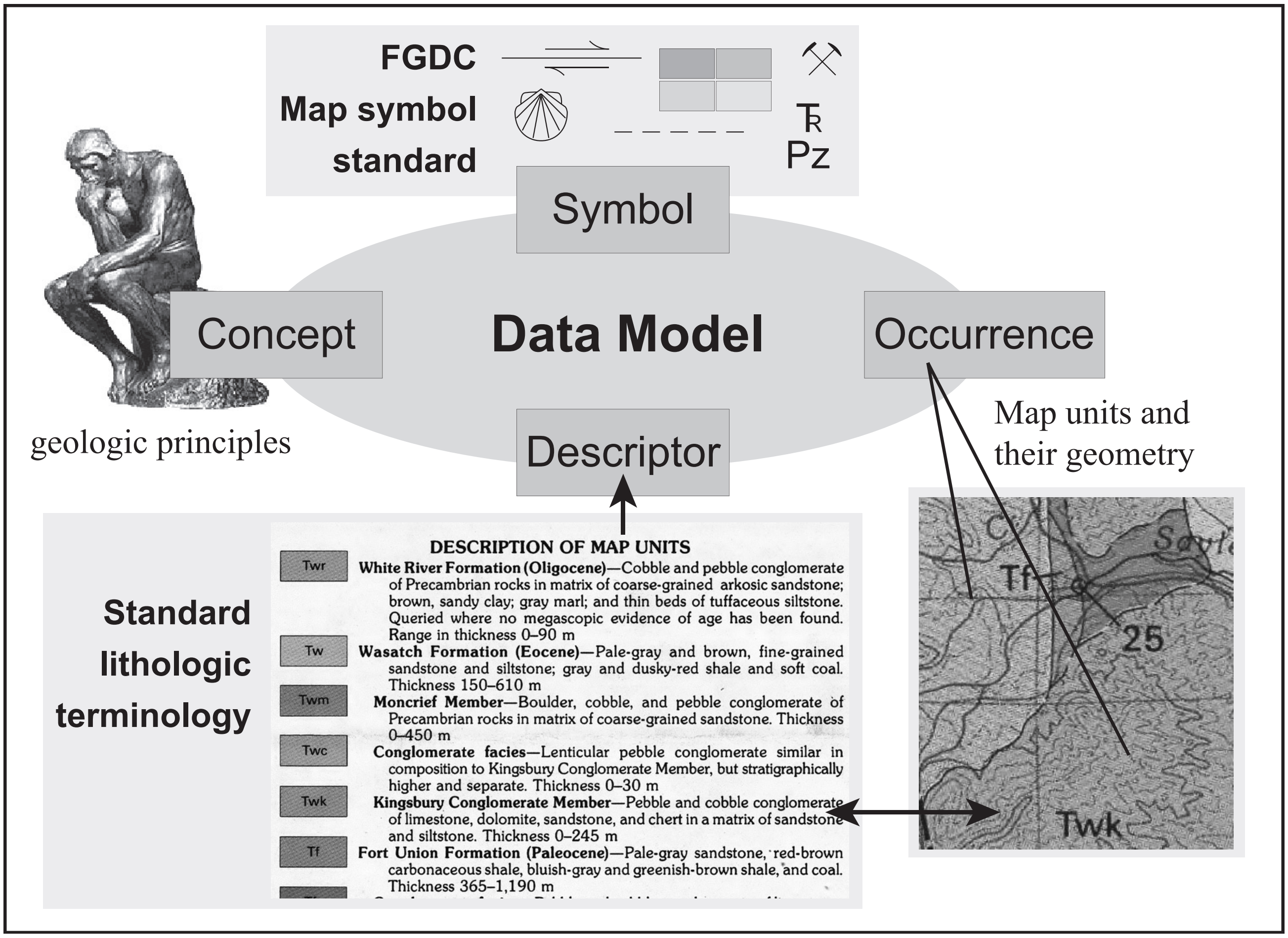


Figure 11. Simplified representation of the data model and its application to a typical, 2-D geologic map. The presence of a geologic unit on the map, referred to in the data model as an "occurrence" of that map unit, is described by: 1) its bounding contacts and faults, whose coordinates are stored as the unit's "geometry"; and 2) its physical properties, which are stored as the unit's "descriptors."

tion to users, especially when using the map for detailed studies. In contrast to vector-based stack-unit maps, voxel maps show every part of a geologic unit as a unique point known as a volume-pixel or voxel. Each voxel can have a unique set of attributes, therefore lateral and vertical variations in texture within the geologic unit can be described in great detail. Such information is difficult to collect at depth, and so in studies where this type of representation is needed, voxel attributes tend to be computed from a few point measurements within the geologic unit.

A third approach to 3-D mapping, raster-based stacked surfaces, offers a useful compromise between vector-based stack-unit and voxel-based mapping. In this approach, a set of 2-D elevation maps shows, in raster format, the surface of each buried geologic unit. These surfaces are in many cases rasterized from conventional, vector-based maps. Unlike the vector-based stack-unit map, they provide the opportunity to model the surface elevation and thickness of each unit, and to assign unique physical properties to each location on the unit's surface. Although not as detailed as a voxel representation, this approach requires less information and fewer assumptions about the 3-D variation of properties within the unit, and can more readily be created using conventional GIS software such as ArcGIS. Lateral variations in a physical property such as texture can be recorded; this is informative for units such as alluvium, which may have distinct subenvironments with different characteristics (for example, coarser material in the main channel, and finer material in overbank areas and tributaries).

Raster-based stacked surfaces (and, by extension, voxel-based maps) can be represented in the data model, as shown in figure 13b. This raster-specific information can significantly improve the value of geologic data when applied to, for example, groundwater modeling. The 3-D geometry of the glacial aquifer shown in figure 13b was provided to a private groundwater consortium in order to develop a regional groundwater flow model. The aquifer is composed of coarse sand and gravel in the main channel but is finer-grained in the tributaries because sedi-

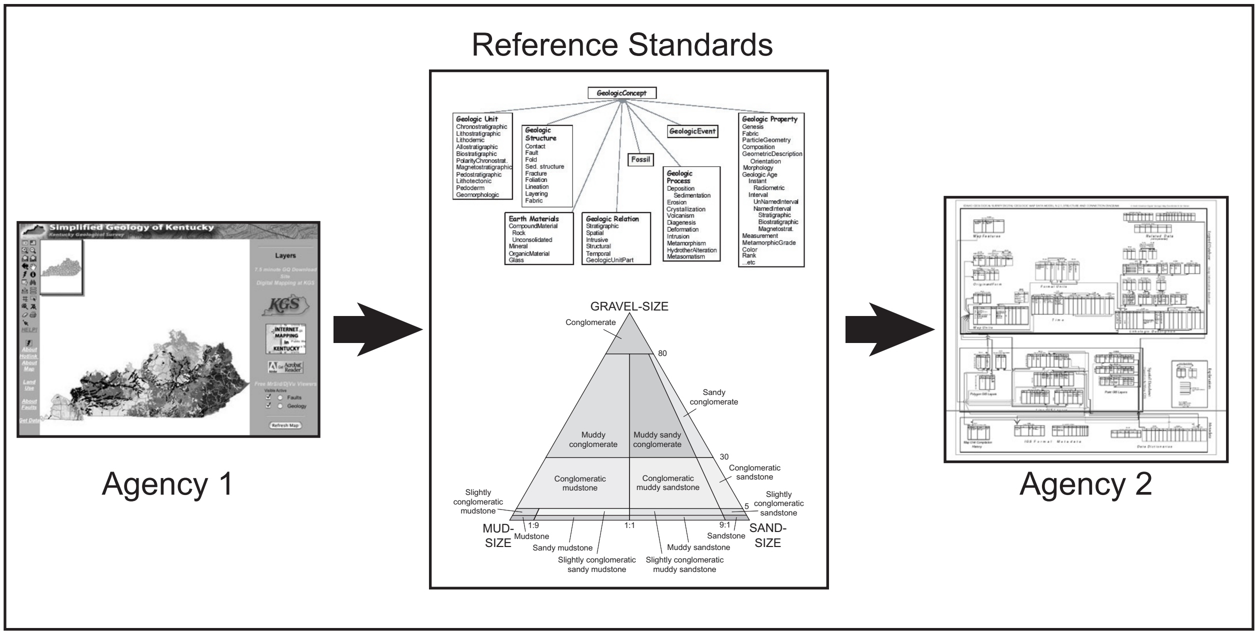


Figure 12. A single, monolithic system design shared by all agencies is unlikely. Rather, interoperability among the many agency databases linked together by the NGMDB database is the most logical design philosophy. In this diagram, we envision that map data from one agency (the Kentucky Geological Survey, http://www.uky.edu/KGS/) will be translated into reference standards (the data model and science language standards adopted by the NGMDB) and translated out to the criteria required by another agency (the Idaho Geological Survey's Geologic Map Data Model, http://www.idahogeology.org/Lab/datamodel.htm). This approach also could permit the NGMDB to coordinate the translation and display of multiple agency databases. In this diagram, the reference standards are represented by a schematic of the draft NGMDB data model (discussed in another paper in this volume) and an example of science language from Folk (1954, fig. 1a) showing a rock classification based on mud-sand-gravel content.

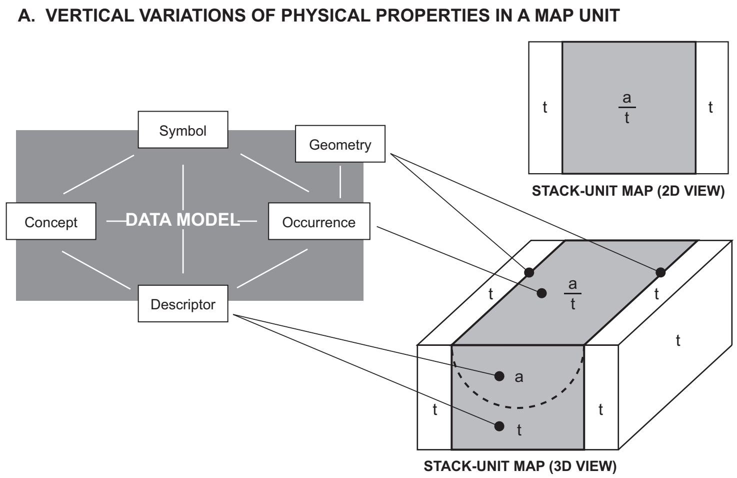
ment dammed the margins of the main channel, causing lakes to form in tributaries. When the 3-D information was provided to the consortium, the authors did not have sufficient data to assign to the units any lateral variations in texture. As a result, the groundwater modelers had to assume a homogenous aquifer. Raster surfaces that showed lateral variations in sediment texture would have enabled the modelers to consider the heterogeneity that was known to exist within that aquifer.

National and regional map coverage

The online map database will be more useful if it includes some geologic map coverage for the entire nation. To that end, the NGMDB has supported compilation and GIS development of several regional maps (fig. 14). Most significant is the digital version of the "Geologic Map of North America". This map is the final product of the Geological Society of America's (GSA) Decade of North American Geology project. The NGMDB has provided funding and expertise for development of the digital files that will be used to print the map, in order to engage GSA in a plan to develop a database for the map. When compilation and review of the map has been completed, hopefully within the next year, we will propose a database design and begin to populate the digital files made available from cartographic production of the map. This work will be conducted in collaboration with GSA and interested national geological surveys. The other maps shown in figure 14 are published or in press, and we intend to process these for inclusion in the online map database.

ACKNOWLEDGMENTS

The authors thank the members of the NGMDB project staff and collaborators for their enthusiastic and expert support, without which the project would not be possible. In particular, we thank: Nancy Stamm (USGS, Reston, VA; Geolex database, and general support and guidance to the project), Ed Pfeifer, Alex Acosta, Dennis McMacken, Jana Ruhlman, and Michael Gishey (USGS, Flagstaff, AZ; Website and database management), Chuck Mayfield and Nancy Blair (USGS Library; Map Catalog content), Bruce Wardlaw (USGS, Reston, VA; Paleontology Database), Robert Wardwell (USGS, Vancouver, WA; Image Library) and Kevin Laurent and Jeremy Skog (USGS, Reston, VA; Image Library), Steve Richard (Arizona Geological Survey, Tucson, AZ; data model and



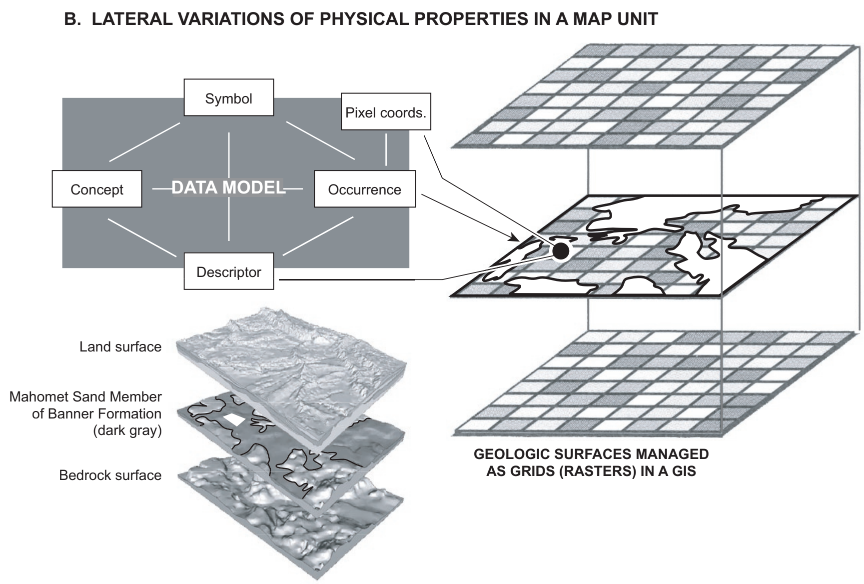


Figure 13. Approaches for representing three-dimensional map information, and for managing it in the data model.

A. Vector-based stack-unit maps depict the vertical succession of geologic units to a specified depth (here, the base of the block diagram). This mapping approach characterizes the vertical variations of physical properties in each 3-D map unit. In this example, an alluvial deposit (unit "a") overlies glacial till (unit "t"), and the stack-unit labeled "a/t" indicates that relationship, whereas the unit "t" indicates that glacial till extends down to the specified depth. In a manner similar to that shown in figure 11, the stack-unit's occurrence (the map unit's outcrop), geometry (the map unit's boundaries), and descriptors (the physical properties of the geologic units included in the stack-unit) are managed as they are for a typical 2-D geologic map.

B. Raster-based stacked surfaces depict the surface of each buried geologic unit, and can accommodate data on lateral variations of physical properties. In this example from Soller and others (1999), the upper surface of each buried geologic unit was represented in raster format as an ArcInfo Grid file. The middle grid is the uppermost surface of an economically important aquifer, the Mahomet Sand, which fills a pre- and inter-glacial valley carved into the bedrock surface. Each geologic unit in raster format can be managed in the data model, in a manner not dissimilar from that shown for the stack-unit map. The Mahomet Sand is continuous in this area, and represents one occurrence of this unit in the data model. Each raster, or pixel, on the Mahomet Sand surface has a set of map coordinates that are recorded in a GIS (in the data model bin that is labeled "Pixel coordinates", which is the raster corollary of the "Geometry" bin for vector map data). Each pixel can have a unique set of descriptive information, such as surface elevation, unit thickness, lithology, transmissivity, etc.).

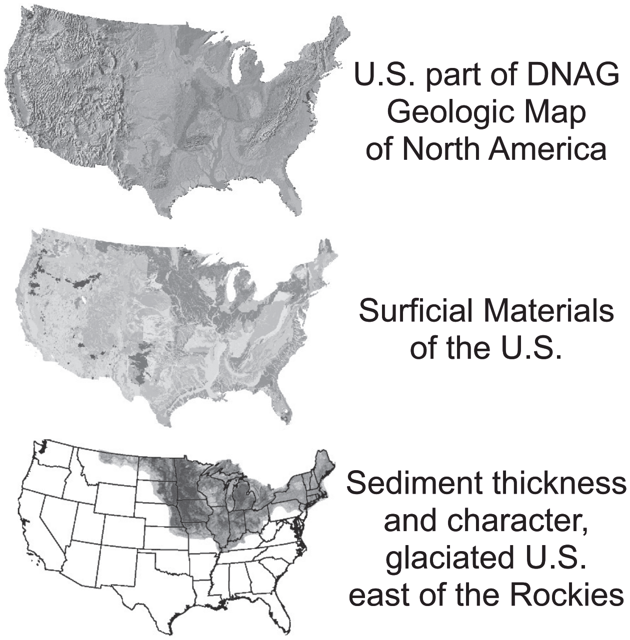


Figure 14. Regional maps whose compilation and/or GIS development is supported by the NGMDB. The uppermost map, the Geologic Map of North America, is discussed in the text. The center map is in press (Soller and Reheis, in press) and must be converted to a database. The database for the lower map is published (Soller and Packard, 1998) and will be adapted to the emerging NGMDB standards.

science language), Jonathan Matti (USGS, Tucson, AZ; data model and science language), and Jordan Hastings (USGS, Santa Barbara, CA; data model).

We also thank the many committee members who provided technical guidance and standards (App. 1).

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APPENDIX A

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Jerry Weisenfluh (Kentucky Geological Survey)

NGDMB contact-persons in each State geological survey:
These people help the NGMDB with the Geoscience Map Catalog, GEOLEX, the Geologic Map Image Library, and the Mapping in Progress Database. Please see <http://ncgmp.usgs.gov/ngmdbproject/statecontacts.html> for this list.

APPENDIX B

List of progress reports on the National Geologic Map Database, and Proceedings of the Digital Mapping Techniques workshops.

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APPENDIX C

List of publishers contained in the National Geologic Map Databases's Geoscience Map Catalog

Alabama Academy of Science
Alaska Division of Geological & Geophysical Surveys (1972-present)
Alaska Division of Geological Survey (1970-72)
Alaska Division of Mines and Geology (1966-70)
Alaska Division of Mines and Minerals (1959-66)
Alaska Territorial Department of Mines (1959)
American Association of Petroleum Geologists
American Geophysical Union
American Institute of Mining, Metallurgical, and Petroleum Engineers
Arizona Bureau of Geology and Mineral Technology
Arizona Bureau of Mines
Arizona Department of Water Resources
Arizona Geological Society
Arizona Geological Survey
Arizona Public Service
Arizona State University
Arkansas Geological Commission
Association of Engineering Geologists
Baylor University
Bowling Green State University
Brigham Young University Department of Geology
British Columbia Ministry of Energy and Mines
California Division of Mines and Geology
California Institute of Technology
California State University, Chico
California State University, Fresno
California State University, Humboldt
California State University, Long Beach
Canadian Hydrographic Service, Department of Fisheries and Oceans
Canyonlands Natural History Association
Colorado Geological Survey
Colorado School of Mines
Colorado State University
Columbia University Libraries
Columbia University School of Mines
Commonwealth of Virginia Department of Conservation and Economic Development
Confederated Tribes of the Colville Reservation
Connecticut Geological and Natural History Survey
Dallas Geological Society
Delaware Geological Survey
Desert Research Institute
Dibblee Geological Foundation
Eastern Washington University
Elsevier Science
Environment Canada
Field Conference of Pennsylvania Geologists, Inc.
Florida Geological Survey
Geodata International, Inc.
Geological Society of America
Geological Society of Nevada
Geological Society of Sacramento
Geological Survey Department, Jamaica
Geological Survey of Alabama
Geological Survey of Canada
Geological Survey of Michigan
Georgia Department of Natural Resources
Georgia Division of Mines, Mining, and Geology
Global Tectonics and Metallogeny
Grand Canyon Association
Great Plains Historical Association
GTR Mapping
Hawaii Commission on Water Resource Management
Hawaii Division of Water and Land Development
Hawaii Institute of Geophysics and Planetology
Hawaii Water Authority
Idaho Bureau of Mines and Geology
Idaho Geological Survey
Idaho State University
Illinois Basin Consortium
Illinois Oil and Gas Association
Illinois State Geological Survey
Indiana Department of Conservation
Indiana Department of Natural Resources
Indiana Geological Survey
Indiana University, Department of Geological Sciences
Institute of Food And Agricultural Sciences Service, University of Florida
Intergovernmental Resource Center, Clark County, Washington
Intermountain Association of Petroleum Geologists
IntraSearch, Inc
Iowa Geological Survey
John Wiley and Sons Publishers
Joint Transportation Research Program, Purdue University/Indiana Department of Transportation
Kansas Academy of Science
Kansas Geological Society
Kansas Geological Survey
Kentucky Department of Commerce
Kentucky Geological Survey
Lincoln-DeVore Engineers and Geologists
Loma Linda University
Los Alamos National Laboratory
Louisiana Geological Survey
Mackay School of Mines
Maine Geological Survey
Martel Laboratories, Inc.
Maryland Geological Survey

Massachusetts Institute of Technology
Medical Association of the State of Alabama
Memorial University of Newfoundland
Miami Geological Society
Miami University, Ohio
Michigan Department of Conservation
Michigan Department of Natural Resources
Mineral Resources Development, Inc.
Mines and Minerals (Scranton, PA)
Minnesota Department of Natural Resources, Division of Waters
Minnesota Geological Survey
Missouri Division of Geology and Land Survey
Missouri Geological Survey
Missouri Geological Survey and Resource Assessment Division
Montana Bureau of Mines and Geology
Montclaire State College, NJ
Mountain Press Publishing Company
Museum of Northern Arizona
National Academy of Sciences - National Research Council
National Well Water Association
Nevada Bureau of Mines and Geology
Nevada Department of Conservation and Natural Resources
Nevada Division of Water Resources
Nevada Petroleum Society
New Hampshire Academy of Science
New Hampshire Department of Environmental Services
New Hampshire Department of Resources & Economic Development
New Hampshire State Planning and Development Commission
New Jersey Geological Survey
New Mexico Bureau of Geology and Mineral Resources
New Mexico Bureau of Mines and Mineral Resources
New Mexico Geological Society
New York Academy of Sciences
New York State Department of Environmental Conservation
New York State Geological Survey
New York State Museum
New York, Oswego County Planning Board
North Carolina Department of Natural Resources and Community Development
North Carolina Department of Transportation, Geotechnical Engineering Unit
North Carolina Division of Mineral Resources
North Carolina Geological Survey
North Dakota Geological Survey
Northern Arizona University
Northwest Scientific Association
Northwestern University
Ohio Division of Geological Survey
Ohio Division of Shore Erosion (Ohio Division of Geological Survey)
Ohio Geological Society
Ohio State Univesity
Ohio University
Oklahoma Geological Survey
Oklahoma State University
Oregon Department of Geology and Mineral Industries
Oregon State University
Oxford University Press
Paleontological Research Institution
Pennsylvania First Geological Survey (1836-1842)
Pennsylvania Geological Survey
Pennsylvania Second Geological Survey (1874-1889)
Pennsylvania State University
Pennsylvania Third Geological Survey (1899-1914)
Petroleum Publishing Company
Portland State University Department of Geology
Primedia Business Magazines & Media
Princeton University
Puerto Rico Department of Public Works
Puerto Rico Division of Mineralogy and Geology
Puget Sound Power and Light Company
Purdue University
Purdue University Office of Agricultural Research Programs
Rhode Island Geological Survey
Rice University
Rockwell International, Rockwell Hanford Operations, Energy System Group
Royal Bank of Canada, Oil and Gas Department
San Diego State University
San Jose State University
Shannon & Wilson, Inc
Sigma Gamma Epsilon
Society of Economic Geologists
Society of Economic Paleontologists and Mineralogists
South Carolina Geological Survey
South Coast Geological Society, Inc.
South Dakota Academy of Science
South Dakota Geological Survey
Southern California Academy of Sciences
Southern Pacific Railroad
Springer-Verlag New York
Stanford University
State Geological Survey of Kansas
State of New Jersey Department of Conservation and Economic Development
Tacoma-Pierce County Health Department
Tennessee Division of Geology
Terrascan Group Ltd., Lakewood, CO
Texas A&M University
Texas Christian University
Texas Tech University
TRW, Inc
Tulane University
U.S. Army Corps of Engineers
U.S. Atomic Energy Commission

U.S. Bureau of Mines
U.S. Bureau of Reclamation
U.S. Department of Agriculture, Forest Service
U.S. Department of Agriculture, Natural Resources Conservation Service
U.S. Department of Energy
U.S. Department of Energy, Grand Junction Office
U.S. Department of Energy, Morgantown Energy Technology Center
U.S. Department of Transportation, Federal Highway Administration, Indiana Division
U.S. Geological Survey
U.S. National Oceanic and Atmospheric Administration
University of Alabama
University of Alaska, Fairbanks
University of Arizona
University of Arizona, Department of Geosciences
University of Arkansas
University of California
University of California, Davis
University of California, Los Angeles
University of California, Riverside
University of California, Santa Barbara
University of Chicago Press
University of Colorado, Boulder
University of Hawaii, Water Resources Research Center
University of Idaho
University of Illinois, Urbana-Champaign
University of Iowa
University of London
University of Missouri, Columbia
University of Missouri, Rolla
University of Nebraska Conservation and Survey Division
University of Nebraska, Lincoln
University of Nevada Las Vegas
University of Nevada, Reno
University of New Mexico
University of New Orleans
University of North Carolina at Chapel Hill
University of Oklahoma
University of Oregon
University of Puerto Rico
University of South Carolina
University of Texas at Austin, Bureau of Economic Geology
University of Texas, Austin
University of Texas, El Paso
University of Toledo
University of Tulsa
University of Utah
University of Utah Research Institute, Earth Science Laboratory Research Institute
University of Washington
University of Wisconsin
University of Wisconsin, Madison
University of Wisconsin, Milwaukee
University of Wyoming
Utah Department of Natural Resources and Energy
Utah Geological and Mineral Survey
Utah Geological and Mineralogical Survey
Utah Geological Association
Utah Geological Survey
Vermont Department of Water Resource
Vermont Geological Survey
Virginia Division of Mineral Resources
Washington Department of Conservation and Development
Washington Department of Ecology
Washington Division of Geology and Earth Resources
Washington Division of Mines and Geology
Washington Division of Water Resources
Washington Geological Survey
Washington State University
West Virginia Geological and Economic Survey
West Virginia Geological Survey
Western Michigan University Department of Geology
Willard Owens Associates, Inc.
Wisconsin Geological and Natural History Survey
Wright State University
Wyoming Geological Association
Wyoming State Geological Survey
Yale University