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CONFERENCIA GENERAL

NEW DIRECTIONS IN GEOLOGIC MAPPING AT THE U.S. GEOLOGICAL SURVEY

Por P. Patrick (*) y R. K. Kotra (**)

R E S U M E N

La cartografía geológica ha sido una actividad central del Servicio Geológico de los Estados Unidos (USGS por sus siglas en inglés) desde su comienzo en el año 1879. Las actividades de cartografía geológica se llevan a cabo primordialmente por el Programa Nacional Cooperativo de Cartografía Geológica. Este programa ha incorporado avances tecnológicos en computación y en análisis espacial de datos desarrollados en la última década para proveer datos geológicos en formatos de mapas digitales que son utilizados de varias maneras por el público como base de análisis y para tomar decisiones. Mapas que contienen varios tipos de información geológica, como los mapas geoquímicos, geofísicos, de recursos, de evaluación de peligro, y mapas que muestran otras características/atributos de terrenos, se producen para complementar los mapas de lecho de roca y de depósitos superficiales. La importancia y el alcance de la cartografía geológica en el USGS es evidente en el número de investigaciones actuales que utilizan mapas geológicos y sus derivados. Los mapas geológicos proveen la base de la estrategia para cumplir las siete metas científicas del USGS. La necesidad de la sociedad de adquirir información geológica y sus productos es mayor ahora que en ningún otro momento en la historia de la humanidad. Consecuentemente, el reto a los científicos contemporáneos estará en cuestionar la esencia misma de los mapas geológicos tradicionales y en el crear nuevos métodos y productos que satisfagan las necesidades y las espectativas crecientes de la sociedad por la información geológica.

A B S T R A C T

Geologic mapping has been a central or core activity of the USGS since its inception in 1879. Geologic mapping activities of the USGS are conducted primarily through the National Cooperative Geologic Mapping Program. Technological advances in computing and spatial-data analysis in the last decade are embraced by the program to provide geologic map data in digital formats that are used by the public at all levels to assist in analysis and decision-making. Maps containing various types of geologic information, such as geochemical maps, geophysical maps, resource maps, hazard assessment maps, and maps showing other land characteristics/attributes are produced to complement geologic maps of bedrock and surficial deposits. A number of current studies that utilize geologic and derivative maps demonstrate the scope and importance of geologic mapping in the USGS. Geologic maps form the foundation for addressing the seven science goals that have been identified for the geologic programs of the USGS. Society's need for geologic mapping and the accompanying products may be greater now than at any time in human history. The challenge to the earth scientist will be to question the very essence of traditional geologic maps and to create new products and approaches that will meet society's increasing needs and expectations for geologic information.

INTRODUCTION

The United States Geological Survey (USGS) was established on March 3, 1879, and was charged with a combination of responsibilities: "classification of the public lands, and examination of the geological structure, mineral resources, and products of the national domain" (Rabbitt, 1990). The year in which the Survey was established was one of great monetary uncertainty, when knowledge of precious-metal resources was vital, and one in which the iron and steel industry faced problems in obtaining suitable raw materials. Information about the Nation's mineral wealth, mining and metallurgical techniques, and production statistics was meager. For the Survey's initial program of work, therefore, our first Director, Clarence King, chose to emphasize mining geology, to devote but a small effort to general geology, and to confine paleontology and topographic mapping to what was necessary to support the geologic studies. Although King in so doing emphasized practical studies at the expense of basic studies, he nonetheless expected that the facts gathered in mining geol-

(*) Associate Director for Geology/Chief Geologist, U.S. Geological Survey
(**) Staff Scientist, Office of the Chief Geologist, U.S. Geological Survey

ogy studies would lead to advances in basic science. The budget for the first year was $100,000. The USGS budget for the last fiscal year was ~$800 million. We have grown from these modest roots during the past 120 years and include expertise and mission responsibilities in geology, hydrology, biology and geography, and a staff of more than 10,000. Geologic mapping has been a central activity of the USGS since its inception.

Today, the vision of the USGS is to be a world leader in the natural sciences through scientific excellence and responsiveness to society's needs. Our Mission is to serve the Nation by providing reliable scientific information to: describe and understand the Earth, minimize loss of life and property from natural disasters, manage water, biological, energy, and mineral resources, and enhance and protect our quality of life. The strategic direction set by our thirteenth Director, Charles Groat, is to combine and enhance USGS' diverse programs, capabilities, and talents and increase customer involvement to strengthen our scientific leadership and contribution to the resolution of complex issues.

The USGS comprises four science Divisions: Geologic, Water Resources, Biological Resources, and National Mapping. Detailed information on the USGS' organizational structure, programs and current activities are available via the Internet (http://www.usgs.gov). The Geologic Division (GD) has recently developed a science strategy for the decade 2000-2010 using the insights and advice of a diverse segment of the earth science community of the U.S. (Bohlen and others, 1998). The strategy consists of seven science goals that address pressing issues facing the Nation in the next decade. The first three goals define future thrusts in traditional areas of national leadership for the Geologic Division — studies of the Nation's geologic hazards and natural resources. The fourth goal defines a leadership role for the USGS within U.S. Global Change activities in carrying out regional- to national-scale syntheses on past climate reconstruction and assessments of the potential impacts of climate change or variability in sensitive geologic settings. The final three goals address societal issues which will be of increasing importance due to increasing concerns over quality of life. These involve establishing the geologic framework for ecosystem structure and function, interpreting the links between human health and geologic processes, and determining the geologic controls on ground-water resources and hazardous waste isolation. The Geologic Division's ability to respond to each of these societal goals requires a sustained investment in documenting the present and past state of the Earth and in using this information to predict future changes. In addition, all of these thrusts require a strong foundation of geologic mapping.

Geologic mapping activities of the USGS are conducted primarily through the National Cooperative Geologic Mapping Program (NCGMP). A Federal mandate, the National Geologic Mapping Act of 1992 established the NCGMP to implement and coordinate an expanded geologic mapping effort by the USGS, the State geological surveys, and universities. The primary goal of the program is to collect, process, analyze, translate, and disseminate earth-science information through geologic maps. Technological advances in computing and spatial-data analysis in the last decade are embraced by the program to provide geologic map data in digital formats that can be used by the public at all levels to assist in analysis and decision-making. In addition, maps containing various types of geologic information, such as geochemical maps, geophysical maps, resource maps, hazard assessment maps, and maps showing other land characteristics/attributes are produced under a number of other USGS programs. From hereon in this paper the term geologic mapping is used in a broad sense to include classical geologic maps as well as a variety of thematic maps which are increasingly produced by the USGS to meet a variety of societal needs.

SELECTED CURRENT GEOLOGIC MAPPING ACTIVITIES

Many USGS scientific studies in the Geologic Division as well as in other Divisions rely heavily on existing geologic maps and ongoing geologic mapping activities. Consistent with the mission and program long-term goals of the USGS, the production of geologic maps is a critical element that contributes to the success of our hazards, natural resources, and environmental investigations/programs. A number of current studies that utilize geologic and derivative maps are briefly described below to demonstrate the scope and importance of geologic mapping in the USGS. Some represent mature investigations in the final stages and others represent new efforts, some of which are in new focus areas for the USGS.

Bedrock Regional Aquifer Systematics Study (BRASS)

A new effort at the USGS has begun that will integrate the day-to-day work of field geologists and hydrologists. Interdisciplinary teams of scientists from the USGS are working together in several pilot projects to determine ways to improve models of the flow and chemical evolution of ground water in regions underlain by fractured bedrock. The goal is to maximize the resources, techniques, and talents of field geologists and hydrologists to answer a series of critical questions in a given watershed. For example, what is the relative influence on ground-water flow and storage, in a given volume of bedrock and regolith, of primary porosity versus secondary porosity? Of all the various types of secondary porosity, which are most influential: bedding planes, compositional contacts, cleavage, foliation, faults, or joints and fractures? How do these relative influences vary in different structural or tectonic regimes? What is the relative chemical influence on ground water of the bulk composition and primary mineralogy of bedrock lithologies and regolith versus the secondary mineralizations of veins and fracture coatings?

Within the study watersheds in New Hampshire, Pennsylvania, and South Dakota, activities by hydrologists and geologists involve the continuous transfer of data between two disciplines as part of an iterative process to refine the hydrogeologic model. The geologists will map the distribution of lithologies, sample them for petrographic and geochemical analysis, map and make extensive measurements of all structural elements and note evidence for ground-water flow through them. They would map seeps, springs, and wetlands, incorporate geophysical data, and define the tectonic history of the area. The hydrologists would gather streamflow, precipitation, and well data, conduct seepage runs, measure stream temperature and conductance, sample streams for water chemistry, conduct aquifer tests, conduct borehole and surface geophysical surveys, and model ground-water flow. A critical element of this new project will be the transfer of information between hydrologists and geologists *when* it is collected, not years later. This will allow continuous redesign and modification of project plans that, for example, would allow hydrologists to place stream gages at significant geologic contacts identified by geologists, and to obtain geologic explanations for anomalous chemical compositions of water.

In the summer of 1998, USGS scientists mapped the bedrock geology of two 71/2-Minute quadrangles in southern New Hampshire as part of the BRASS effort. The primary objective centered on evaluating the influence of geologic structures (particularly fractures) on the distribution and quality of ground-water resources. Analysis of the distribution of lithologies, brittle fracture parameters, and ductile deformation were coupled with results from spatial analysis of domestic well yields. This analysis showed very distinct trends with different orientations for the different mapped rock units. Comparison of the geological data with these spatial analysis patterns showed a direct correlation between mapped tectonically controlled fracture domains present in each of the rock units and the directional trend of ground-water flow.

In addition to their work in southern New Hampshire, detailed geologic mapping and brittle fracture analysis was conducted within the Hubbard Brook watershed in central New Hampshire. This work included the subdivision of the complex crystalline rocks into twelve different lithologic units, the identification of two major fault zones, which may provide constraints upon bedrock ground-water flow paths and stream discharge. This work supports the growing conclusion that precise geologic boundary constraints are essential towards developing effective ground-water models of fractured bedrock and accompanying surface water.

3-Dimensional (3-D) Geologic Maps

To ensure that our scientific information and data are incorporated into public policy decisionmaking, we are continuously making the Nation aware of our research and are helping the public understand its significance. Innovative presentations of geologic data are more useful to planners than standard geologic maps or data. One example of such innovative presentations is 3-D geologic maps. As much as possible, the 3-D maps incorporate point and surface data, continuous property information, and geologic relationships. The maps include geologic units as well as physical or chemical properties throughout. Available software permits the manipulation of the images to slice, twist, turn, etc. Some of the specific 3-D geologic maps being developed currently address: (i) earthquake hazards in the San Francisco Bay region, (ii) mineral resource potential in the Basin and Range Province , (iii) ground water movement beneath Pahute Mesa in the Nevada Test Site, and (iv) contaminant plume propagation in the southern Santa Clara Valley - San Francisco Bay region.

Figure 1 shows an application of the 3-D approach to earthquake hazards. This is part of an effort to estimate potential ground shaking due to earthquakes on faults of the San Andreas system in the San Francisco Bay region. The specific task is to create a 3-D velocity/density/attenuation model of the region to a depth of about 30 km, and to use this database for computer simulations of ground shaking due to scenario earthquakes on specific faults. The figure is derived from a 3-D geologic and geophysical database consisting of digitally defined 3-D map elements (e.g. faults, depositional strata, and topography). It also includes scattered data such as earthquake hypocenters for 1969-1994

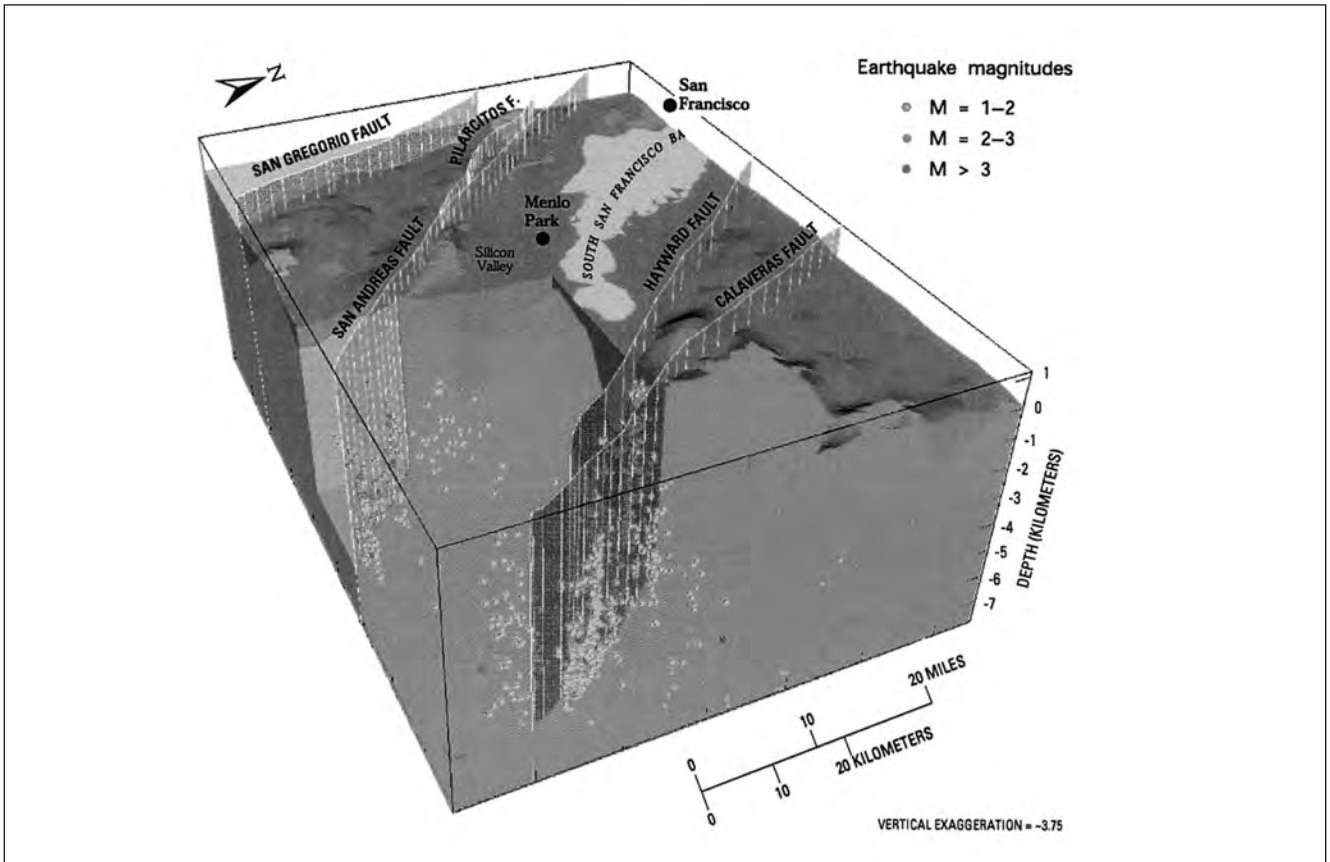

Figure 1: Experimental three-dimensional depiction of geologic and seismic data for the southern San Francisco Bay area. From Robert C. Jachens, USGS.

and continuous physical and chemical property fields. These elements are linked by quantitative relationships that specify the spatial interaction among the various data. This and other examples of our 3-D maps take advantage of the latest advances in technology and illustrate the importance of visualization for both scientific understanding and breakthroughs and understanding by the public of issues and phenomena which affect the quality of life.

Geology and Human Health

Interpreting the links between human health and geologic processes is a relatively new area of endeavor for the USGS. In the past, some of our topical studies touched on the affect of geologic factors on health. However, they were focused mainly on resource issues and the findings pertaining to human or animal health were ancillary benefits. Our intent is to take a systematic approach to understand aspects of human health which can be affected by geologic materials and processes. Toward this goal cooperative research efforts with specialists in human health, toxicity, epidemiology, and other life sciences are being increased. Several workshops and agreements have been completed with organizations such as the Armed Forces Institute of Pathology, the Centers for Disease Control, and the Environmental Protection Agency.

Some of our initial scientific investigations have involved the possible effects of domestic coal utilization in rural China and the potential influence of coal beds on quality of ground water in the Balkans. In rural areas of China coal containing high levels of arsenic and other toxic elements is routinely used as fuel. Incidences of human disease caused by high levels of arsenic and other toxic elements in coal are being identified utilizing maps of coal occurrence. Associated with the coal deposits are a series of Carlin-type gold deposits which may be a source of the high levels of arsenic and antimony in the coals. Map products in the future will take into account the geology, hydrology, mineral and energy resource occurrences along with toxic element poisoning trends in the remote locations of China.

In areas of Eastern Europe a kidney disease known as Balkan Endemic Nephropathy (BEN), as well as a number of other diseases, are hypothesized to be related to leached constituents from coal beds in the the vicinity. Investigations of the geologic, hydrologic, and epidemiological factors influencing the occurrence of these diseases are currently under way. Comparative studies of incidences of BEN and related diseases in locations within the U.S. where similar types of coal exist have also been initiated.

Middle Rio Grande Valley, New Mexico

Studies over the last few years by the USGS, the State of New Mexico, and cities and counties in the Albuquerque area have aimed to improve quantitative understanding of the hydrogeologic framework of the Rio Grande rift basins (Bartolino, 1999). Sediments deposited in these rift basins over the last 15 million years are the principal aquifers that provide more than 80 percent of the water needed by the growing population of the Santa Fe-Albuquerque areas. Of major interest is the long-term sustainability of the ground-water system of the Albuquerque area. The quantity and quality of this ground-water resource will have a direct influence on the growth of this area. An important part of this study is to develop an understanding of the interaction of the ground-water system with the Rio Grande River and its tributaries. Defining the hydraulic properties of the ground-water system is essential for this study. The hydraulic properties of the aquifers are strongly influenced by the sediment grain size and sorting, and these properties reflect the interaction of fault-tectonic events and sedimentation patterns of tributary and through-flowing rivers. The continuity of these aquifers is also affected by slip on post-depositional faults and, in some cases, by rock alteration caused by reactions with ground water moving along and near fault zones.

Detailed aeromagnetic surveys have been especially valuable in helping to define the patterns and offsets on numerous buried fault systems in the rift basins (Figure 2). These high-resolution surveys clearly show detailed fault offsets that displace the slightly magnetic sediments of the rift basins. Airborne electromagnetic surveys help to map in three dimensions the distribution

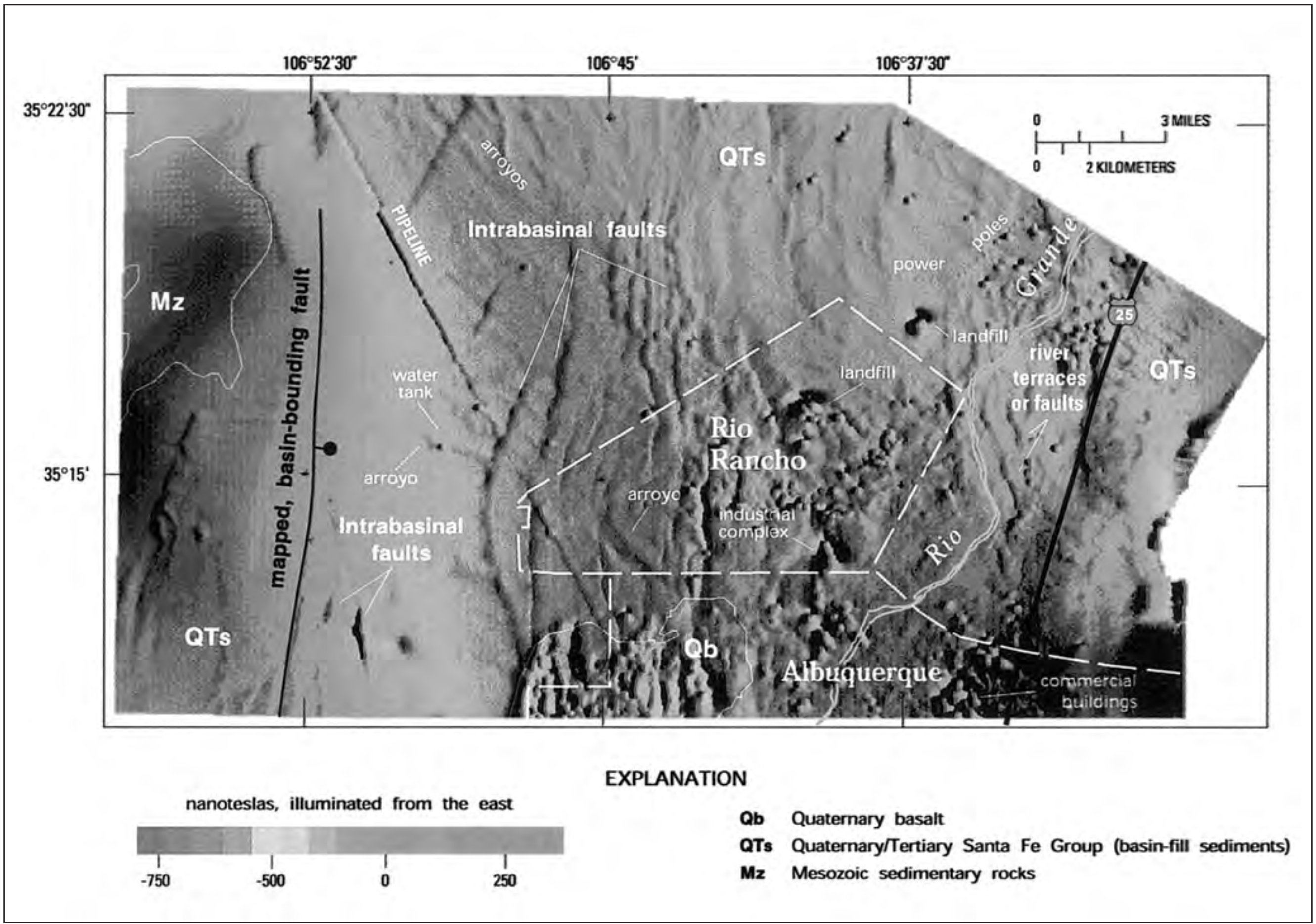

Figure 2: Buried intrabasinal faults that limit the extent of the aquifer units in the Middle Rio Grande Basin near Albuquerque, New Mexico. Magnetic data collected by high-resolution airborne geophysical surveys were used to identify the location and geometry of the faults. 1 nanotesla = 1 gamma, a measurement of magnetic field strength. From Grauch and Millegan (1998).

of conductive, low permeability clay and silt units in the subsurface, and to distinguish them from the higher permeability gravel and sand deposits laid down through time by the trunk streams of the basins. Coupled with detailed geologic mapping, the information from the geophysical surveys is being used to develop a geologic model for the basin which will be a key component in a revised ground-water flow model for the Albuquerque basin. In addition, geochemical studies of core samples and ground waters have helped track the origin and pathways of naturally elevated arsenic concentrations in some of the municipal water-supply wells. Similar USGS projects in Flagstaff, AZ, and Las Vegas, NV, have helped identify important basins or geologic structures that may host ground water or affect its flow. The objective is to provide the information used to make water management decisions by local governments for long-range planning. The use and development of advanced geophysical techniques is important to the detailed geologic maps needed for these applications.

Central Great Lakes Geologic Mapping Coalition

The central Great Lakes region, with a large and growing population, has an acute need for geologic maps to better define the three-dimensional framework of regional aquifers and confining units. The need to properly characterize and model these ground-water aquifers, which supply much of the drinking water in the region, is

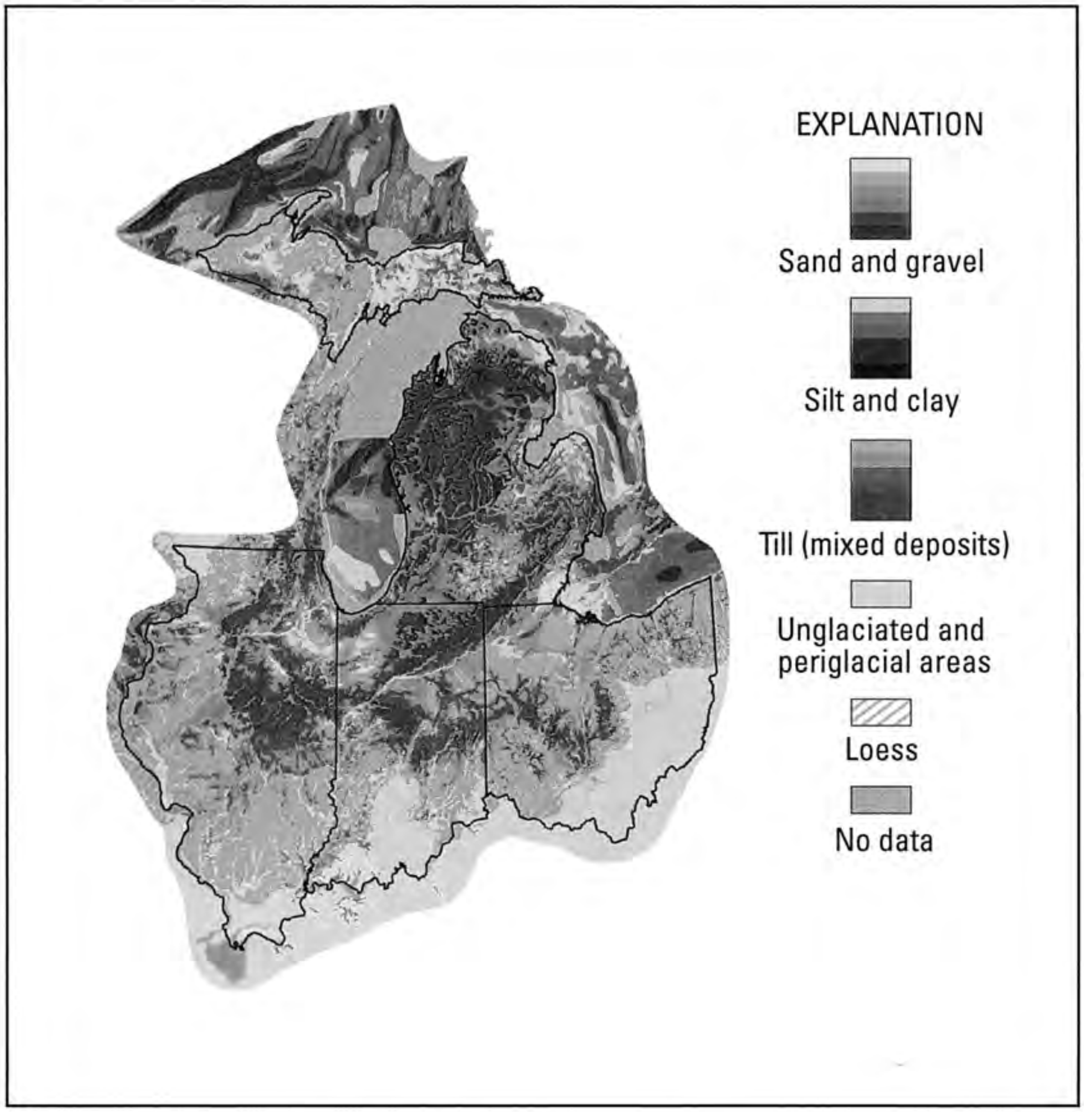

Figure 3: Map showing the thickness and character of Quaternary sediments in the glaciated region near the Great Lakes. From Soller (1998).

recognized by the State Geological Surveys of Indiana, Illinois, Michigan and Ohio, as an issue that crosses traditional political boundaries. Ground water from aquifers in shallow glacial materials is a critical resource, fulfilling the domestic water needs of 50 percent of the residents of Illinois and Indiana, while Michigan and Ohio rank first and fifth among states in the nation, respectively, in total number of domestic water wells. It is also clear that to tackle this large problem, resources must be pooled and leveraged; to that end the USGS has joined the four state geological surveys in a long-range planning process that describes the roles and responsibilities of each organization, including mechanisms to determine priorities. Because the critical third dimension of the glacial cover cannot be mapped by conventional methods, it must be explored using expensive drilling and geophysical techniques.

The central Great Lakes states are facing numerous economic and environmental decisions that are directly related to a clear understanding of the fragile and complex glacial deposits including their interaction with surface waters. Figure 3 is a reconnaisance map depicting the glacial and related deposits of the central Great Lakes states (Soller, 1998). These deposits range in thickness from a few inches to more than 1,300 feet. Darker colors indicate thicker deposits. Understanding the connections between surface and ground water in areas where the aquifers and confining units are not clearly defined is presently impossible. This is another example where the iterative interaction between geologists and hydrologists is necessary to construct meaningful ground-water flow models.

Many of the problems facing the Great Lakes states arise from the fact that the glacial deposits have multiple and often conflicting uses. These sediments are the foundation of some of the richest farmland in the United States and contain sand and gravel deposits, which are acutely needed for sustaining industrial and private infrastructure. Rapid development and growth in this region is forcing regulatory and zoning agencies to make difficult decisions on competing land uses. Better information provided in user-friendly three-dimensional geologic map databases will allow these governing bodies to better understand the full consequences of their actions. Only when geologists and hydrologists present their interpretations of the glacial sediments and the complex ground-water system in a unified manner will the full impact of land-use decisions on both ground- and surface-water resources be appreciated.

Gulf of Mexico and Southeast Tidal Wetlands

In the Gulf of Mexico and parts of the southeastern U.S. loss of coastal wetland is a major ecological concern. The USGS, in cooperation with other Federal agencies and state agencies, is investigating the loss of coastal wetlands and adjacent uplands in order to determine long-term change in wetlands and to provide a model for determining areas that are most vulnerable to loss because of combinations of human and natural impacts. The investigation is determining change over historical time at these regions, identifying the significance of change over the past 20 years when detailed satellite imagery is available, and match these changes to known factors such as sea level change, sedimentation, and human impacts. A landscape evolution model will be applied to evaluate existing studies and understanding of critical processes for assessing change and vulnerability of coastal environments with development and projected rises in sea level. Geologic maps form the basis for determining the lithologies that may be most vulnerable to erosion.

Everglades Ecosystem Restoration

The Everglades, the magnificent “River of Grass” in South Florida, is threatened by enormous water demands for rapid urban development and water diversions for intensive agriculture and flood control. The flow of freshwater through the Everglades into Florida Bay at the southern coastal tip of Florida is critical to the well-being of this fragile ecosystem. The USGS is participating in a multibillion dollar restoration program, in partnership with other Federal agencies, to mitigate the impact of current water management policies in South Florida. A major concern is the degree of saltwater intrusion into the aquifer underlying the Everglades, causing changes in plant communities that adversely affect fish and wildlife habitats.

USGS scientists use a helicopter-borne electromagnetic device to conduct rapid and economical surveys of aquifer quality where ground access is difficult; these surveys determine ground-water salinity by mapping in 3 dimensions changes in electrical resistivity of shallow subsurface rocks. The surveys have demonstrated an abrupt increase in resistivity 5-10 km (3-6 miles) inland from Florida Bay, corresponding to the infiltration of seawater beneath the Everglades and have provided a detailed mapping of the saltwater/freshwater interface in the ground-water system. In addition to mapping saltwater intrusion, these surveys monitor changes in subsurface conditions and help constrain regional flow models. The imprint of human activity is dramatically apparent at several locations within the park, particularly along old roads and canals. This information is contributing to strategies that are being developed by policymakers to protect living resources in the endangered Everglades ecosystem.

National Geochemical Survey

The USGS has a long established tradition of geochemical surveys and research. Beginning with the pioneering rock chemistry studies in the early part of this century through the more recent numerous resource assessments our geochemical databases have grown to impressive size (proportions). Despite these long-term geochemical investigations, coverage of the U.S. can still be described as spotty. One reason for the partial completeness is expense. We have recently begun a more systematic effort to expand the existing national geochemical database through reanalysis of geologic materials collected during the National Uranium Resource Evaluation (NURE) effort. In addition, soils and stream sediments are being collected from large parts of the U.S. that were not covered by NURE or any other program. Consistent with the theme of partnership the present effort is a collaborative effort involving many state geological surveys and other state organizations. Much of the new sample collection is being carried out through state cooperators. State-of-the-art analytical chemistry techniques as well as quality assurance and quality control measures are being applied. One of the principal products will be element maps based on soil and stream sediment data for most of the U.S. Utilizing up to date Geographic Information Systems (GIS) technology several different types of 2- and 3-D maps and products are planned to address fundamental geologic, resource, and environmental questions.

FUTURE DIRECTIONS/SUMMARY

This series of examples provides a glimpse of the ongoing activities that rely on geologic mapping at the USGS. The USGS is the premier earth and natural science agency in the United States and its mission may be unique in the world. A major goal of the USGS is to understand earth systems in an integrated manner that addresses societal issues and concerns. The Geologic Programs of the USGS are focused on seven science goals. These goals will require the diverse skills of the USGS to: (1) conduct research to advance fundamental understanding, (2) monitor earth systems, and finally (3) use this understanding and observations to interpret and assess earth systems in an applied context addressing critical problems and issues in specific geographic areas of concern to policymakers.

The largest geologic mapping effort in the United States is conducted by the USGS in partnership with 50 State geological surveys and universities with geology departments. Geologic mapping and the accompanying products are fundamental to understanding the earth system as it responds to both natural and human-induced change. Geologic maps form the foundation for addressing the seven science goals that have been identified for the geologic programs of the USGS and for the challenges involved in developing interdisciplinary and integrated approaches to problems requiring a strong geoscience aspect.

Fundamental geologic maps are the basis for the wide array of thematic and derivative maps that are needed by decisionmakers for the development of policy, implementation of regulations, education, and awareness of the public relative to the trade-off of risk and benefit.

Because many of the issues faced by society today require knowledge of the interaction of the biosphere, hydrosphere, and geosphere, there must be greater emphasis on the mapping of surficial geologic deposits. Human actions because of the continuing increase in global population have become a significant geologic process that must be considered along with natural processes in describing and understanding changes in earth systems.

The most effective use of geologic maps and their derivative products requires that geologic mapping information be considered in three dimensions. In some cases, the fourth dimension, time, must be effectively portrayed to users of the information if the information is to be used to impact decisionmaking and influence public opinion. The earth sciences, especially geologic mapping are at a crossroads in their evolution. Technology and the digital revolution afford opportunities but also great costs to the geologist of the next millennium. Society's need for geologic mapping and the accompanying products may be greater now than at any time in human history. The challenge to the earth scientist will be to question the very essence of traditional geologic maps and to create new products and approaches that will meet the society's increasing needs and expectations for geologic information.

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