Guide to the Development and Application of Geographic Information Systems for Sedimentary Basin Analysis—Case Study for the San Juan Basin, New Mexico and Colorado

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Guide to the Development and Application of Geographic Information Systems for Sedimentary Basin Analysis—Case Study for the San Juan Basin, New Mexico and Colorado

By BETTY M. MILLER

An evaluation of the feasibility of applying geographic information systems technology to the development of a prototype computer-based system that provides the framework for three-dimensional analysis of sedimentary basins. The San Juan Basin, New Mexico and Colorado, is used as the pilot study for the development of a geographic information system data base

U.S. GEOLOGICAL SURVEY BULLETIN 2025

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, Jr., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1992

For sale by
Book and Open-File Report Sales
U.S. Geological Survey
Federal Center, Box 25286
Denver, CO 80225

Library of Congress Cataloging in Publication Data

Miller, Betty M.
Guide to the development and application of geographic information systems for sedimentary basin analysis : case study for the San Juan Basin, New Mexico and Colorado / by Betty M. Miller.
p. cm. — (U.S. Geological Survey bulletin ;2025)
Includes bibliographical references.
Supt. of Docs. no.:I 19.3:2025
1. Sedimentary basins—San Juan Basin (N.M. and Colo.)—Data processing—Case studies. 2. San Juan Basin (N.M. and Colo.) 3. Geographic information systems. 4 Geological modeling. I Title. II. Series.
QE75.B9 no. 2025
[QE144.S24]
557.3 s—dc20
[025.06'5514'1] 92–8528
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By Betty M. Miller

Abstract

Analysis of sedimentary basins requires a multidisciplinary approach drawing on many areas of geologic expertise supported by the integration and analysis of large volumes of multivariate spatial data. Such an extensive data base requires computer technology to make the most effective use of all the available information and to analyze the data within a three-dimensional framework. One such method being investigated for analyzing sedimentary basins is the application of geographic information systems (GIS). GIS technology involves the integration of mapping and data base functions so that a geologist can combine complex geographic, geologic, and geophysical data sets into overlay and composite maps. The technology allows a geologist to conduct multivariate spatial data analysis and to access a variety of options for analyzing these basin data bases. GIS technology when applied to sedimentary basin analysis is used to establish a three-dimensional perspective of a basin's fundamental stratigraphic and structural framework and to aid in the identification of its temporal and tectonic relationships relative to origin, subsequent development, and occurrence of its natural resources.

A GIS program can be organized into a series of four logical steps, each of which builds upon the previous one. The four steps are determining the objectives, building the data base, performing the analysis, and presenting the results of the analysis. Determining the objectives defines the scope and purpose of the project, which in turn dictate the design and content of the data base. Building the data base is the most critical and the most time-consuming part of the project. The completeness and accuracy of the data base determine the quality of the analysis and final products. The principal value of the GIS, however, is its ability to analyze a data base by developing and applying models to reveal underlying trends in the geographic data and making new information available. The GIS provides new data coverages that can be combined in meaningful sequences to develop new models. Results of geographic analysis can be presented by creating customized maps to display geographic relationships and by preparing reports for summarizing tabular data and documenting any calculated values.

The San Juan Basin in northwestern New Mexico and southwestern Colorado is used as the pilot study area to demonstrate the feasibility of applying GIS techniques to a basin analysis and to develop a prototype to assess the GIS data base for the basin. The GIS study focuses on those formations in the Upper Cretaceous that are recognized as the major oil and gas producers within the basin. The four formations studied are the Dakota, Gallup, Point Lookout, and Pictured Cliffs Sandstones.

Data bases for surface coverages within the San Juan Basin include digital base maps; hydrography, landownership, and surficial geology data; well-location maps of more than 26,000 oil, gas, and nonproductive wells; and information on well status and oil and gas fields. Data bases created for subsurface mapping and analysis include geologic information, such as structure-contour, isopach, and lithology maps for the four major oil- and gas-producing formations; stratigraphic information for cross sections and fence diagrams; and composited map products.

GIS analysis techniques successfully applied in the San Juan Basin are designed to address the basin's fundamental geologic, stratigraphic, and structural framework with particular emphasis on the petroleum geology of the basin. Some of the GIS applications used in this basin study are analyzing (1) composite map coverages for structural configurations relative to the basin tectonics, (2) depositional patterns by using isopach maps relative to production trends within the producing formations, (3) spatial relationships depicting geologic conditions favorable for the occurrence of oil and gas trends within productive formations, and (4) spatial geometries of transgressive and regressive cycles of deposition for productive sandstones.

Manuscript approved for publication February 26, 1992.

GIS technology is demonstrated to be an important new tool for the earth scientist for geological interpretation of three-dimensional, multivariate spatial data in conducting an integrated analysis of sedimentary basins. GIS technology can contribute to innovative research in geological interpretation, to updating and documenting information data bases, and to developing new concepts in basin analysis and resource appraisal methodology.

INTRODUCTION

Most of the world's energy resources and many of its metallic and mineral resources are derived from sedimentary rocks. Exploration and assessment of these resources require an understanding of their relation to the host strata within sedimentary basins, whether the resources are primary or postsedimentation deposits. The most important result of a study of these host strata is a basin analysis that documents the geologic and paleogeographic evolution of the sedimentary basin and its related resource occurrences (Miall, 1984). Such a comprehensive basin analysis requires an understanding of data from many diverse components, including sedimentology, stratigraphy, structural geology, geophysics, and geochemistry, and the ability to assess the interrelations of many types of multivariate spatial data.

The concepts and methods for conducting sedimentary basin analysis have evolved from fairly simplistic geological studies that employed primarily qualitative and semiquantitative techniques, to studies of ever-increasing complexity that employ quantitative evaluations from total basin systems. Two of the major guiding principles of basin analysis are the importance of an integrated approach and the consideration of the sedimentary basin as a whole (Potter and Pettijohn, 1963). This complex quantitative approach requires enormous amounts of multivariate spatial data to quantify the geologic, geophysical, geochemical, and hydrologic processes reacting over time throughout the history of a sedimentary basin.

Such an integrated analysis of a sedimentary basin is difficult to accomplish without computer assistance. The analysis requires a multidisciplinary approach that draws on many areas of geologic expertise supported by the integration and analysis of large volumes of multivariate spatial data. However, new applications of knowledge-based computer mapping techniques (geographic information systems) can provide the tools needed to define new strategies and technologies for conducting and automating the complex tasks common to sedimentary basin analysis, particularly for extending two-dimensional mapping techniques to three-dimensional basin analysis. Geographic information system (GIS) technology involves the integration of digital mapping techniques and data base functions so that a geologist can combine complex geographic, geologic, and geophysical data sets into overlay and composite maps. It also allows a geologist to conduct multivariate exploratory data analysis and to access a variety of options for analyzing these basin data bases.

In 1986, the Director of the U.S. Geological Survey (USGS) established a research fund designated the "GIS Sweepstakes." The objectives of this funding were to (1) develop and provide GIS capabilities to the traditional USGS geologic missions and (2) promote interdivisional research. One project supported by this fund, and headed by the author, is entitled "Three-Dimensional Analysis of Sedimentary Basins Using Knowledge-Based Geographic Information Systems (KB–GIS) and Artificial Intelligence (AI)-Expert Systems."

The major objectives of this project are to explore the feasibility of applying (1) GIS digital mapping techniques to integrate and manipulate spatial and attribute data, to combine complex data sets (geographic, geologic, and geophysical) into overlay maps, and to conduct exploratory data analysis and (2) AI-expert systems techniques to simulate the logic of basin experts to model geologic concepts, to document and analyze geologic attributes, and to characterize the history of a sedimentary basin.

This report is written for the geologist as an introduction to GIS development and its application to geologic basin studies. The report is limited to a discussion of GIS techniques and applications used to conduct a sedimentary basin analysis. The San Juan Basin is used as the pilot study area to test the feasibility of applying GIS techniques to a basin study and of developing a GIS data base. This report is not intended to serve as a complete geologic analysis of the San Juan Basin. The work on applying AI-expert systems techniques to classification and analysis is covered in separate reports and will continue to be developed (Miller, 1987, 1989a).

BASIN ANALYSIS—A REVIEW OF THE LITERATURE

The geologic literature reflects a considerable difference of opinion among geologists over the last three to four decades as to what constitutes a basin analysis. The expression "basin analysis" was first introduced by Potter and Pettijohn (1963) in their well-known textbook "Paleocurrents and Basin Analysis." The objective of basin analysis in the 1960's was essentially paleogeographic, with emphasis on the mode of the sediments filling the basin. Basins were analyzed by using a combination of paleocurrent measurements and facies distributions. Basin analysis, or the paleogeographic reconstruction of a sedimentary basin as it evolved, was simply a tool, along with isopach and lithofacies maps, for understanding the relationships between sedimentation and tectonics, with the major emphasis placed on tectonics (Krynine, 1942, 1948; Kay, 1951; Pettijohn, 1957; Krumbein and Sloss, 1963; Potter and Pettijohn, 1963; Aubouin, 1965; Reading, 1988).

Sedimentologists of the 1960's, however, were highly critical of the direct correlation of sedimentary suites with tectonic regimes and stressed the hydrodynamics of clastic sediments and the monitoring of modern sedimentary processes. They contended that sedimentary facies, sequences, and cycles should be interpreted as responses to observable sedimentary processes rather than to tectonic movements (Reading, 1988).

Much of basin analysis has changed with the development of the concept of tectonics. Most sedimentary basins now can be explained in terms of plate-margin or plate-interior processes, and their structure and stratigraphy can be described with more comprehension. The importance of plate tectonics to basin analysis is now nearly universally recognized.

After the advancement of plate-tectonic models, near the end of the 1960's, three lines of study emerged in basin analysis. Sedimentologists continued to concentrate on more detailed sedimentary processes, without major concern for the wider geologic implications. Two other schools of thought reflected both tectonics and sedimentation. One emphasized the dominant role of tectonics in controlling sandstone composition and was a continuation of the Krynine tradition (Krynine, 1942, 1948). The second school focused more on sedimentary facies than on composition and attempted to understand sedimentation in terms of structural tectonic patterns and the magmatic and metamorphic background (Reading, 1988).

Toward the end of the 1970's, the interrelationship of tectonics, sedimentology, and basin analysis was firmly established. An important factor added to this integration of specialties was the research of petroleum geologists in their analysis of sedimentary basins to establish the hydrocarbon potential of petroleum source rocks. The study of tectonics and sedimentation for basin analysis is approached by theoretical geophysical and sedimentological modeling, by classical global tectonic modeling, and by detailed field studies (Reading, 1988). Many of these techniques have been made possible or enhanced by the availability of computers and computer techniques that can manipulate the large and diverse data bases necessary for basin analysis.

Current geologic textbooks, however, still consider basin analysis from somewhat differing viewpoints on specific, as well as general, approaches. The textbook "New Perspectives in Basin Analysis" (Kleinspehn and Paola, 1988) emphasizes two major areas of sedimentological research: (1) source-area characterization and lithostratigraphy (McBride, 1988; Van Houten, 1988) and (2) tectonics and sedimentation (Reading, 1988).

Miall (1984), in his textbook "Principles of Sedimentary Basin Analysis," emphasizes five new developments in sedimentary geology: the evolution of sedimentology in terms of explaining the origin of sedimentary rocks through facies studies and facies models, the study of depositional systems relative to their complete package of environments and sedimentary products, the evolution of modern seismic stratigraphic techniques, the developments in plate-tectonic theory and its impact on understanding basin evolution and sedimentary styles, and the evolutionary refinements in chronostratigraphy through developments in radiometric dating techniques. The first two steps for basin analysis, as proposed by Miall (1984), are (1) establishment of the framework of major sequences through seismic methods and detailed lithostratigraphic correlation and biostratigraphic zonation and (2) interpretation of each sequence in terms of its component depositional systems, using sedimentological data, the principles of facies analysis, and basin mapping methods.

Lerche (1990), in his textbook "Basin Analysis: Quantitative Methods," addresses the problem of quantitative basin analysis in relation to oil accumulations. His book is devoted to examining the quantitative methods of reconstructing the burial history of sediments in basins; the problem of quantitative reconstruction of the thermal histories of sedimentary basins, based on model-derived heat fluxes and an inversion of present-day thermal indicator data; and the integration of the hydrocarbon generation, migration, and accumulation modeling aspects with the burial history and thermal history as the basic foundation for the basin studies. Lerche examines the quantitative aspects of basin analysis viewed as an integrated picture, unlike many other authors who address only the qualitative application of basin analysis methods (Hunt, 1979).

This review of some of the more recent literature demonstrates the complexity of basin analyses, the value of older tectonic and sedimentological techniques, and some updated approaches. Because of the enormous amounts of data required to describe complex basin systems, quantification of these processes was not feasible in past studies. Thus, until recently, only qualitative or semiquantitative basin studies were made and presented as case studies. The increasing capacity and speed of computers, however, should support the initiation and development of quantitative basin studies.

Two examples of such quantitative studies are those of Green (1987) and Welte and Yukler (1981). Green's study is an integrated sedimentary basin analysis that involves the construction of a geologic model documenting how a basin formed, filled with sediments, compacted, and matured within the natural system of the Earth's geochemical-geologic cycle (Green, 1987). Welte and Yukler's (1981) study is a construction of a three-dimensional deterministic dynamic basin model and the quantification of complex dynamic processes of petroleum formation and occurrence in a given sedimentary basin. The study describes a basin system in which the generation, migration, and accumulation of petroleum occur within the three-dimensional dynamic geologic framework.

COMPUTER MAPPING

Geologists routinely perform three-dimensional analyses and employ three-dimensional concepts to understand and describe spatial relationships. In contrast, the typical mode of display, such as maps and cross sections, is two dimensional. As a result, geologists have used two-dimensional tools (such as graphic displays that involve specialized maps, cross sections, fence diagrams, and geometrical constructions such as stereonets) to project information from three-dimensional space to a more manageable, but less accurate, two-dimensional space.

Computers, and modern software programs, offer important advantages in (1) manipulating large quantities of data, (2) speed, (3) manipulating maps and map data, (4) updating and documenting, (5) ensuring objectivity and consistency, and (6) incorporating geological interpretations (Jones and others, 1986). This paper does not discuss the various computer mapping techniques available to the geologist interested in spatial analysis and using the computer for data preparation and processing, methods, applications, and interpretations. The reader interested in the techniques for two-dimensional geological coverages, concentrating on mapping structural surfaces and thickness intervals, is referred to "Contouring Geologic Surfaces with the Computer" by Jones and others (1986).

Mapping Systems Versus Geographic Information Systems

Two principal types of computer mapping have evolved—mapping systems and geographic information systems. The two types offer similar kinds of data capture, edit, and display capabilities, and both can be applied to some of the same tasks. However, mapping systems and GIS's have different philosophies, data structures, and preferred coordinate systems (Aanstoos, 1989).

Mapping systems focus mainly on boundaries and so generally are best for data base management and high-quality cartographic map output. Two kinds of mapping systems are available: those used for map drafting and those used for facilities mapping. Most mapping systems store data in Cartesian, or x, y, coordinates.

GIS is intended primarily for geographic data analysis and thematic mapping. GIS focuses on areas or polygons and so is stronger in spatial data analysis (Lang, 1988; Aanstoos, 1989). The basic data structure is topological; that is, each map element is treated as a point, line, or polygon. Like flat maps, GIS uses various planar coordinate systems to map the Earth's surface. Each coordinate system used is based on a particular map projection, such as the Universal Transverse Mercator (UTM), the Albers Equal-Area Conic, or the Polar Stereographic Coordinate system. The functions of mapping systems and GIS's, however, are evolving slowly toward each other. In the future, there may be little distinction between them.

Geographic Information Systems

One definition of GIS is "a computer based technology composed of hardware, software, and data used to capture, edit, display, and, most importantly, analyze geographic information.... The key distinction between mapping software and GIS software lies in its [GIS] ability to analyze spatial data" (Lang, 1989, p. 17). According to Dangermond (1989, p. 25), "A GIS is, first of all, an automated information system. A GIS brings information together, it unifies and integrates that information. It makes available information to which no one had access before, and places old information in a new context. It often brings together information which either was not or could not be brought together previously."

GIS's originally were designed and developed nearly 20 years ago as a method to overlay and combine diverse kinds of data into a single map to summarize geographic, cultural, and scientific attributes. Since that time, these systems have evolved to serve many different applications, such as inventory mapping of forests, water, and other natural resources; lease management; topographic mapping; exploration; marketing and facility information; municipality planning; land use planning; military applications; teaching; and scientific research.

With the growing interest in three-dimensional geologic modeling and the need for subsurface geologic analysis, new applications of GIS are being investigated that provide data integration to link surface and subsurface geology with associated rock attributes such as geochemical and geophysical data (Loudon, 1986). A GIS typically links different data sets and allows many different types of data to be spatially and statistically analyzed (Robinove, 1986). Figure 1 shows the linking of a number of related data layers that can be extracted from various surface and subsurface geographic and geologic data bases.

A GIS data model, such as the commercial product ARC/INFO, involves storage of tabular data (attributes) in association with simple cartographic features, such as points, lines, and polygons. Cartographic data are stored in tables recording spatial location in relation to other descriptive attributes and not as graphic primitives or symbols. (A brief description of the ARC/INFO software system is presented in appendix A.) Because of this data structure, GIS's can analyze geographic (and geologic) data and provide a geologist with the ability to view and analyze spatial data relationships, as well as to map, query, and manipulate spatial information (Chrisman, 1987). GIS's also can be used for entry, editing, and maintaining digital maps.

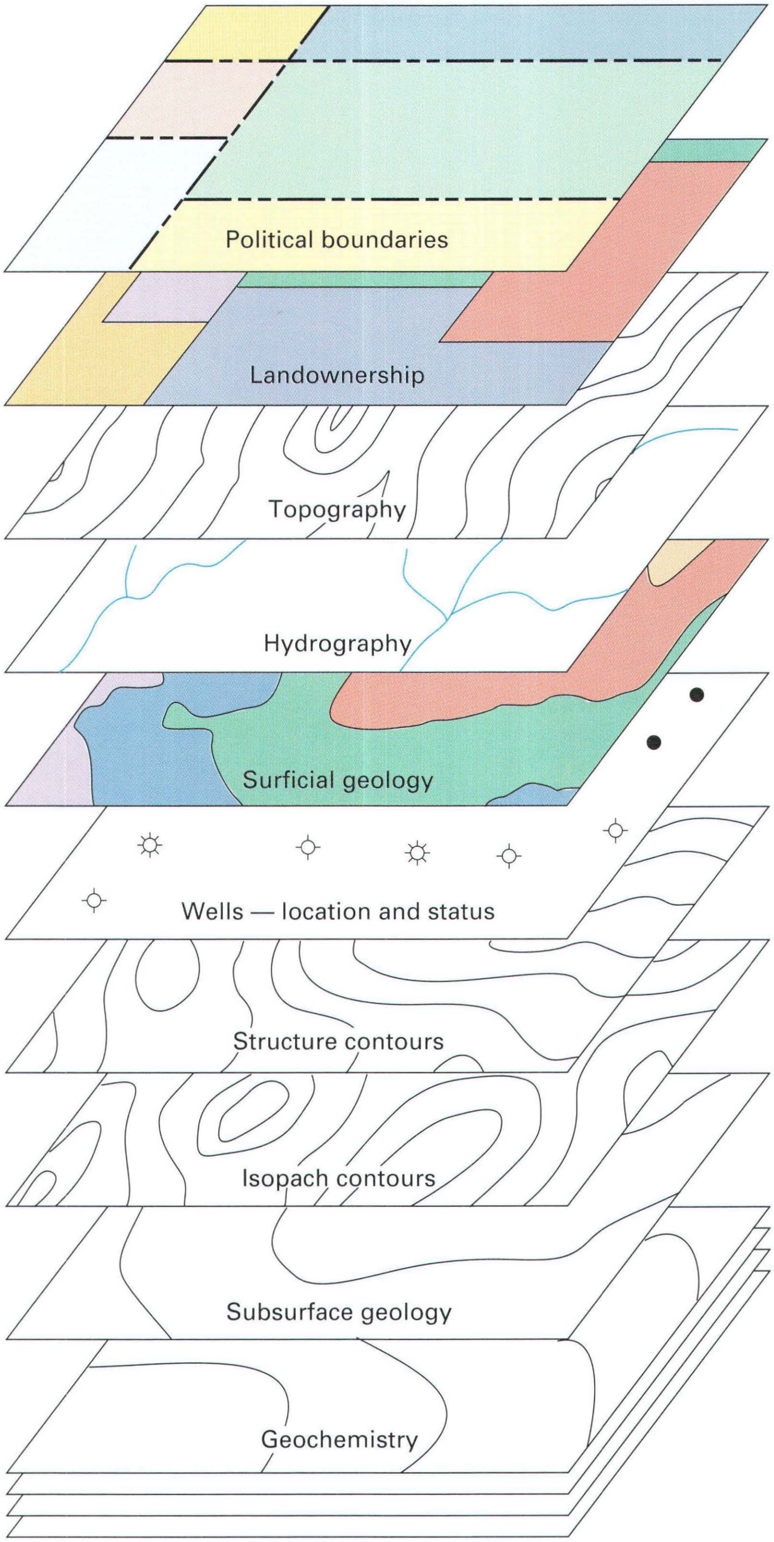


Figure 1. Map features organized into sets of data layers or themes of information. Linking of surface and subsurface geographic data bases is represented by a number of related data layers or coverages in geographic information systems.

THE ROLE OF GIS IN SUBSURFACE CHARACTERIZATION FOR BASIN ANALYSIS

Early GIS applications involved mapping essentially two-dimensional land-surface phenomena such as land use, landownership, hydrographic features, vegetation, and soils. Most commercially available GIS products cannot represent true three-dimensional data, although they can represent topographic data, usually as a digital elevation model (DEM), and can display isometric views, contour maps, and so on. Most DEM's use either gridded elevation matrices or triangular meshes to allow these terrain representations. In these cases, the elevation, or *z* coordinate, is treated as a dependent variable. Some systems also allow the draping of another mapped feature, such as soils or land cover data, onto an isometric view of a topographic elevation surface, thereby creating the illusion of a three-dimensional model (Turner, 1989).

Some geological applications using a GIS can be accomplished by reducing the three-dimensional data to a quasi-three-dimensional mode by using individual surfaces or stacked subsurface layers. These surfaces, which can represent bedding planes or formation boundaries for example, then can be contoured or displayed as isometric views. In these cases, however, the elevation of the surface is not a truly independent variable, and so these systems are best defined as quasi-three-dimensional, or 2.5-dimensional systems. Many regional geological studies operate in a 2.5-dimensional mode because the geographic dimensions (*x* and *y*) are several orders of magnitude larger than the depth dimension (*z*) (Turner, 1989).

Detailed three-dimensional subsurface data are especially crucial in applications such as petroleum reservoir characterization (Jones, 1988), ground water contamination modeling, and geotechnical site characterization for increasingly complex construction projects. Three-dimensional subsurface data characterization is also crucial for conducting studies on basin evolution and basin analysis and for the exploration, evaluation, and management of natural resources (Bak and Mill, 1989). All of these applications have one thing in common; they require increasingly quantitative and accurate rock-property characterizations within the three-dimensional subsurface environment (Unger and others, 1989; Van Driel, 1989; Youngmann, 1989). Subsurface studies require a true three-dimensional data framework because the geographic dimensions (*x* and *y*) are of the same general order of magnitude as the depth dimension (*z*) and because the accurate depiction of spatial relations is essential for basin analysis (Turner, 1989). This study investigates the application of GIS technology to subsurface data and subsurface mapping, whereas previously it has been applied only to surface data and surface mapping (Miller, 1988, 1989b, 1991). Major problems, however, occur when working with subsurface data in geological applications, and these problems differ considerably from those encountered in other fields of study. Some examples follow:

1. Geologists deal with information that is frequently incomplete, inferred or interpretive, often uncertain, and sometimes unreliable. They must extrapolate and interpolate to construct a complete subsurface model. The quality and accuracy of three-dimensional geologic models are severely constrained by the availability of subsurface information about depths, boundaries, or geometries and the variable nature of the rock properties, ranging from microscopic to megascopic, being recorded.
2. The natural subsurface geology or basin configuration can be characterized by extremely complex spatial relations, such as intricate faulting and folding, or by complicated and frequently discontinuous boundaries or geometries for depositional facies.
3. The irregularly spaced or clustered location of wells and well data or the lack of seismic data frequently results in insufficient sampling. As a result, less than adequate subsurface information is available to resolve all uncertainties in mapping and geologic interpretation.
4. The relationships of sampled rock properties derived from geological and engineering data developed from exploration procedures (such as well tests and core data, seismic exploration, and stratigraphic or sedimentological descriptions of depositional systems) to the three-dimensional or volumetric distribution of the rock units are usually unknown and must be treated as interpretive in nature.

True three-dimensional GIS products could greatly aid the resolution of these difficulties by enabling the visualization of spatial relations and by providing data-management capabilities. Unfortunately, true three-dimensional GIS is unavailable at this time. "By 'true 3-D' we mean manipulation of solid, volumetric cubes of the real world" (Davis and Williams, 1989, p. 51). To date, the inability to visualize these three-dimensional features has been a major constraint. By making true three-dimensional visualization possible in realtime, three-dimensional GIS could substantially improve existing analytical capabilities (Turner, 1989). Recently announced commercial systems, such as the Dynamic Graphics Interactive Volume Modeling (IVM), are attempting to address these visualization needs (Smith and Paradis, 1989; Paradis and Belcher, 1990).

Future three-dimensional GIS technology must strike a balance between its dual roles of spatial visualization and data management. Recent speculations concerning the merging of GIS and computer-aided drafting and mapping technologies emphasize the shortcomings of the current systems for many geoscience applications (Lang, 1988).

Geological applications of GIS currently form a very small part of the total GIS market. The inclusion of the third coordinate (*z*) and the conversion from planar to solid

BUILDING THE DATA BASE					ANALYSIS	PRESENTATION
DESIGN	DATA AUTOMATION					
Starting the ARC/INFO project	Getting spatial data into ARC/INFO	Making spatial data usable	Getting attribute data into ARC/INFO	Managing the data base	Performing geographic design	Presenting the results of the analysis
Identify required layers and attributes Collect existing data Create master tic file	Prepare map manuscript Digitize manuscript Reformat digital data Construct topology	Create coverages Display and correct errors Reconstruct topology	Create data file and add attributes Join data to attribute table	Convert coverages to UTM coordinate system Join map sheets	Evaluate and interpret spatial data	Create final maps Create reports

Figure 2. Major steps in conducting a GIS project by using the ARC/INFO method. Modified from Environmental Systems Research Institute, Inc. (1990).

geometry add storage and computational costs to the GIS software. Thus, until very recently, developers and vendors of GIS software have not pursued the three-dimensional GIS market. This situation is rapidly changing, due largely to the increasing interest in three-dimensional graphics systems for many uses and the development of new hardware that can support the generation of three-dimensional graphical displays. However, the lack of affordable, fully functional, three-dimensional GIS products to date has had ramifications for many geological applications. This report, therefore, is basically restricted to the applications of the quasi-three-dimensional or 2.5-dimensional systems to subsurface characterization for support of geological basin studies.

DEVELOPING THE GIS FOR BASIN ANALYSIS

The following section is a brief overview of the basic steps used in developing a typical GIS project. The four major steps are determining the objectives, building the data base, performing the analysis, and presenting the results of the analysis. Each of these steps is briefly discussed below as it relates to the design and development of the San Juan Basin GIS. Most GIS projects will follow a similar sequence. Figure 2 summarizes the basic steps in conducting a GIS project by using ARC/INFO. For a more detailed account of how to start an ARC/INFO project, refer to "Understanding GIS—The ARC/INFO Method" (Environmental Systems Research Institute, Inc. (ESRI), 1990, chap. 3).

Determining the Objectives

Determining the objectives of a GIS study is important to define the scope of the project and its implementation. The purpose and objectives of the project dictate the design and contents of the data base. The nature of the geologic problems to be resolved and the final products of the project (that is, reports, working maps, and presentation-quality maps) determine the types of coverages needed in the data base to perform the various analyses.

In the San Juan Basin pilot study, the basic objectives are (1) to explore the feasibility of applying GIS technology to the analysis of the basin's fundamental geologic, stratigraphic, and structural framework and (2) to develop a working prototype system that will provide a model for conducting three-dimensional analysis of sedimentary basins. New lines of inquiry relative to geological interpretations and spatial relationships emerged during the course of the pilot study as the feasibility of applying these GIS techniques successfully to a basin study became evident.

Building the Data Base

The most important and frequently the most time-consuming part of the GIS project is building the data base. The steps involved in building an ARC/INFO data base are designing the data base, automating the data by entering the spatial data and the attribute data in the data base, and managing the data base by transforming the coordinate system for all map coverages to a common planar coordinate system (fig. 2).

The first step in designing any data base is determining what data are to be included by identifying the geographic features and their attributes, organizing the data layers, and identifying the map coverages to be automated. Some of the decisions to be made about the coverages are determining the study area boundary, the map coordinate system to be used, the data layers (or map coverages) required, the features to be included in each coverage, the attributes needed for each feature type, and the attribute coding scheme and organization to be used. The coverages and their associated feature-attribute tables are the basic building blocks of the data base.

Automation of the data involves getting the spatial and attribute data for the map coverages into the data base. Spatial data can be captured directly from a map by entering the data manually, by digitizing, or by using an electronic scanner and putting the data into a computer file. Another method involves reformatting existing digital data and converting the data into an ARC/INFO format. Map coverages are composed of sets of features where each feature has a location defined by coordinates and topological "pointers" to other features, as well as attributes defined by a set of fields or as items in a feature-attribute table. There are a number of important aspects in coverage creation, in addition to digitizing coordinates, such as creating feature topology, building feature-attribute tables, and connecting feature attributes to a corresponding coverage feature. For a more detailed account of building coverages for the data base, refer to an ARC/INFO user's manual (for example, ESRI, 1990).

After designing and automating the basic coverages for the study area, the geologist must ensure that each coverage is topologically correct, that the feature-attribute tables are present, that the accuracy of all feature locations and feature attribute values has been verified, and that a system of tics or ground control points exists. Additionally, to manage the data base, all geographic features and map coverages must be converted into real-world coordinates, and the features of each coverage must be spatially referenced against features in associated coverages (see fig. 2). For example, when the maps were digitized for the San Juan Basin study, the *x* and *y* coordinates used for the geographic features, tics, and Petroleum Information-Well History Control System (PI–WHCS) data (Petroleum Information Corp.) were in latitude and longitude coordinates, a geographic reference system—not a two-dimensional (planar) coordinate system. Because GIS's use planar coordinate systems to map the Earth's surface, the latitude and longitude coordinates were transformed into planar (UTM) projection units.

Performing the Geographic Analysis

The ability to perform geographic analysis sets geographic information systems apart from digital mapping systems and is where the true value of a GIS becomes evident. Analytical tasks that are otherwise extremely time consuming, or even impossible, if done manually can be performed efficiently by using a GIS.

Geographic analysis helps the geologist to study real-world processes, such as three-dimensional analysis of sedimentary basins, by developing and applying models. Such models can reveal underlying trends in the geographic (geologic) data and thus make new interpretations or concepts possible. A GIS enhances this process by providing tools that can be used to combine map coverages in meaningful sequences to develop new models. These models may reveal new or previously unidentified relationships within and between data sets or coverages, thus increasing our understanding of the three-dimensional framework and processes within a sedimentary basin. Alternative scenarios also can be tested by making minor revisions in the analytical method.

Three types of spatial operations can be performed on the coverages for a geographic analysis. The first is the generation of buffer zones within a given distance of an identified region where the analysis requires interpreting the attributes in an area surrounding a specified set of geographic features. A buffer zone generates one or more polygons surrounding existing specified geographic features identified by the user and creates a new polygon coverage. The second type of spatial operation creates new coverages by either removing or adding features to a coverage; that is, manipulating spatial features by selecting, erasing, and (or) adding features. The third type of operation is polygon overlay, which lays one or more polygon coverages over another and thereby creates new polygon coverages. The spatial locations of each set of polygons and their polygon attributes are joined to derive new data relations. Joining polygons enables the user to perform operations that require new polygon combinations; thus, existing coverages can be combined to remove, replace, or merge geographic features.

The following example of an analysis procedure illustrates the three types of spatial operations that can be performed on the coverages for a basin data base. The problem to be analyzed is locating sites favorable for productive gas wells in the San Juan Basin. Selection criteria for the proposed well sites follow:

1. Site must be in San Juan County, N. Mex.
2. Site must be on privately owned lands (not on Federal or State lands).
3. Preferred target formation is the Pictured Cliffs Sandstone (PCSS).
4. Preferred depth to top of the PCSS formation is between 3,500 and 4,500 ft.
5. Preferred thickness of the PCSS formation is between 50 and 120 ft.
6. Preferred porosity of PCSS formation is greater than 10 percent.
7. Site must be beyond 1,500 ft of existing streams.
8. Site must be within 2 mi of gas wells currently producing more than 200 million cubic feet of gas per day (MCFGD) from the PCSS formation.

First, new coverages must be created from the existing data base coverages by selecting, erasing, and adding features that address the selection criteria needed to solve the problem. For example, the following selections would be made: (1) from the digital line graphs (DLG) base-map coverage, only San Juan County and all streams in that county; (2) from the landownership coverage, only the private lands within the county; and (3) from the well-location coverages, the gas wells producing more than 200 MCFGD within the county. New coverages also must address the Pictured Cliffs Sandstone attributes as follows: (1) from the structure-contour map coverage, those polygons covering areas that have depths ranging from 3,500 to 4,500 ft to the top of the PCSS formation; (2) from the isopach map coverage, those polygons covering areas where the PCSS formation ranges in thickness from 50 to 120 ft; and (3) from the porosity distribution map coverage, those polygons covering areas having porosities greater than 10 percent. Two buffer-zone coverages must be generated: (1) one from the newly created producing-gas-well coverage by identifying the buffer zones within 2 mi of each gas well that meets the production criteria and (2) one from the new DLG coverage for the existing streams in San Juan County by identifying the buffer zones within 1,500 ft of each stream.

Additionally, to meet all the selection criteria for the proposed favorable well-site locations, all of the above data coverages, a minimum of 10, must be combined to identify the polygons that meet all 8 criteria. The final coverage will include only those polygons that meet the preferred criteria for the well-site locations that are considered favorable for prospective gas wells in San Juan County.

The combination of more than 10 data coverages is too complex to illustrate here. However, an example of generating the buffer zones to identify the gas-producing areas within 2 mi of the designated gas wells and the buffer zones identifying the areas within 1,500 ft of existing streams is shown in figure 3*A*. If all of the other selection criteria are met, wells can be drilled within the areas of the buffer zones 2 mi around the producing gas wells but not within 1,500 ft of an existing stream. Figure 3*B* shows a very simple example of performing polygon overlays to create a new polygon coverage. In the figure, the landownership polygon coverage is overlain with the polygon coverages of the preferred depths to the top of the PCSS formation and the preferred porosities of the PCSS formation. The three sets of coverages (landownership, preferred depths, and preferred porosities) are combined to create 14 new polygons.

Performing geographic analysis in basin studies.— Each of the data layers or map coverages in the data base contains specific information required for the basin analysis. To identify new associations between the data layers, geologic information within the GIS must be manipulated. Geographic analysis allows a geologist to manipulate the data and investigate the relationships between the data layers by developing and applying different models or by changing the values of the attributes in the selection criteria. These models may reveal underlying trends in the geographic and geologic data and thus make new information available that will aid in geologic interpretations.

Presenting the Results

Results of geographic analysis can be communicated by computer-generated maps, reports, or both. A GIS offers many options for creating customized maps and reports. The maps are best used to visualize and (or) display geographic or spatial relations, whereas reports are more appropriate for summarizing tabular data and documenting any calculated values.

A GIS FOR THE SAN JUAN BASIN

GIS technology applied to the San Juan Basin pilot study initially was directed to the development and integration of a multivariate spatial data base needed for the basin analysis. This technology when applied to sedimentary basins is used to establish a three-dimensional perspective of the basin's fundamental geologic, stratigraphic, and structural framework based on subsurface data. The San Juan Basin GIS integrates mapping and data base functions that not only allow a geologist to generate various maps but also provide a variety of options for analyzing and manipulating geographic information. The GIS, through its ability to carry out spatial operations, typically links the different data sets (surface and subsurface) by using the geographic location as the common key. In this pilot study, subsurface geologic data representing geological surfaces and attributes were designed as a part of the geographically referenced information (fig. 1). Surface data were used for data bases pertinent to the project, such as landownership, surficial geology, topography, hydrography, and the location and status of all oil and gas wells.

Data bases created for subsurface mapping include structure contour, isopach, and facies information for the major oil- and gas-producing formations; cross sections and fence diagrams; input for paleogeographic reconstructions; and composited map products. The PI–WHCS data base (Petroleum Information Corp.) is one of the major sources of well, depth, and thickness information for identified formations within the basin and a variety of data on productive reservoirs.

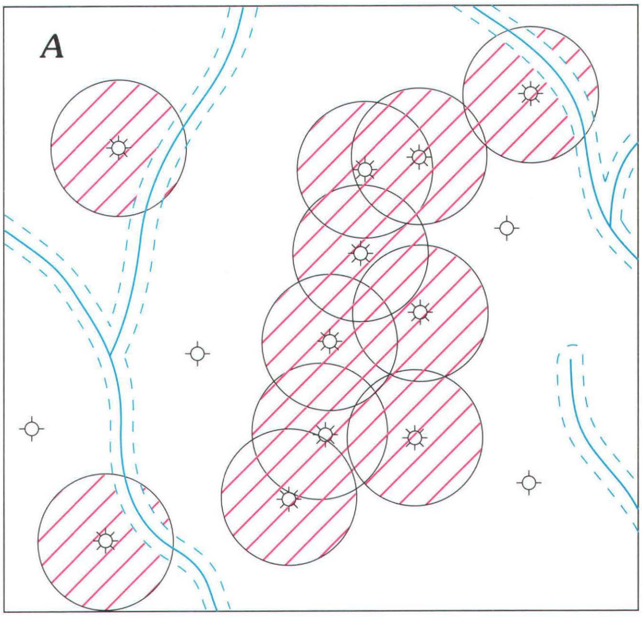
Among the cartographic data bases investigated for surface mapping in the San Juan Basin are (1) the US GeoData system from the USGS's National Mapping Program, including Digital Elevation Models (DEM) for terrain elevations; (2) Digital Line Graphs (DLG) for planimetric information on boundaries, transportation, and hydrography; (3) the U.S. Public Land Survey System; and (4) Land Use and Land Cover (LULC) data. Additional data bases investigated for surface mapping include surficial geology, locations of oil and gas wells, dry holes, well status, and oil and gas fields.

Current GIS technology and mapping software being used in this project for the three-dimensional analysis of the San Juan Basin include ESRI's ARC/INFO GIS software (Environmental Systems Research Institute, Inc., 1987, 1990) and the Interactive Surface Modeling (ISM) mapping software package (Dynamic Graphics, Inc., 1984). Both programs run on the USGS PRIME computer system.

SAN JUAN BASIN, NEW MEXICO AND COLORADO—THE PILOT STUDY AREA

The San Juan Basin, located in northwestern New Mexico and southwestern Colorado, was chosen for the GIS pilot study for several reasons. First, and foremost, the basin contains major economic deposits of natural gas, oil, coal, and uranium; thus, it is a prime candidate for a study in the applications of GIS techniques to evaluate its energy resources for natural resource management. The basin is moderately to well explored and has a greater than 80-year history of development; more than 26,000 wells have been drilled in the area. The abundant well data and the results of many studies conducted in this basin by industry, government, and academic geologists using geophysical logs, well cuttings, core, and other subsurface data provide a major source of information for building the basin data base. The San Juan Basin is also one of the selected areas of study for the USGS Evolution of Sedimentary Basins Program. This program was created in 1985 to provide a mechanism for conducting multidisciplinary geological research for regional studies on the evolution of ancient and modern sedimentary basins (Dean and others, 1990; Ridgley and Huffman, 1990).

Using the San Juan Basin for the pilot study also capitalizes on the experience and expertise of the USGS in GIS projects that were already underway. These projects include (1) the development of a new digital map base for the basin and improved methods for moving digital data into the ARC/INFO GIS system and (2) the implementation of the ARC/INFO system and the application of mapping software for digital mapping of aquifer systems in the San Juan Basin. The work on the San Juan Basin aquifer system was conducted as part of the USGS Regional Aquifer-System Analysis Program (Sun, 1986; Welder, 1986). As part of a hydrogeology atlas series for the San Juan Basin, maps of the following formations have been published to date: Dakota Sandstone (Craigg and others, 1989), Gallup Sandstone (Kernodle and others, 1989), Morrison Sandstone (Dam and others, 1990), Point Lookout Sandstone (Craigg and others, 1990), Cliff House Sandstone (Thorn and others, 1990), Kirtland Shale and Fruitland Formation (Kernodle and others, 1990), San Jose, Nacimiento, and Animas Formations (Levings and others, 1990a), and the Menefee Formation (Levings and others, 1990b).



EXPLANATION

Gas well — Dry hole

2–mi buffer zone around well

Stream and buffer zone within 1,500 ft of stream

Figure 3*A*. Intersection of buffer zones within 2 mi of gas wells producing from the Pictured Cliffs Formation and buffer zones within 1,500 ft of existing streams.

Regional Geology of the San Juan Basin

The San Juan Basin occupies the southeastern part of the Colorado Plateaus physiographic province. The 14,000-mi^2 Laramide structural basin, slightly elongated north to south, is more than 150 mi long and 100 mi wide. It is strongly asymmetrical; the axial trace forms an arcuate belt paralleling its northern and northeastern boundaries, where the deepest part of the basin to the top of the Precambrian is in excess of 7,500 ft below sea level (Woodward and Callender, 1977, p. 209). Structural relief between the uplift and the deepest part of the basin is more than 15,000 ft (Ridgley, 1989).

The basin is bounded on the north and northwest by the San Juan-La Plata Mountains and the Hogback monocline of the Colorado Plateaus; on the northeast, east, and southeast, by the Archuleta-Nacimiento uplifts and the Puerco fault zone; on the south, by the Zuni uplift and the Chaco slope (a broad structural shelf sloping gently northeastward into the main part of the basin); and on the west and southwest, by the Defiance uplift. Structures of the San Juan Basin and adjacent uplifts developed primarily during the Laramide orogeny (Late Cretaceous and early Tertiary). Figure 4 shows the structural elements of the San Juan Basin and adjacent areas.

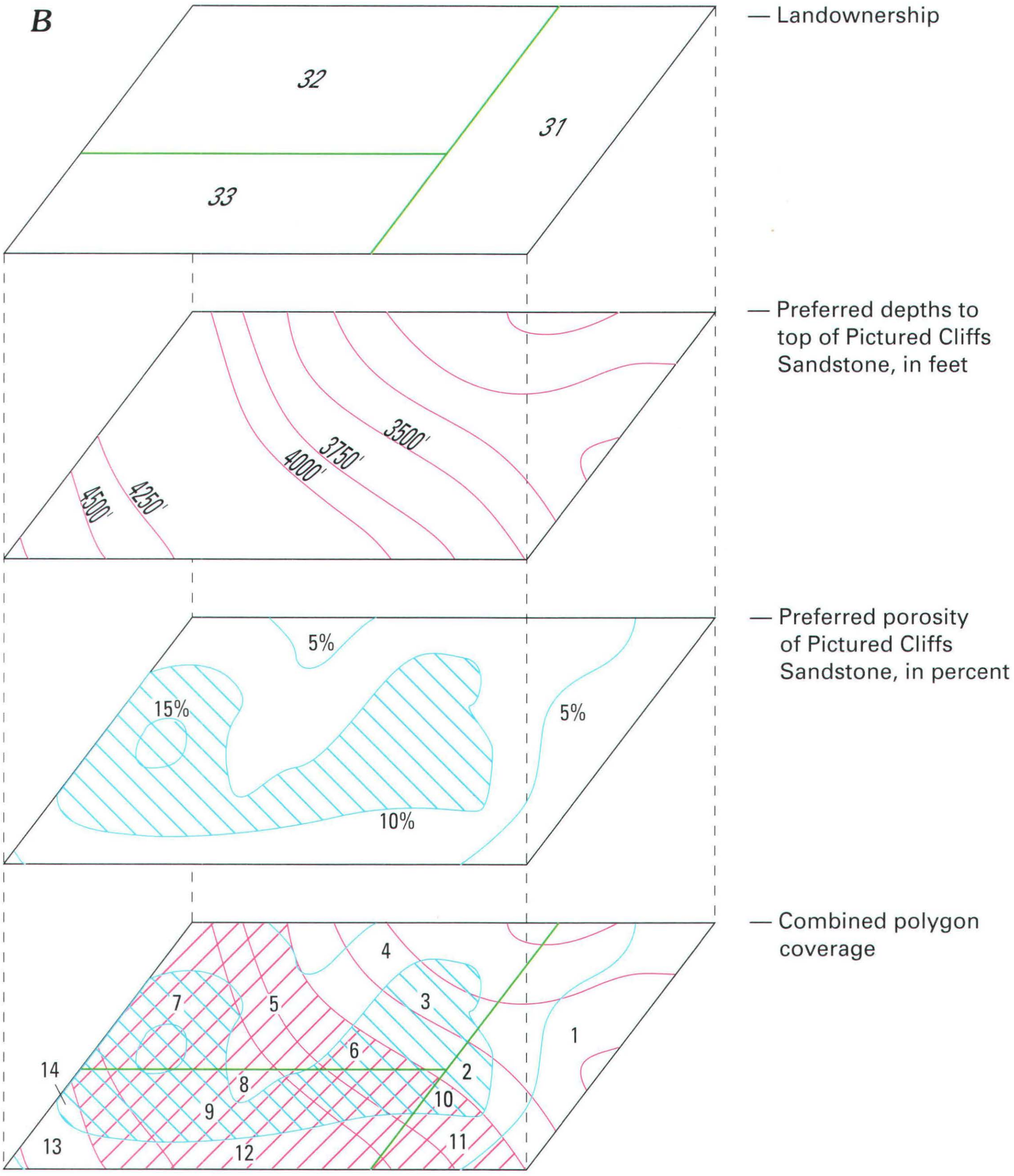


Figure 3*B*. Topological overlay joining polygons from three coverages to establish the spatial relationships among landownership, preferred depths to the top of the Pictured Cliffs Formation, and preferred porosities of the Pictured Cliffs Formation. Three sets of coverages are combined to create 14 new polygons.

The San Juan structural basin contains a thick sequence of sedimentary rocks ranging in age from Cambrian through Tertiary. The maximum thickness is about 15,000 ft in the northern part of the basin, and in this area the sequence is composed mostly of Pennsylvanian through Tertiary age rocks. The older sedimentary rocks crop out around the basin margins and are successively overlain by younger rocks toward the northern part of the basin.

Stratigraphy and Petroleum Geology

This report is not intended to be a complete and detailed geologic discussion of the San Juan Basin. The reader is referred to other publications for details on the tectonic and stratigraphic framework for the basin.

This pilot study applies GIS techniques to those formations in the Upper Cretaceous that are recognized as

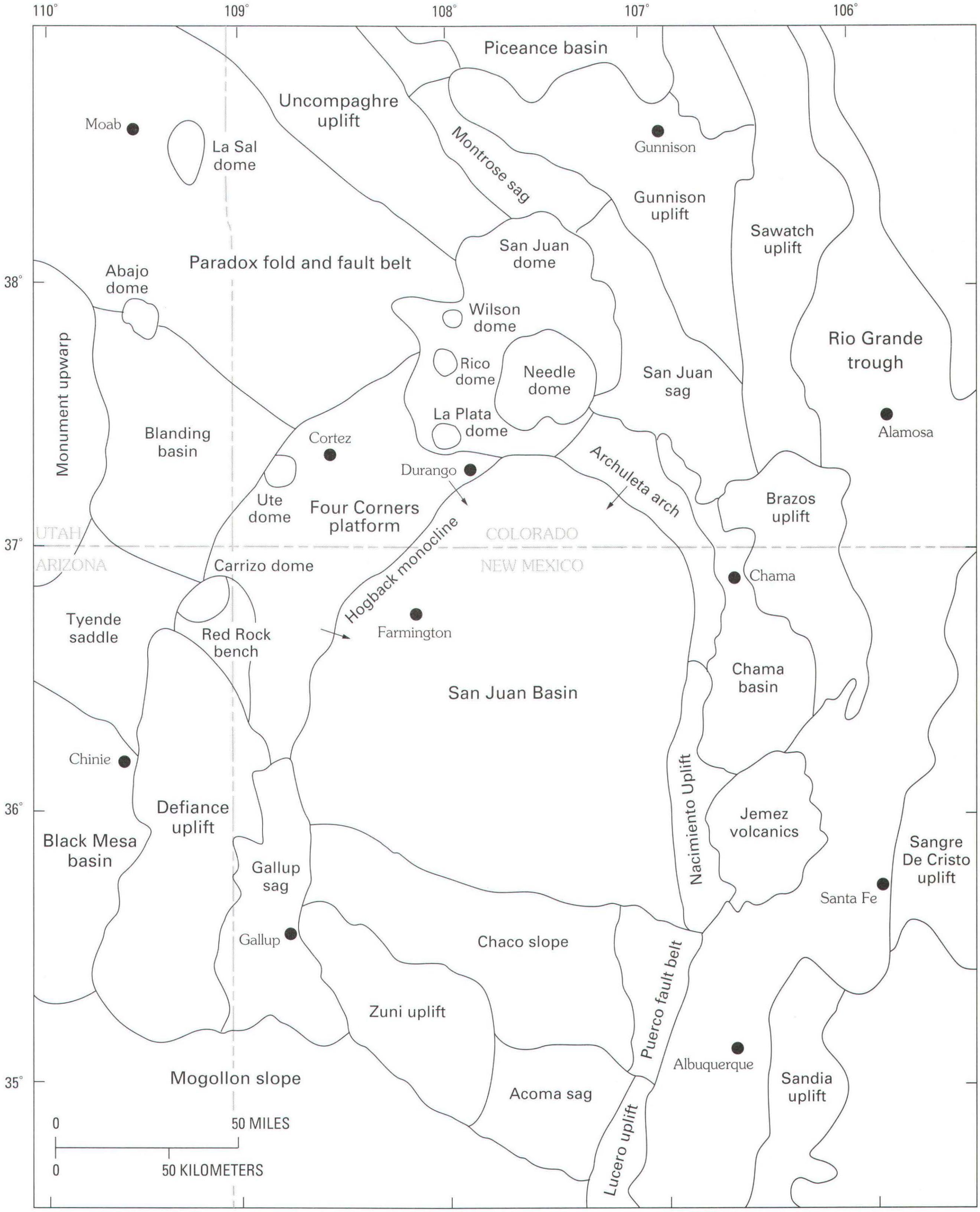


Figure 4. Structural elements of the San Juan Basin and adjacent areas. Compiled by Finch and others (1989); modified from Kelley and Clinton (1960), Grose (1972), and Woodward (1974).

the major oil and gas producers in the San Juan Basin. The four formations discussed in this report are the Dakota, Gallup, Point Lookout, and Pictured Cliffs Sandstones. The Gallup represents the only major oil producer; the remaining three formations are primarily natural gas producers. The San Juan Basin stratigraphic correlation chart is shown in figure 5.

The Cretaceous stratigraphy of northwestern New Mexico and southwestern Colorado represents numerous transgressions and regressions depositing intertonguing sequences of shale, sandstone, and lesser amounts of limestone and coal in marine, nearshore marine, coastal-barrier, deltaic, and fluvial environments. The interbedded marine and continental deposits range in thickness from 4,000 to more than 6,000 ft. The total sediment thickness for the Cretaceous is relatively uniform despite the abrupt transgressive and regressive facies changes across the basin and the recognized unconformity within the Gallup sequence.

Due to limited exposures, little is known about the Early Cretaceous in the San Juan Basin. The Burro Canyon Formation in the northern and northeastern parts of the basin is considered by most geologists to be Early Cretaceous in age (Saucier, 1974; Aubrey, 1988). Tschudy and others (1984, p. 1) report that the upper parts of the Cedar Mountain and Burro Canyon Formations yield palynomorphs that are palynologically of Early Cretaceous age.

Upper Cretaceous rocks of continental origin are the lower part of the Dakota Sandstone, most of the Crevasse Canyon Formation, the Menefee Formation, the Fruitland Formation, and the Kirtland Shale. The major transgressive and regressive Upper Cretaceous marine sandstones in the basin are the Gallup Sandstone; Tocito Sandstone Lentil of the Mancos Shale; and Point Lookout, Cliff House, and Pictured Cliffs Sandstones (Condon and Huffman, 1989). These sandstones are important reservoirs for oil and gas resources. The stratigraphy of the four Upper Cretaceous formations included in this GIS pilot study is discussed in the following sections.

Dakota Sandstone

The Dakota Sandstone, deposited on a regional erosion surface, rests unconformably on sandstone and shale of the Morrison (Upper Jurassic) or Burro Canyon (Lower Cretaceous) Formations (fig. 5). The upper contact of the Dakota is conformable with the Graneros Member of the Mancos Shale (Upper Cretaceous), and intertonguing of these two units is common near the contact. The strata represent a transition from continental alluvial-plain deposition in the lower part of the formation to marine coastal deposition in the upper part. The stratigraphy of the Dakota Sandstone is complex and consists of four major members—(in ascending order) the Oak Canyon Member, Cubero Tongue, Paguate Tongue, and Twowells Tongue (Landis and others, 1973; Owen, 1973). The two upper sandstone members intertongue with the Graneros Member of the Mancos Shale.

The Dakota Sandstone consists of fine-grained quartzose sandstones, carbonaceous shales, and occasional conglomerates and coals generally in the basal section (Deischl, 1973). Because of correlation problems concerning the location of the top and bottom of the Dakota Sandstone in many areas of the basin, the thickness of the Dakota is reported as ranging from a few tens of feet to about 500 ft. Stone and others (1983) report that 200 to 300 ft probably is a more common range. Depth to the top of the Dakota Sandstone ranges from 0 ft in areas of outcrop to about 8,500 ft in the northeastern part of the study area.

Data used in this study to compute the depths to the top of the Dakota Sandstone were taken from the PI–WHCS data base (Petroleum Information Corp.). Supplemental information was taken from existing water-well records in the USGS national Water-Data Storage and Retrieval System (WATSTORE) data base (Craigg and others, 1989) and from outcrop elevations.

The Dakota Sandstone produces both gas and oil in the San Juan Basin. Most of the gas produced from the Dakota is from the Basin Dakota field, which was discovered in 1947 and covers an area of approximately 1,500 mi^2. Dakota production is not continuous, however, across the productive trend due both to lack of continuity of the reservoir sandstones and to areas of little or no porosity. The trapping mechanism for the gas accumulation is considered to be stratigraphic and hydrodynamic rather than structural. Oil production from the Dakota Sandstone occurs toward the more shallow margins of the basin and is mostly structurally controlled, with some stratigraphic production. No satisfactory explanation of this juxtaposition of oil and gas has yet been given (Fassett and others, 1978).

Total cumulative production from seven Dakota gas fields in New Mexico, as of December 31, 1989, was more than 4.4 trillion cubic feet (TCF) and 37 million barrels of oil. The total cumulative production from 16 oil pools and undesignated wells, as of December 31, 1989, was more than 20 million barrels of oil and more than 13 billion cubic feet (BCF) of casinghead gas (New Mexico Oil and Gas Engineering Committee, 1989).

Gallup Sandstone

The Gallup Sandstone is the first major regressive sequence in the San Juan Basin and lies approximately 400 to 700 ft above the Dakota. The New Mexico Oil Conservation Commission defines the Gallup producing interval as that stratigraphic interval between the top of the Greenhorn Limestone Member of the Mancos Shale and the base of the overlying Mesaverde Group (Fassett and others, 1983).

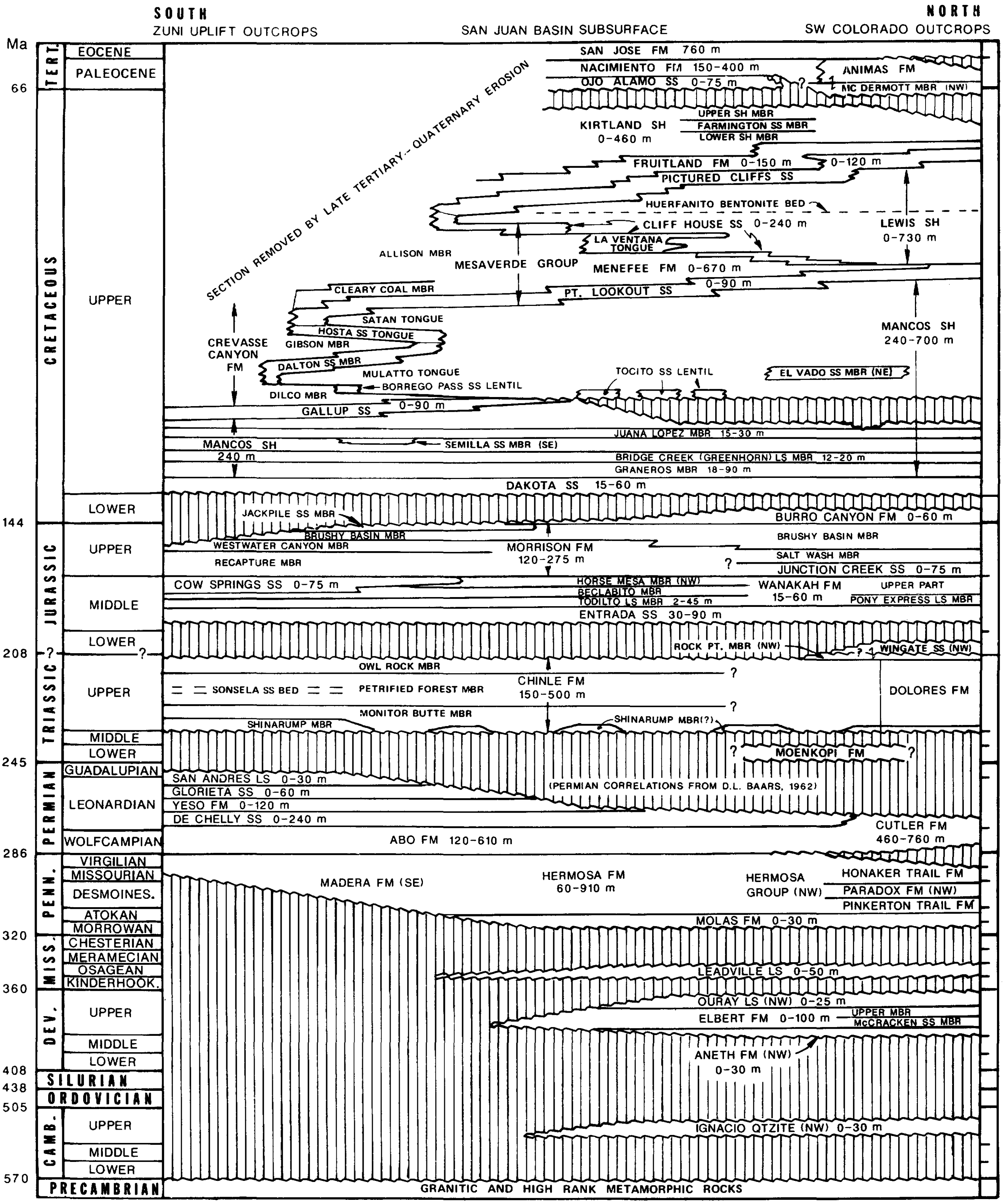


Figure 5. San Juan Basin stratigraphic correlation chart. Compiled by Molenaar (1977a,b); revised by Molenaar (1989). LS, limestone; SS, sandstone; SH, shale; | | | |, disconformity.

(This definition includes other named stratigraphic units.[1]) The Gallup producing interval can be divided into two stratigraphic parts in the San Juan Basin. The first or lower stratigraphic part, containing a series of marine and fluvial sandstones and shales, represents a major regression of the sea across the basin toward the northeast and has been called the regressive or true Gallup Sandstone. The uppermost section of this regressive unit has been named the Torrivio Sandstone Member of the Gallup Sandstone by Molenaar (1973).

The second or upper stratigraphic interval commonly contains a series of sandstone lenses at its base, which have been assigned to several different formations. These elongate bodies occur above and seaward from the regressive Gallup in a band of discontinuous, northwest-trending sandstone lenses in the northwestern part of the basin and lie northeast of the edge of the regressive Gallup unit. These upper Gallup sandstones have been referred to as the transgressive Gallup and basal Niobrara transgressive sandstone (Molenaar, 1973, 1974) and as the Tocito Sandstone Lentil in the Mancos, as used by Reeside (1924), Lamb (1968), Molenaar (1977a), and Fassett and Jentgen (1983). As shown on Molenaar's 1989 San Juan Basin stratigraphic correlation chart (fig. 5), an unconformity separates the regressive Gallup unit from the transgressive Gallup in the northern part of the basin (Molenaar, 1989).

The transgressive Gallup sandstones (Tocito Sandstone Lentil) are the major oil-producing rocks of the San Juan Basin. Most of the 33 oil fields in the basin are stratigraphic traps consisting of sandstone lenses enclosed by the marine Mancos Shale (Fassett and others, 1978; Fassett, 1983). A few of the fields also may be structurally controlled. The origin of these long, narrow, northwest-trending sandstone lenses, commonly less than 50 ft thick, is still poorly understood, but some may be associated with topography on the underlying Niobrara unconformity that represents Niobrara time (McCubbin, 1969; Huffman, 1989). Oil has been produced from the transgressive Gallup interval at depths ranging from about 400 to 7,700 ft. The northwestern trend of sandstone lenses (Tocito Sandstone Lentil) produces from about 1,500-ft depth on the Four Corners Platform and from about 4,500- to 5,500-ft depth to the southeast in the south-central part of the basin. The largest oil fields in the transgressive Gallup are the Horseshoe and the Lower Bisti fields, which had a cumulative production of more than 38.5 million barrels and 37 million barrels, respectively, as of December 31, 1989.

The regressive Gallup in the southern part of the basin produces oil from about 1,500-ft depth at the Hospah field, which is the only known field producing from the regressive Gallup. The field appears to be structurally controlled and produces from the "Hospah Sandstone," which is equivalent to the Torrivio Sandstone Member of the Gallup (Molenaar, 1973). It has produced nearly 20 million barrels of oil, as of December 31, 1989.

The Gallup producing interval in northwestern New Mexico, as of 1989, had a total cumulative production of more than 170 million barrels of oil, 520 thousand barrels of condensate, 88 BCF of dry gas, and 350 BCF of casinghead gas (New Mexico Oil and Gas Engineering Committee, 1989).

Data used in this study to compute the depths to the top of the Gallup were taken from the PI–WHCS well data file (Petroleum Information Corp.). Because most of the transgressive Gallup or Tocito Sandstone Lentil tops are identified in this well data file as Gallup, the productive Gallup interval in this study includes both the regressive and transgressive Gallup sandstones. Supplemental information taken from the USGS WATSTORE data base was restricted to the regressive Gallup Sandstone, as used by Kernodle and others (1989).

Point Lookout Sandstone

The Upper Cretaceous Mesaverde Group is the major gas-producing interval in the San Juan Basin. It consists of three formations—(in ascending order) the regressive marine Point Lookout Sandstone, the nonmarine Menefee Formation (consisting of sandstone, shale, and coal beds), and the transgressive marine Cliff House Sandstone (Peterson and others, 1965; Huffman, 1989).

The Point Lookout Sandstone, probably the largest gas-producing formation in the Mesaverde Group, was chosen as one of the four petroleum-productive formations used in this study. It is the most extensive regressive coastal-barrier sandstone in the San Juan Basin and represents a regional regression throughout the area of the Western Interior. The Point Lookout Sandstone consists of very fine to medium-grained, light- to medium-gray, well-cemented sandstones having laminations of light- to dark-gray carbonaceous shale and ranges in thickness from 140 to 250 ft (Peterson and others, 1965; Pritchard, 1973). It merges with the transgressive Cliff House Sandstone on the northern side of the basin (Molenaar, 1977a).

Because most of the gas production from wells completed in the Mesaverde section is comingled, knowing exactly how much gas has been produced from the Point Lookout, Menefee, or Cliff House units individually is impossible. However, the Point Lookout Sandstone is thought to be the largest gas producer as it is thicker and has greater continuity than the Cliff House Sandstone. A small amount of dry nonassociated gas has been produced from thin lenticular channel sandstone bodies and thin coal beds of the Menefee. The total production from all Mesaverde

[1] This definition was applied by the New Mexico Oil Conservation Commission for convenience in describing an oil and gas productive interval. The definition is used in this report and includes the identification of the Gallup Sandstone tops in the PI–WHCS well data files (Petroleum Information Corp.).

Group pools, as of December 31, 1989, was more than 7.2 TCF of gas and nearly 32 million barrels of oil.

The trapping mechanism for Mesaverde gas is not fully understood and is as much of an enigma as that of the Dakota Sandstone gas; that is, huge reserves of natural gas in the deeper central part of the basin have no apparent seal to prevent the gas from migrating updip and escaping. It is believed that swelling clays or hydrodynamic pressures may be sufficient to contain the gas within the traps, but such an explanation has its problems, and more studies are needed.

Data used in this study to compute the depths to the top of the Point Lookout Sandstone were taken from the PI–WHCS well data file (Petroleum Information Corp.). In some cases, the tops for the Mesaverde Group in the well-data file were not differentiated as to Point Lookout, Menefee, or Cliff House but reported only as the Mesaverde Group. These undifferentiated wells were not included in the data base coverages for the structural and isopach maps for the Point Lookout Sandstone. Supplemental information from the USGS WATSTORE data base also was used, when available.

Pictured Cliffs Sandstone

The Pictured Cliffs Sandstone, a regressive coastal-barrier sandstone, is the youngest marine rock unit in the San Juan Basin and represents the final regression of the Late Cretaceous Western Interior sea from the area. The Pictured Cliffs Sandstone, like the Point Lookout Sandstone, was deposited during regression of the Cretaceous sea (Fassett, 1977). The configuration of the Pictured Cliffs Sandstone is remarkably similar to that of the Point Lookout Sandstone; that is, both units rise to the northeast in a series of steplike stillstands, but the younger Pictured Cliffs extends farther to the northeast.

The Pictured Cliffs Sandstone occurs above the marine Lewis Shale and below a prominent basal coal interval of the Fruitland Formation. Stillstands or brief reversals in the regression of the seas to the northeast produced the thick Pictured Cliffs shoreline sandstones, which are locally as much as 400 ft thick (Molenaar, 1977a) and have been the most gas productive. The average thickness of these sandstones, however, is much less, but exact thickness is difficult to measure because of intertonguing with the underlying Lewis Shale. Pay thicknesses range from 5 to 150 ft but are typically less than 40 ft.

The Pictured Cliffs Sandstone is made up of very fine to fine-grained, fairly well sorted quartz grains and a small amount of darker grains including glauconite, mica, and carbonaceous shale, cemented by authigenic clay. Gas is produced from stratigraphic traps in the elongate northwest-trending beach or nearshore sandstone beds enclosed in shale or coal at the top of the unit. The producing area for the Pictured Cliffs trends northwest across the central part of the San Juan basin, is about 80 mi long by 20 mi wide, and covers nearly 1,600 mi^2 (Brown, 1973).

Total cumulative production through 1989 from pools in the Pictured Cliffs Sandstone was about 716,000 barrels of oil, more than 3 TCF of gas, and more than 500,000 barrels of condensate.

Data used in this study to compute the depths to the top of the Pictured Cliffs Sandstone were taken from the PI–WHCS well data file (Petroleum Information Corp.). Supplemental information from the USGS WATSTORE data base also was used, when available.

MAP COVERAGES FOR THE SAN JUAN BASIN

Each of the digitized map coverages or data layers that are in the San Juan Basin data base contains specific information required for the basin analysis. Separate coverages must be created for each data layer that may be needed in the project. To identify new associations between the map coverages, or to visualize combinations of data layers, map overlays, or composite map products, the geographic and geologic information must be manipulated. Geographic analysis techniques allow a geologist to visualize, manipulate, and investigate the relationships among the data layers by developing and applying different models. The models may reveal underlying trends in the related surface and subsurface data and thus provide new information or insight that will aid in the geologic interpretation.

This section briefly describes some of the specific surface and subsurface digital map and data coverages that were developed for the San Juan Basin data base. In addition, the section discusses some examples of composite map coverages that were generated by using the GIS for the automated geographic analysis of the basin data base.

Surface Map Coverages

Area Map

A simplified map coverage, shown in figure 6, of the Utah, Colorado, New Mexico, and Arizona State boundaries was derived from scanned USGS base maps and from digitized map boundaries (Craigg and others, 1989). Digitized outlines are shown on figure 6 for the San Juan Basin boundary, the study area boundary, the Colorado Plateaus boundary, and the State boundaries.

Base Map

Figure 7 is a simplified computer graphic taken from the more detailed base map coverage of the San Juan Basin study area showing State and county lines, some cities, and latitude and longitude. Information was derived from DLG

Figure 6. Map coverage of the Four Corners area showing the location of the San Juan structural basin and the study area. The study area is approximately 150 mi long by 100 mi wide.

format, scale 1:100,000. The base map was clipped[2] to the study area boundary as shown.

When certain map features appear in more than one coverage, such as the study area boundary or base map data, a template coverage is made with all these features included on it. New map coverages can be created more rapidly by using this template. New features specific to each coverage are then added. A template coverage of the study area boundary combined with a simplified base map was used repeatedly in this study in combination with many of the following map coverages.

[2]Clipping is the process of extracting data from a coverage that resides entirely within the boundary of features in another coverage (called the clip coverage).

Landownership Map

A digital map was generated showing landownership in the San Juan Basin, principally in northwestern New Mexico, covering private, Indian, Federal, and State lands. The landownership polygon coverage shown in figure 8 was derived from data in MOSS (Mapping Overlay and Statistical System) format provided by the Bureau of Land Management. Landownership maps, when combined with producing-well data and oil and gas field information, can pinpoint the occurrence of petroleum resources on private, Federal, State, or Indian lands.

Surficial Geology Maps

Map coverages were generated showing the surficial geology of the San Juan Basin, with each of the major

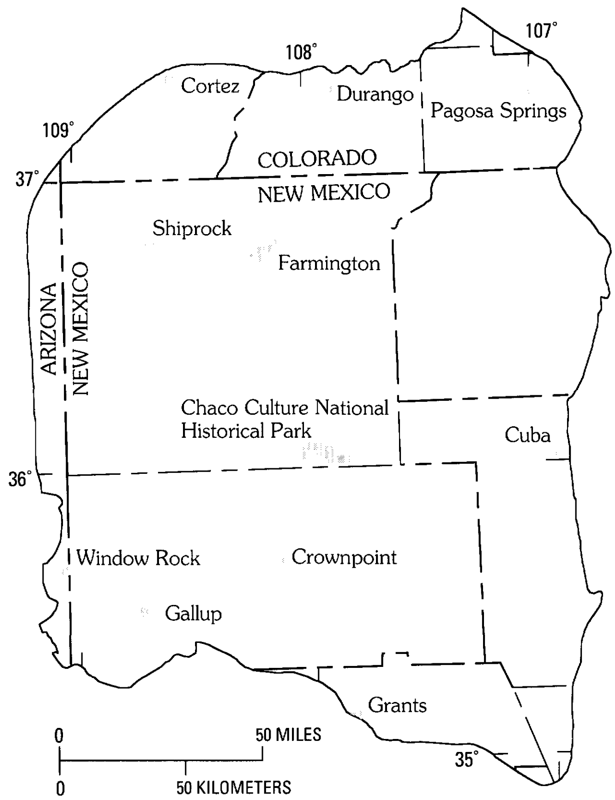


Figure 7. Computer graphic of the San Juan Basin study area taken from the more detailed base map coverage for the San Juan Basin illustrating a highly simplified base map clipped to the study area boundaries. Political boundaries are derived from data in digital line graph format.

formations identified and in color. The GIS allows the user to select from a list of 43 identified geologic units that were digitized from geologic map sources (Dane and Bachman, 1965; Wilson and others, 1969; Tweto, 1979; Hintze, 1980) at a scale of 1:500,000 and are in the San Juan Basin data base. Composite map coverages of the surficial geology can be generated by selecting various geologic units or groupings (categories) of geologic units to be identified on the map (limitations are set by ARC/INFO on the total number of units to be displayed at one time). For example, by using geographic analysis techniques, one such composite surficial geology map was generated with emphasis on the maximum extent for the Dakota Sandstone within the study area. Figure 9 shows the composite geology map identifying the following 10 geologic categories:

1. Surface deposits (includes alluvium, terrace deposits, dune sand, valley-fill, glacial, bolson, and other surface deposits).
2. Paleocene and younger rocks (includes the Chuska, San Jose, Nacimiento, and Ojo Alamo Formations).
3. Igneous rocks (includes Tertiary extrusive and intrusive rocks, volcanic rocks, basalts, and other intrusive rocks).
4. Kirtland and Fruitland Formations.
5. Pictured Cliffs Sandstone.
6. Shale formations (includes Mancos Shale, Lewis Shale, and other Cretaceous shale members).
7. Mesaverde Group (includes Mesaverde Group undifferentiated, La Ventana Tongue of Cliff House Sandstone, Cliff House Sandstone, Hosta Tongue of Point Lookout Sandstone, and the Point Lookout Sandstone).
8. Gallup Sandstone.
9. Dakota Sandstone.
10. Jurassic and older rocks (includes the Morrison Formation, San Rafael Group, and Triassic age rocks).

Outcrop Maps

Map coverages were generated showing selected outcrops for oil- and gas-bearing formations within the San Juan Basin study area. The outcrop coverages are derived from the digitized surficial geology coverages. The GIS allows a geologist to select any one or more of the geologic units from the list of identified geologic units in the data base for display on an outcrop map coverage. For example, figure 10 shows one composite outcrop map generated for this study that includes the following seven geologic units: the Pictured Cliffs Sandstone, the Cliff House Sandstone, the undifferentiated Mesaverde Group, the Menefee Formation, the Point Lookout Sandstone, the Gallup Sandstone, and the Dakota Sandstone.

Well-Location Maps

A series of map coverages was prepared showing the well locations in the San Juan Basin by using the location coordinates and other information taken from the PI–WHCS data base (Petroleum Information Corp.). These map files, built in INFO, were created by using data from PI–WHCS cards 10002, 10010, 103, and 104 containing the following items: a unique well number, latitude and longitude in decimal degrees, the producing formation and zone codes, general well classification (56 well categories), specific final well status, operator, commercial well elevation, elevation reference datum, and log total depth or driller's total depth for the well. Point coverages were generated by selecting a formation and all the wells by well class or status that either produced from or penetrated that formation (that is, oil, gas, or nonproductive (dry hole) wells). Then a series of map coverages showing the location of all oil, gas, and nonproductive wells was generated for each of the formations. Figure 11 shows a composite computer-generated map with the point coverages for all wells that either produce from or penetrate the Dakota Sandstone, for the Dakota Sandstone outcrops, and for the Dakota Sandstone subcrop extent. Well coverages, organized by

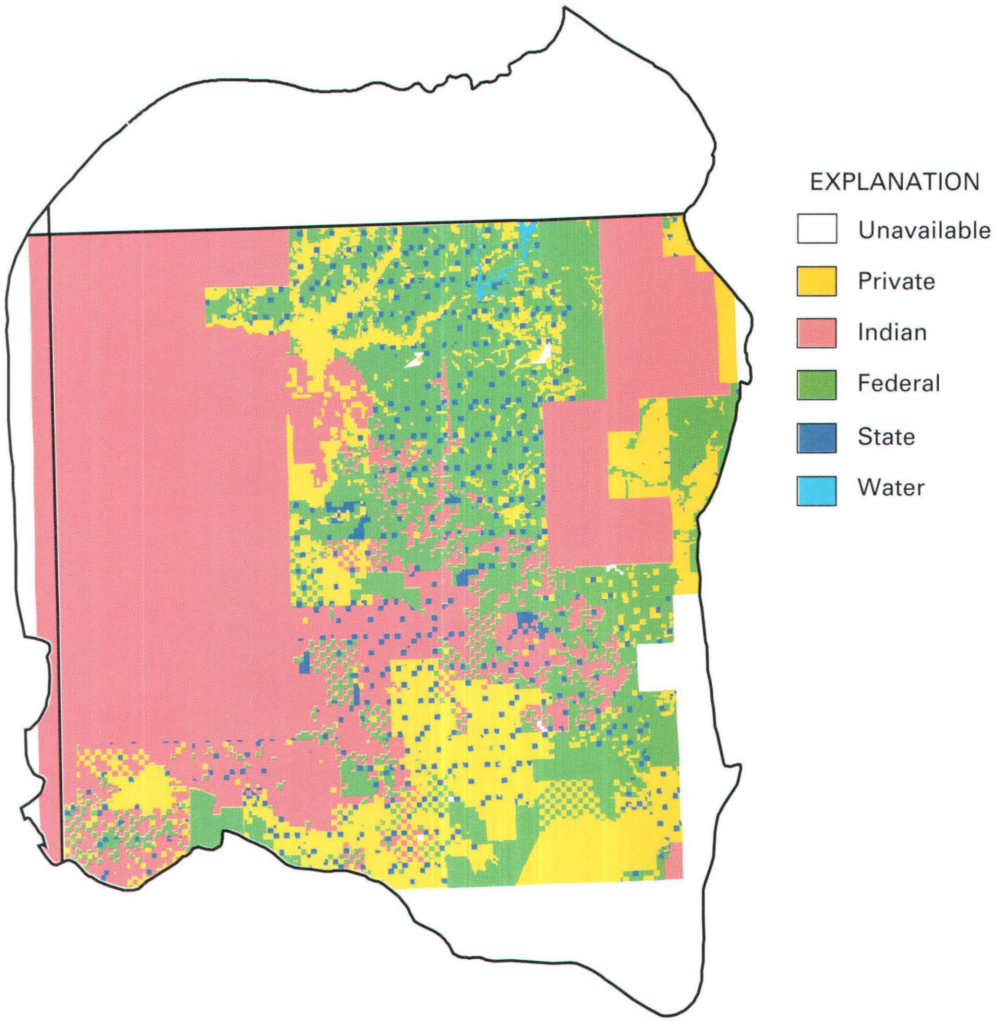


Figure 8. Map coverage display of landownership in the San Juan Basin study area, showing private, Indian, Federal, and State lands. The landownership polygon coverage was derived from data provided by the Bureau of Land Management.

formation and well status, can be combined with any other associated map coverages, such as structure or isopach contours for each of the formations, to create additional composite maps.

Subsurface Map Coverages

Stratigraphic Section

A time-stratigraphic correlation chart (fig. 5) was digitized and generated to provide a stratigraphic section and nomenclature chart in the data base for the San Juan Basin. The features for the stratigraphic section were digitized from published sources (Molenaar, 1977a,b, 1989). The stratigraphic section can be manipulated, revised, and updated, just as the other digitized coverages in the data base can.

Structural Maps

A series of structural maps, such as those shown for the Dakota Sandstone in figures 12 and 13, was generated for each of the producing formations by using depth to tops of formations as taken from the PI–WHCS well data file (Petroleum Information Corp.). Locations for all well data points and the calculated depths to the tops of the formations were stored in the data base. All of the structure contours in this study represent the depths to the top of the formations corrected to sea level. Figure 12 shows a structure contour map for the top of the Dakota Sandstone within the Dakota Sandstone subcrop extent. Figure 13 shows composite map coverage for the Dakota Sandstone, including productive wells, structure contours for the top of the Dakota, the Dakota Sandstone outcrops within the study area, and the Dakota Sandstone subcrop extent.

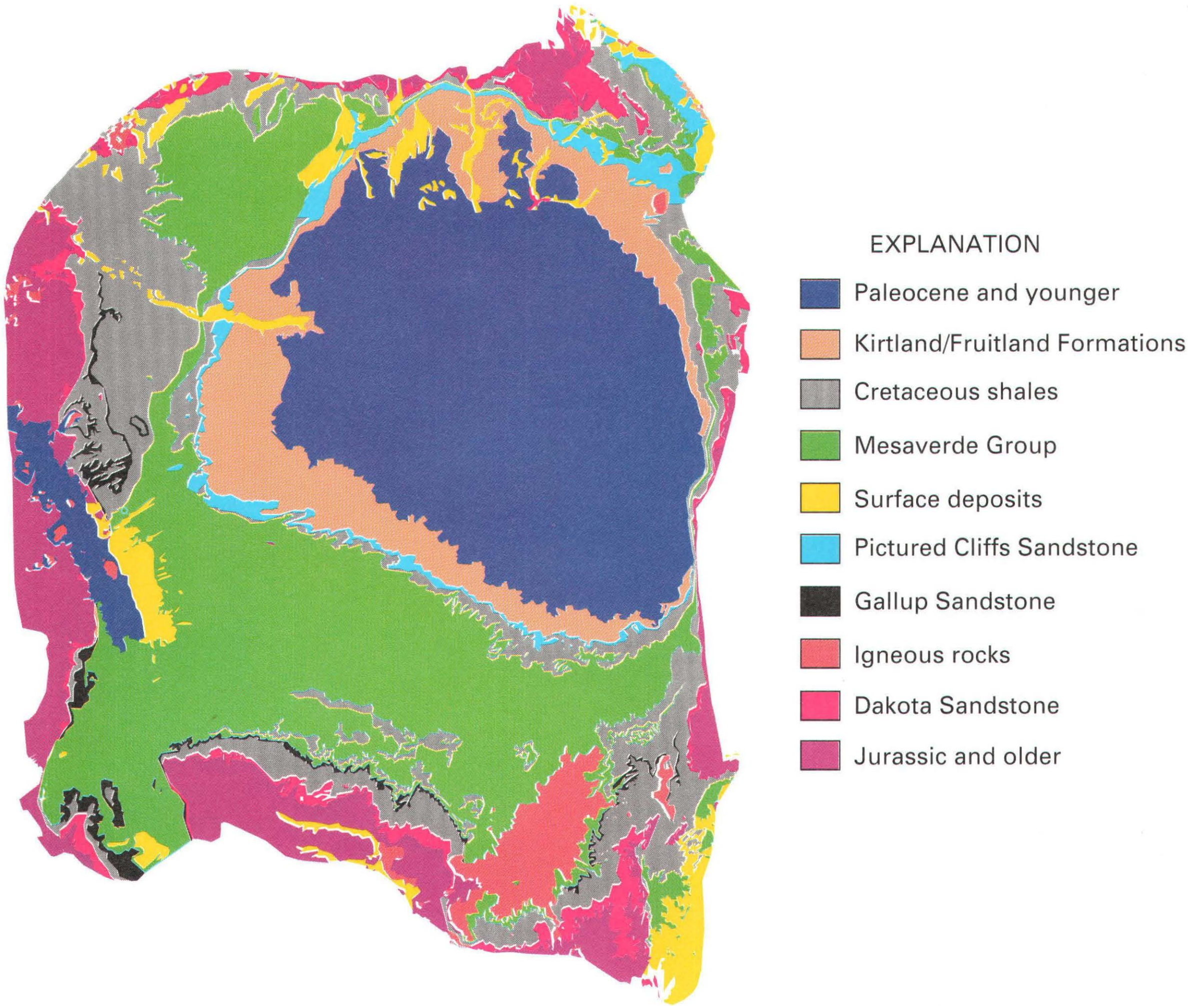


Figure 9. Map coverage showing one combination of identified geologic units of the surficial geology in the San Juan Basin study area. This map is based on 43 detailed geologic-unit codes stored as attributes for the digital data.

Isopach Maps

A series of isopach maps, such as the one shown in figure 14 for the Pictured Cliffs Sandstone, was generated for each of the producing formations by using thickness data taken from the PI–WHCS well data files (Petroleum Information Corp.). Locations for all well data points and thickness measurements for the producing formations were stored in the data base. Thickness data represent the calculated differences between depths to the top of a formation and to the top of the underlying formation in most cases.

All of the digitized structure and isopach contour maps for each of the producing formations were created for the basin data base by using the Interactive Surface Modeling (ISM) mapping software program. ISM mapping techniques were substituted for ARC/INFO's mapping software program, TIN (Triangulated Irregular Network; appendix B). The file of well data locations (point data) and depths to formation tops and thickness data was used as input data for the ISM mapping software package. The ISM mapping program calculates a grid from the scattered well data from which can be plotted base maps, contour (structure and isopach) maps, cross sections, fence diagrams, and perspective views or block diagrams. The structural and isopach line data are saved in ASCII format in ISM and imported back to the ARC/INFO system where a line coverage is generated. For a detailed accounting of the use of ISM mapping software, refer to "ISM Interactive Surface Modeling User's Guide" (Dynamic Graphics, 1984).

Composite structural or isopach maps showing associated map coverages can be generated automatically by using the GIS. For example, to produce a composite structural map for the Pictured Cliffs Sandstone, (1) the study area boundaries, (2) the outcrops and subcrops recording the extent of the Pictured Cliffs Sandstone, and

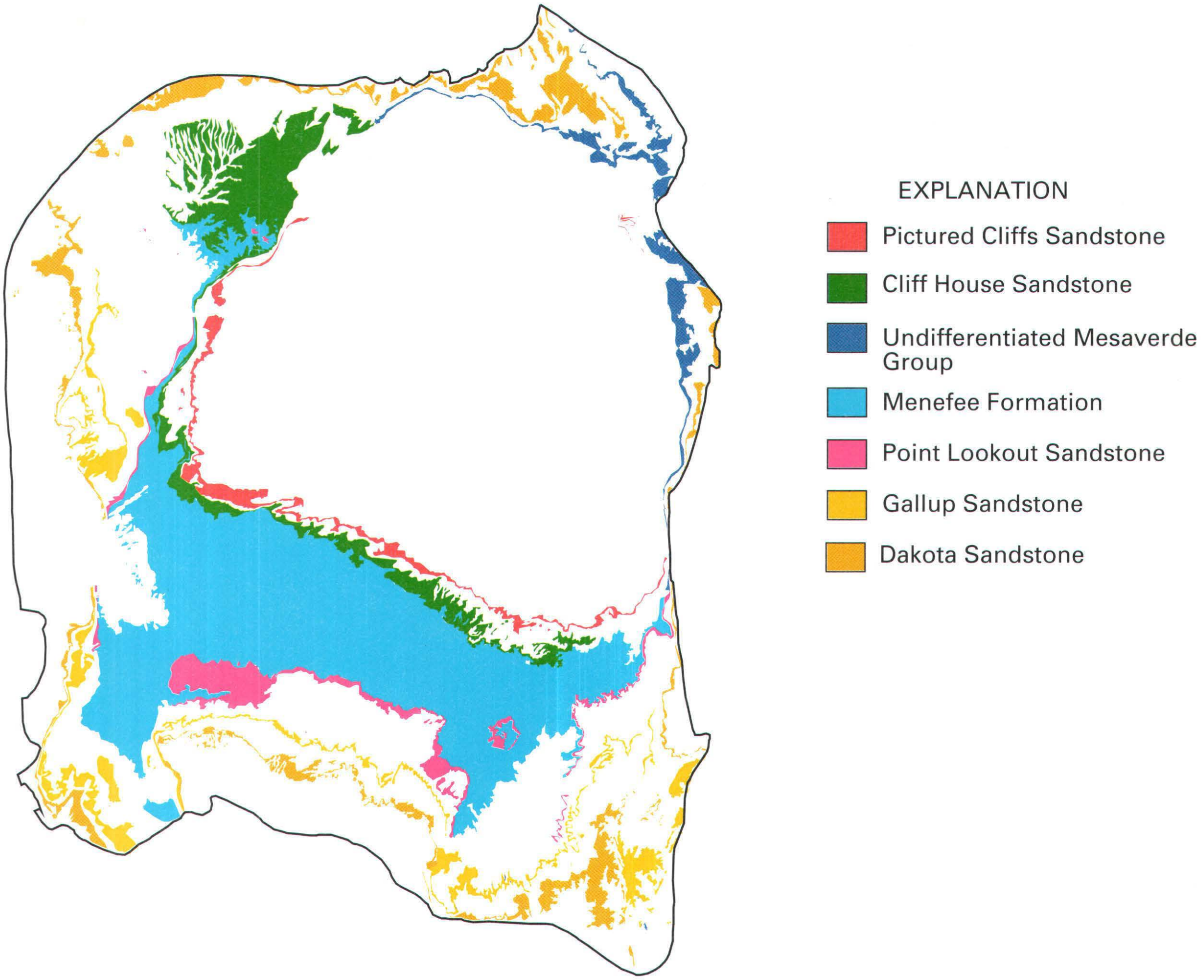


Figure 10. Map coverage showing selected outcrops of some of the Cretaceous oil- and gas-bearing formations within the San Juan Basin study area.

(3) the structure contour map using the depths to the top of the Pictured Cliffs are combined. Then all coverages for the oil and gas wells producing from the formation and for the nonproductive (dry hole) wells that penetrate this formation are added. To produce a similar composite map by using an isopach contour coverage, the same sequence of selections is repeated, but coverage for the structure contour map is replaced with coverage for the isopach contour map.

Figure 15 shows a composite map of the Pictured Cliffs Sandstone combining the coverages for the outcrops and subcrops, the structure contour map, and the locations of the 13 oil and 5,047 gas wells producing from the formation. This composite structural map shows the spatial relationships of the productive trends for the oil and gas wells within the Pictured Cliffs Sandstone relative to the structural configuration of the formation within the basin. The nonproductive wells (dry holes) penetrating the Pictured Cliffs were omitted from figure 15 because there are nearly 10,000 and their depiction would completely clutter the map at this scale. Figure 16 shows a composite map of the Pictured Cliffs Sandstone combining the isopach contour coverage in place of the structure contour coverage with the same associated map coverages as shown in figure 15. This composite map shows the spatial relationships for the productive trends for the oil and gas wells within the formation relative to the thickness configuration of the producing sandstones. The nonproductive well coverage was omitted from figure 16 also.

These composite map coverages may reveal new spatial data patterns or previously unidentified spatial relationships that can be recognized by a geologist as pertinent to new interpretations for the geological data. The San Juan Basin data base contains 21 point coverages that map the location of oil, gas, and nonproductive wells by the formations that they produce from or, in the case of dry holes, by the formations that they penetrate (table 1). Figure 17 shows

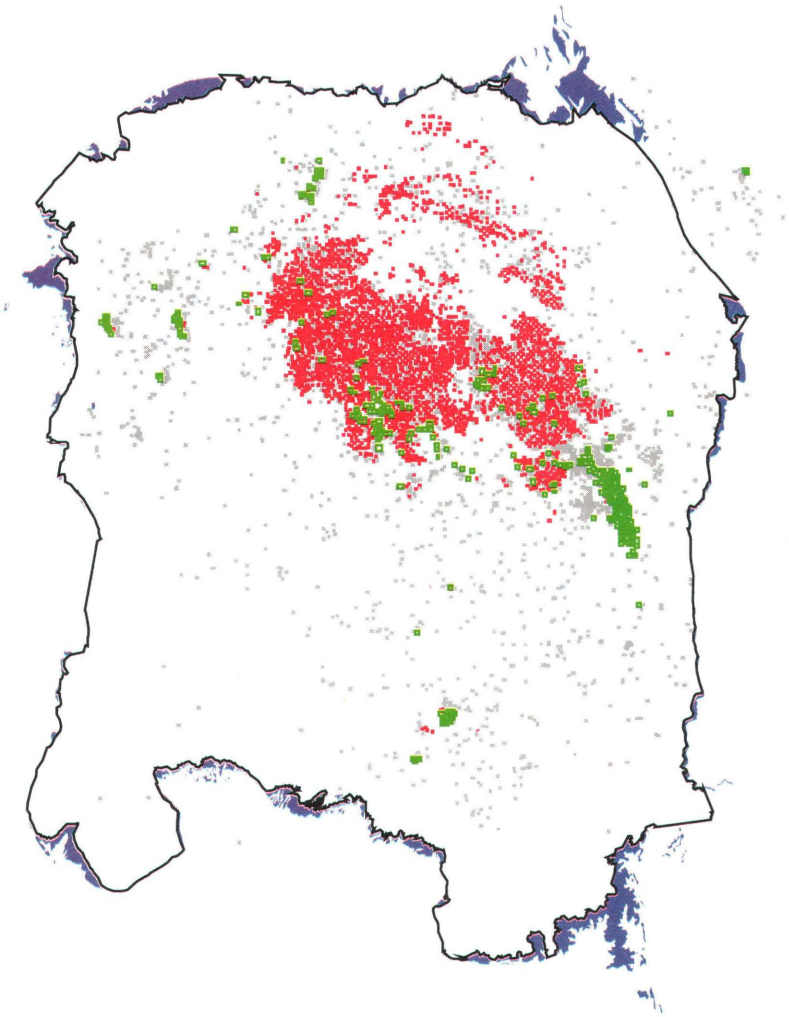


Figure 11. Composite computer-generated map coverage showing (1) the locations of all oil, gas, and nonproductive (dry hole) wells that either produce from or penetrate the Dakota Sandstone, (2) Dakota Sandstone outcrops, and (3) the Dakota Sandstone subcrop extent.

Table 1. Map (point) coverages for locations of oil, gas, and nonproductive wells (dry holes) listed by formation in the San Juan Basin GIS data base

	Number of wells		
Formations (older to younger)	Oil	Gas	Nonproductive (dry holes)[1]
Dakota Sandstone	443	3,168	3,116
Gallup Sandstone	2,554	250	5,430
Undifferentiated Mesaverde Group.	63	3,583	2,633
Menefee Member of the Mesaverde Group	41	56	6,047
Cliff House Member of the Mesaverde Group	63	109	7,256
Point Lookout Member of the Mesaverde Group	17	276	9,837
Pictured Cliffs Sandstone	13	5,047	9,907

[1] The nonproductive wells (dry holes) either reach total depth (TD) within the respective formation or penetrate the formation to reach TD in an underlying formation.

an example of the composite map coverage for the oil and gas wells producing from the Pictured Cliffs Sandstone and from the productive interval in the transgressive Gallup Sandstone. The spatial relationships for the producing trends within the two formations are strikingly different and reflect (1) the timing of the geologic conditions controlling the location of shorelines and subsequent reservoir occurrences and (2) the juxtaposition of the older oil-producing trend in the Gallup Sandstone and the younger gas-producing trend of the Pictured Cliffs. The San Juan Basin data base lists 13 oil wells and 5,047 gas wells producing from the Pictured Cliffs Sandstone and 2,554 oil wells and 250 gas wells producing from the Gallup Sandstone. There are more than 5,430 nonproducing wells penetrating the Gallup Sandstone, and nearly 10,000 nonproducing wells penetrating the Pictured Cliffs Sandstone.

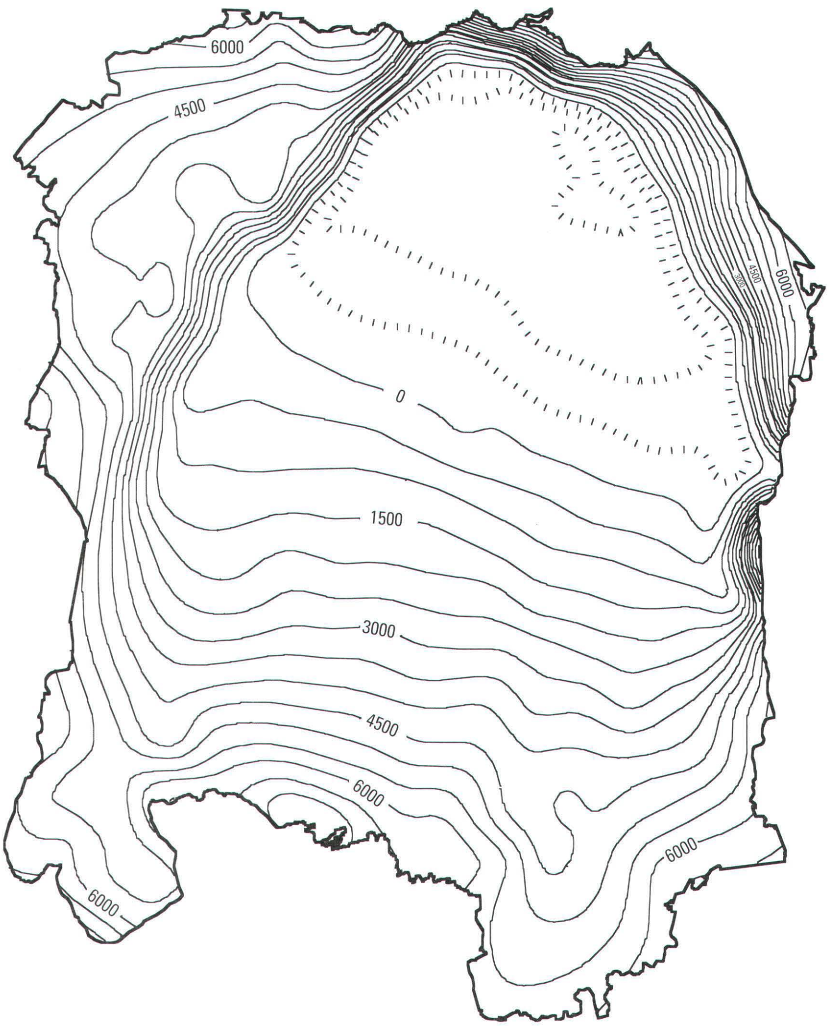


Figure 12. Map coverage showing structure contours for the top of the Dakota Sandstone within the Dakota Sandstone subcrop extent.

PERFORMING A GEOGRAPHIC ANALYSIS IN THE SAN JUAN BASIN

San Juan Basin Data Base

The current San Juan Basin data base includes all of the mapped data layers or coverages discussed in this report and all of the accompanying feature-attribute tables, lookup tables, and annotation coverages. It requires approximately 30,000 physical records of storage on a PRIME 50 series minicomputer, located in Reston, Va. This coverage does not include the PI–WHCS well-data file (Petroleum Information Corp.) for more than 24,000 wells in the San Juan Basin.

Several teaching tools were prepared as a part of this project to demonstrate some of the features of a GIS using ARC/INFO and the potential for using GIS techniques in the analysis of sedimentary basins. Information from the San Juan Basin data base was used for the demonstrated applications. The first tool, the San Juan Basin Demonstration System, runs on a PRIME 50 series minicomputer and is available on magnetic tape. The San Juan Basin Demonstration System requires approximately 15,000 physical records, or 30,720,000 bytes of storage (Person, 1989). The second teaching tool is a videocassette demonstrating the applications of geographic information systems techniques to basin characterization by using the San Juan Basin as a case study. The techniques demonstrated include the ARC/INFO software system and the ISM automated mapping software package, as well as well information taken from the PI–WHCS data base (Petroleum Information Corp.). The video tape demonstration is designed for the geologist or earth scientist unfamiliar with GIS technology, who is interested in adapting new computer techniques to analyzing spatial data used in sedimentary basin analysis or for petroleum exploration studies (Miller and others, 1990a,b).

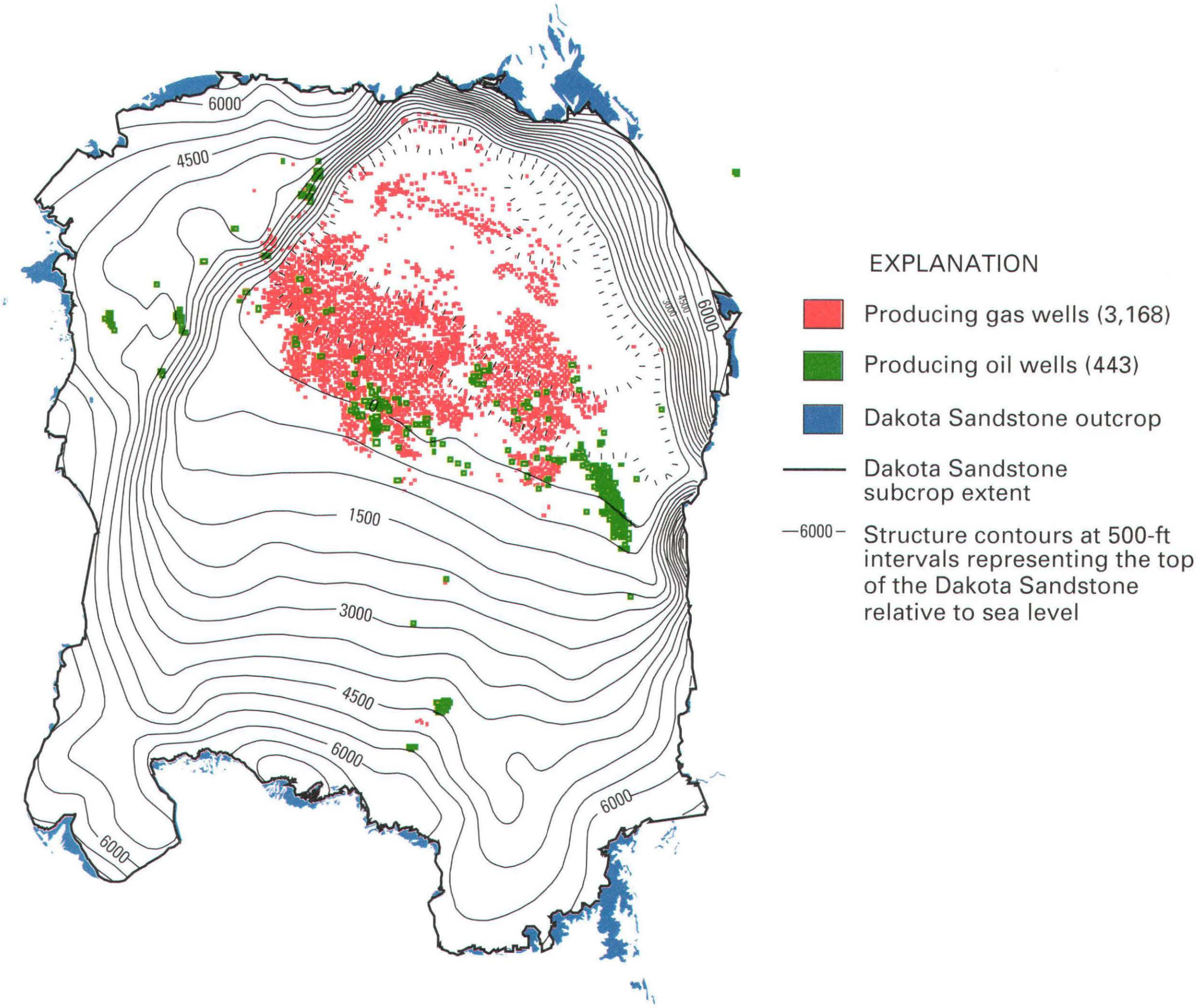


Figure 13. Composite map coverage for the Dakota Sandstone, including oil- and gas-producing wells, structure contours for the top of the Dakota, Dakota Sandstone outcrops in the San Juan Basin study area, and Dakota Sandstone subcrop extent.

Using the GIS for San Juan Basin Analysis

The following two scenarios taken from the San Juan Basin pilot study illustrate how a geologist can use the GIS's ability to interpret and display geographic information by generating geographic (geologic) models and performing geographic analysis. Addressing these geologic problems by using composite map coverages is best shown in an automated onscreen display using the computer. However, the reader will need to visualize these procedures through the following descriptions, which identify a sequence of spatial and attribute manipulations, and through the two-dimensional computer-generated graphics, which illustrate the spatial relationships onscreen.

The first scenario involves the Point Lookout and the Pictured Cliffs Sandstones, which have both been identified as major regressive cycles in the San Juan Basin. The map coverages containing information for these sandstone formations can be combined for direct onscreen visualization and comparison in various sequences to determine whether any meaningful relationships exist within and between data sets from the two formations. Comparisons can be made automatically and rapidly for the geologic relationships being investigated, without resorting to time-consuming manual procedures that use transparent overlay maps to explore the probable spatial relationships within and between these data coverages. The following stages describe some of the geologic comparisons and analyses that can be made by using onscreen visualization:

1. Develop a composite coverage showing an overlay of the structure contour maps for the two formations to determine if the surfaces are conformable.
2. Develop a composite coverage showing an overlay of the isopach contour maps to determine if patterns of

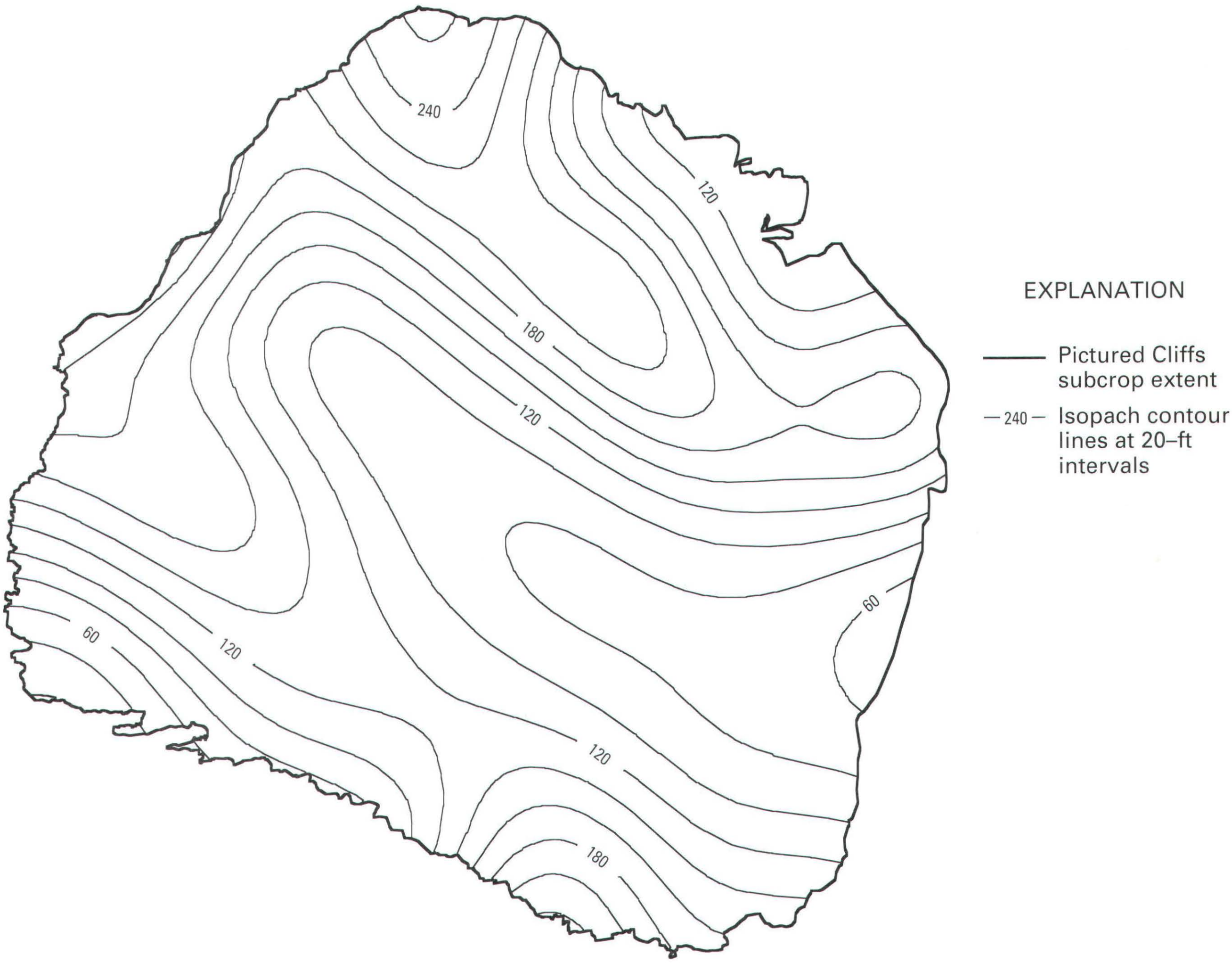


Figure 14. Map coverage showing the subcrop extent of and isopach contours for the Pictured Cliffs Sandstone in the San Juan Basin study area.

sediment thicknesses and deposition are similar or different for the two formations (see example in fig. 18).

3. Add the gas-producing wells from each of the two formations (in different colors) to each of the composite maps described above to determine if there are significant spatial patterns of occurrence for the producing trends relative to each other and relative to the structure and thickness patterns within each formation.
4. Develop a composite coverage showing an overlay of the isopach map onto the structure contour map for each formation separately to determine if structural highs or lows coincide with depositional patterns of sand thicknesses; then add oil and gas wells to determine if there are any structural or thickness patterns relative to the occurrence of the productive zones.

The number and combinations of realistic composite map coverages that can be generated are dependent only upon the availability of the required data in the GIS data base and the nature of the geologic problems to be resolved.

A second scenario describes the process of addressing a problem by using composite surface and subsurface map coverages. A geologist, wanting to see all the gas wells that produce from the Dakota Sandstone drilled on Indian lands, can generate a composite map showing the features necessary to respond to this question. This computer-generated map will include a clip showing the extent of the Dakota Sandstone both as an outcrop and subcrop map, an overlay of the Indian lands within the Dakota clip, and an additional overlay of the location of all the gas wells producing from the Dakota Sandstone. By zooming in and enlarging various land tracts by using the data manipulation features of the GIS, the individual gas wells producing on Indian lands can be identified, and well information can be retrieved from the PI–WHCS well data base (Petroleum Information Corp.). Additional coverages, such as the location of all the oil wells producing from the Dakota or the structure contours from the top of the Dakota, can be added. The major limitation to such an exercise is the amount of clutter

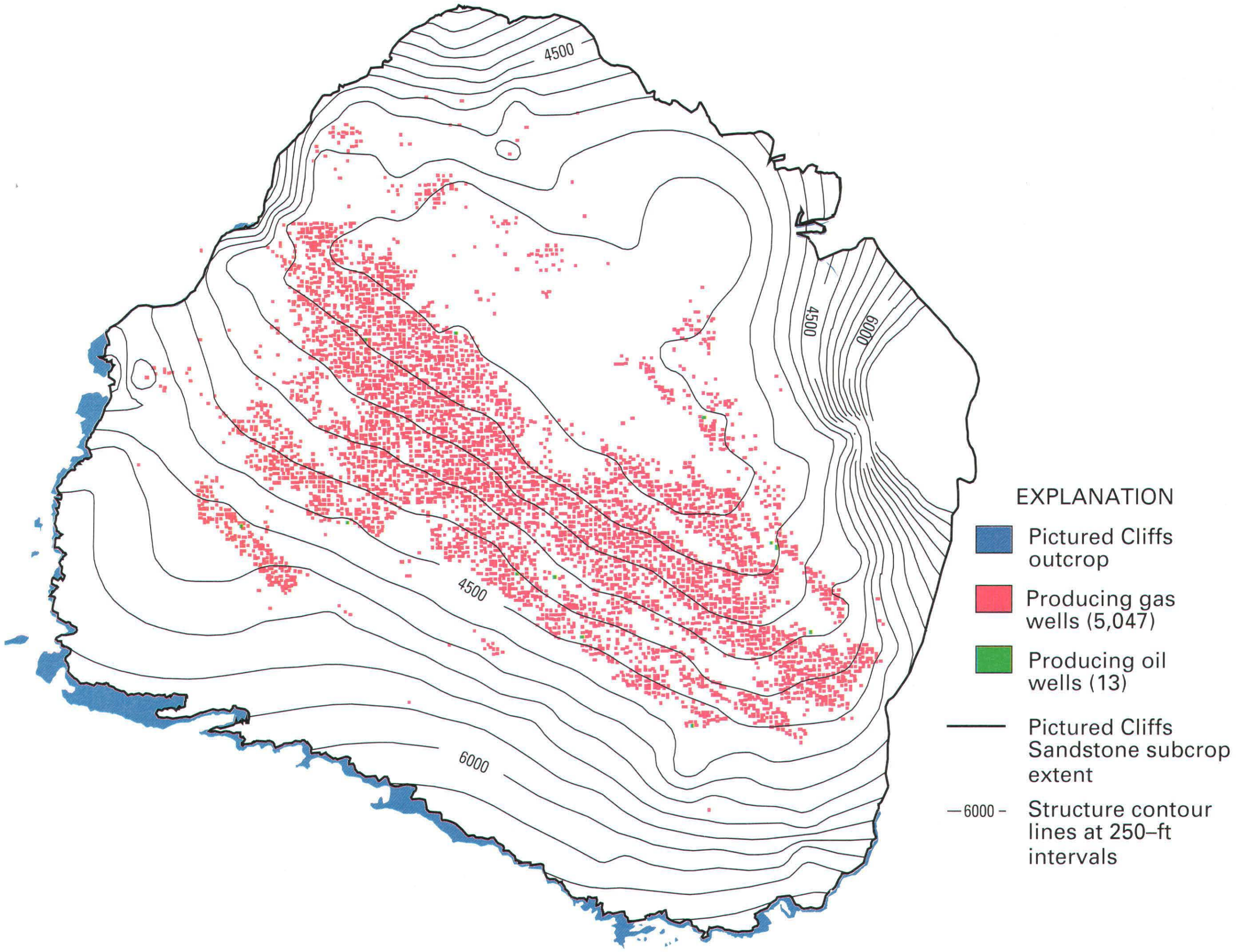


Figure 15. Composite map coverage for the Pictured Cliffs Sandstone showing structure contour coverage, outcrop and subcrop extent, and oil and gas wells producing from the formation.

building up on the display screen and eventually making viewing impossible. This buildup is especially evident when visualizing the maps of the entire basin at a smaller scale, rather than smaller areas in the basin viewed at a larger scale.

Additional Map and Data Coverages

A geologist, by using the joint capabilities of the ISM mapping software and the ARC/INFO system, can generate a variety of subsurface map coverages, depending on the geological data that have been added to the GIS data base. The number and types of geological data that can be entered into a data base for sedimentary basin analysis are endless. Theoretically, the only limitations on such a data base, assuming access to the necessary computer facilities, are the availability of the respective geological data needed to complete the study and the creativity and ingenuity of the geologist for investigating the relationships that may exist in and among the multivariate spatial data sets.

In addition to structural and isopach data that are essential to understanding the basin framework and stratigraphy for interpreting basin history, there are many other types of geological information that can be added to a basin data base. Selection of data types to be incorporated into the data base is dependent upon the objectives of the study and availability of the data. A few of the more typical data sets that can be added are lithologic data for facies analysis and depositional environment studies; engineering data (such as porosity, permeability, water saturation, bottom-hole and formation temperatures and pressures) for reservoir characterization; stratigraphic data and deposition, compaction, and subsidence information for stratigraphic analysis and burial history of the basin; organic data for hydrocarbon generation and thermal history; and petrographic and geochemical data for analysis.

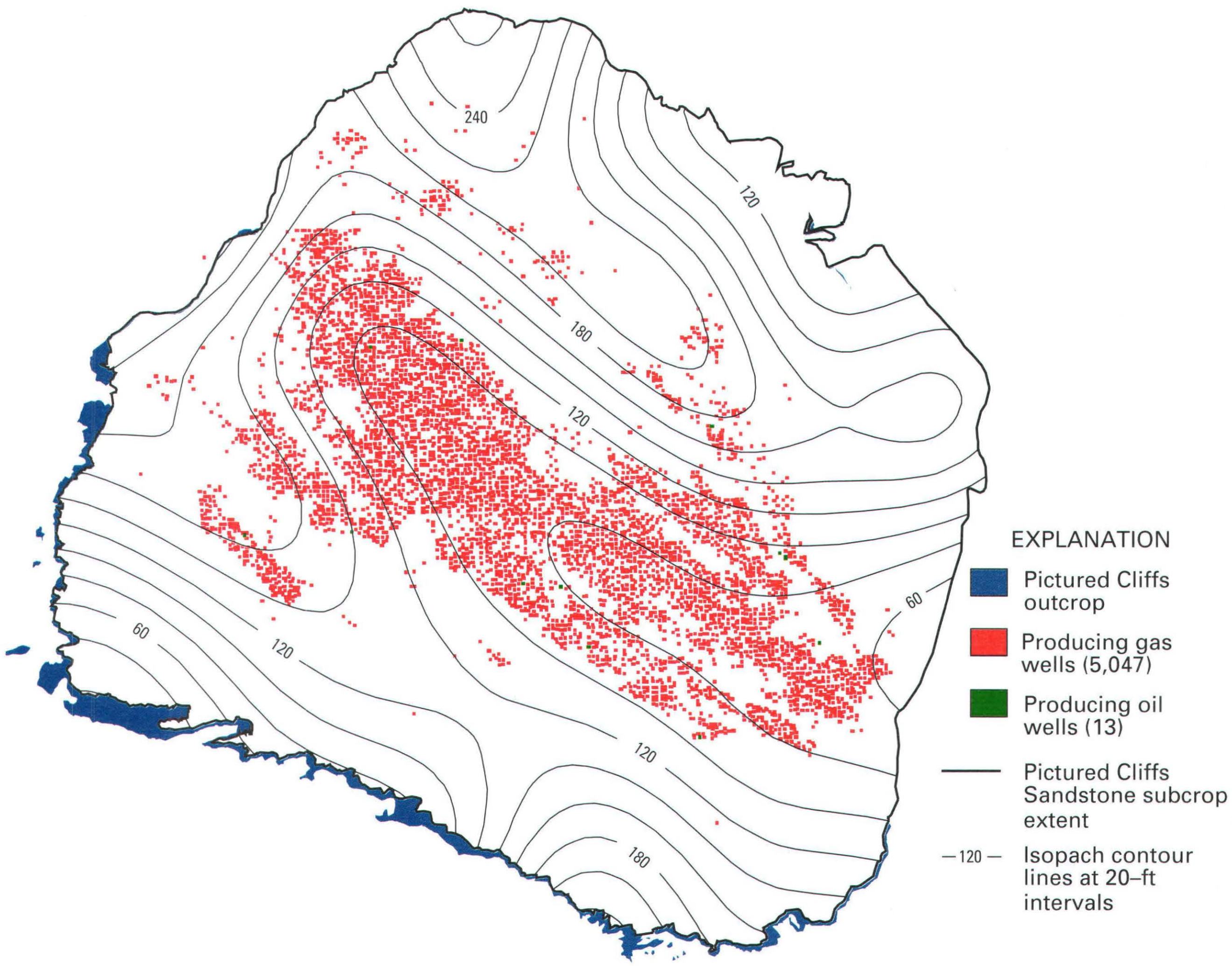


Figure 16. Composite map coverage for the Pictured Cliffs Sandstone showing isopach contour coverage, outcrop and subcrop extent, and oil and gas wells producing from the formation.

Further Applications of GIS for the San Juan Basin

During the review of the stratigraphy and petroleum geology for the San Juan Basin, a number of interesting and complex spatial geometries were revealed in the subsurface framework of the basin. If the data needed to address the geological problems were available in the basin's GIS data base, then the following situations would lend themselves to additional studies for a three-dimensional geologic analysis using GIS.

1. Dakota gas is present in the deeper parts of the interior basin, whereas most Dakota oil is located near the rim of the basin. No satisfactory explanation of this juxtaposition of shallow oil and deep gas has yet been given (Fassett and others, 1978). Investigations using GIS techniques of the spatial relationships for oil and gas occurrence within the Dakota Sandstone may be useful for the three-dimensional geological analysis of these conditions.
2. The spatial relationships represented between the regressive and transgressive Gallup sandstones and the Niobrara unconformity lend themselves to future correlation studies using GIS within the three-dimensional basin framework.
3. The trapping mechanism for Mesaverde gas is not fully understood and is as much of an enigma as that of the Dakota Sandstone gas. The spatial relationships represented by the deep-basin gas reservoirs and the structural and trapping configuration within the Point Lookout Sandstone are appropriate studies for a three-dimensional investigation using GIS computer mapping techniques.

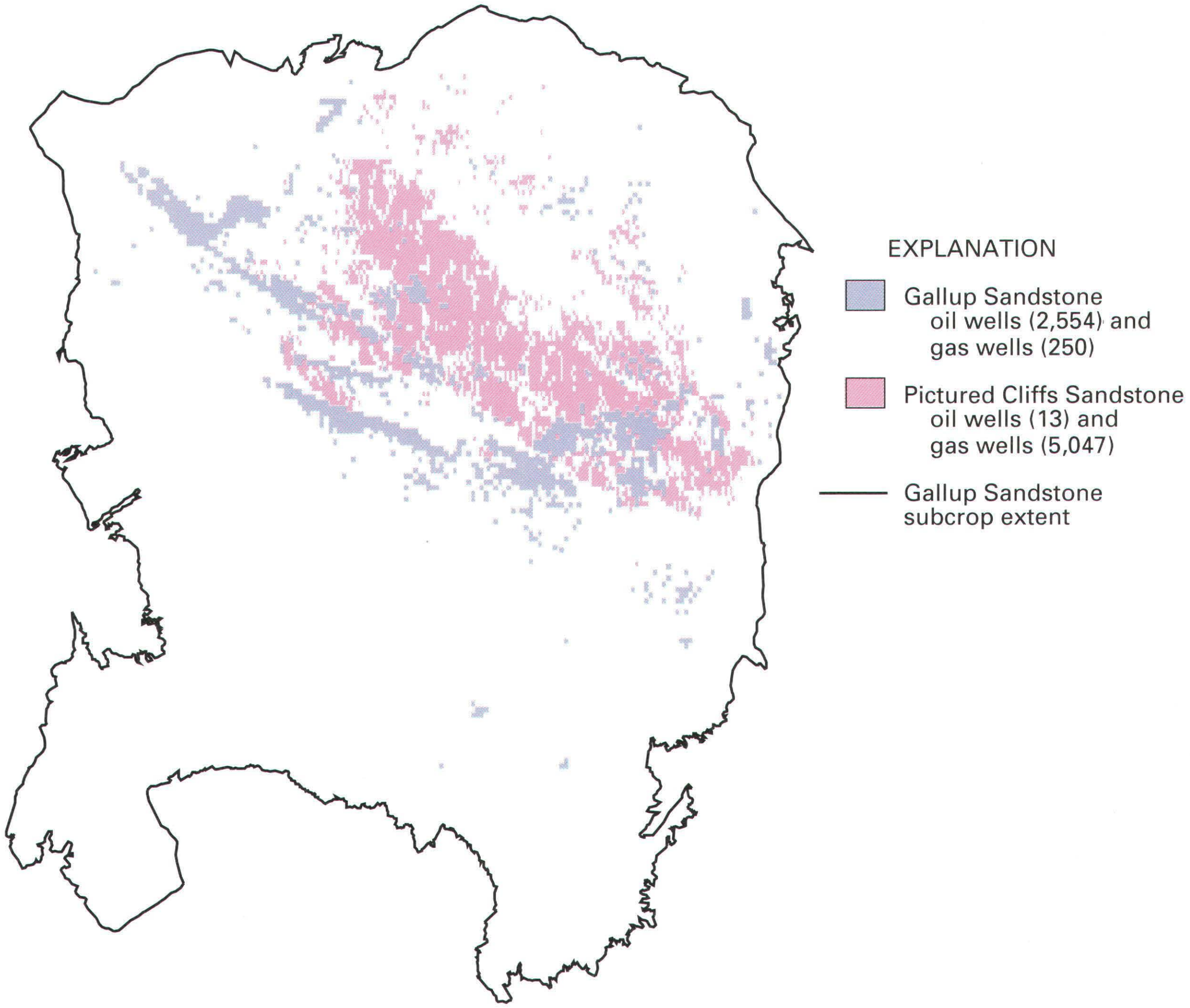


Figure 17. Composite map coverage for oil and gas wells producing from the Pictured Cliffs Sandstone and from the Gallup Sandstone. The spatial relationships for the producing trends within the two formations are strikingly different and reflect the geologic conditions controlling the reservoir occurrences within each formation.

4. The spatial relationships represented by the remarkably similar isopach configurations of the regressive Point Lookout and Pictured Cliffs Sandstones and the occurrence of their respective gas fields provide additional opportunities for a three-dimensional geological analysis using GIS computer mapping techniques, especially for exploration.

SUMMARY

Modern sedimentary basin analysis requires an understanding of many diverse geological specialties, vast quantities of multivariate spatial data, and the application of sophisticated computer technology to make the most effective analyses of the available data within the three-dimensional basin framework. One method being investigated for analyzing basins is the application of a geographic information system.

This report provides an introduction to geographic information systems and is a guide to the planning, development, and applications of a GIS data base to be used in the analysis of a sedimentary basin. The report demonstrates the application of GIS's and their potential for providing the tools needed to define new strategies and technologies for conducting and automating the complex tasks common to sedimentary basin analysis and particularly for extending two-dimensional computer mapping techniques to three-dimensional basin analysis.

GIS technology, involving the integration of computer mapping and data base functions, enables a geologist not only to query large data bases but also to integrate and manipulate spatial (coordinate) data with attribute (thematic) data. As a result, complex geographic and geological data sets can be combined to develop and apply new models and generate new composite maps. But more importantly,

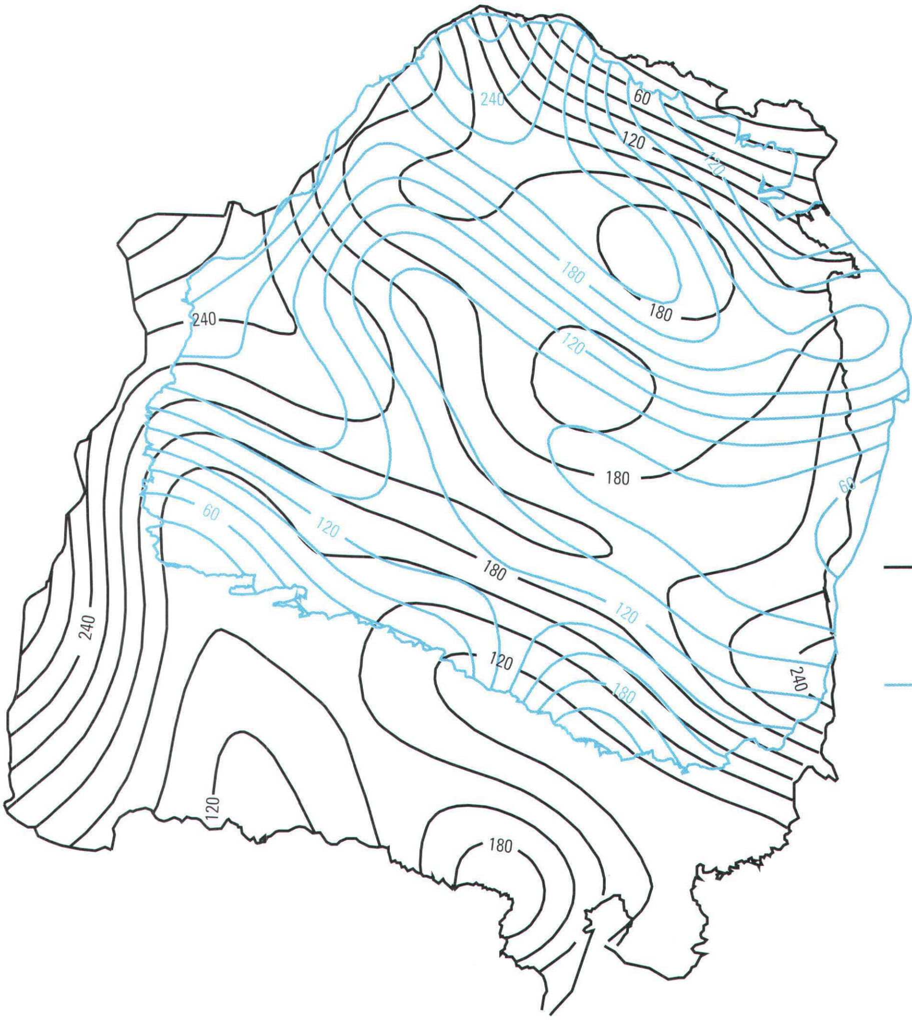


Figure 18. Composite map coverage showing an overlay of the subcrop extent (blue boundary) and isopach contours for the Pictured Cliffs Sandstone onto map coverages for subcrop extent (black boundary) and isopach contours for the Point Lookout Sandstone to determine if patterns of deposition are similar or different for the two formations.

GIS allows a user to conduct multivariate spatial data analysis and to have access to a variety of options for analyzing these data bases.

The San Juan Basin was used as a pilot study area to test the feasibility of applying GIS techniques to a basin analysis and for the development of a GIS data base. Specific GIS applications were designed to address the San Juan Basin's fundamental geologic, stratigraphic, and structural framework. These applications include the analysis of composite coverages for structural configurations relative to tectonics, depositional patterns using isopach contour maps relative to production trends, spatial relationships depicting geologic conditions favorable for the occurrence of oil and gas trends within productive formations, oil- and gas-field locations relative to their spatial occurrences within and between the producing formations, spatial geometries of transgressive and regressive cycles of deposition for productive sandstones, and landownership relative to the locations of favorable producing and perspective trends.

The relationships that may occur in and among the multivariate spatial data sets to be investigated are nearly unlimited, depending upon the number and types of geological, geophysical, and engineering data that can be entered into a data base for a sedimentary basin. The number of relational investigations that can be conducted for a basin study is, in turn, determined by the availability of the required data, the objectives of the study, and the interpretive ingenuity of the researcher.

GIS is an important new tool for the geologist, particularly for geological interpretation of three-dimensional multivariate spatial data in conducting basin analysis. As the advantages of a GIS become more obvious, the greater will be the versatility and scope of these basin studies. The nature of the additional map coverages needed to conduct these analyses will change and become more specialized as the objectives for new studies focus upon more specific geologic problems. Along with these changes will come geological applications that require new solutions to data base access and three-dimensional representation due to the range of data types, irregular data distribution, and the complex spatial geometries of the subsurface environment. Much research remains to be done in three-dimensional GIS, particularly for geoscientific modeling and basin studies.

ACKNOWLEDGMENTS

The work described in this paper was funded for the most part by an award to the writer in 1988 from USGS research funds, designated the Director's "GIS Sweepstakes," to support GIS research for geological applications. Grateful acknowledgment is made to Darcy Person, J. Mike Kernodle, and other Regional Aquifer-System Analysis personnel in the U.S. Geological Survey, Albuquerque, N. Mex., for some of the initial work completed on the data base for the San Juan Basin. The writer thanks Patricia C. Latzke (USGS) for her technical assistance in this project and for continuing to develop the digital data base for the San Juan Basin. Special thanks goes to Brian R. Schachte, computer specialist (USGS), for his assistance in using ARC/INFO and computer graphics.

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APPENDIXES

A. ARC/INFO GEOGRAPHIC INFORMATION SYSTEM
B. TIN MAPPING PROGRAMS FOR ARC/INFO

APPENDIX A. ARC/INFO GEOGRAPHIC INFORMATION SYSTEM

The following is an introduction to the ARC/INFO GIS and a very brief description of the ARC/INFO GIS method. For detailed instructions on the operation of the ARC/INFO system, the reader is referred to the "ARC/INFO Users Guide," volume 1 (Environmental Systems Research Institute, Inc. (ESRI), 1987), "Understanding GIS—The ARC/INFO Method" (ESRI, 1990), "Basic Readings in Geographic Information Systems" (Marble and others, 1984), and "ARC/INFO: A Geo-Relational Model for Spatial Information" (Morehouse, 1985).

ARC/INFO is a GIS cartographic system built around a hybrid data model and designed to provide a tool box of general purpose GIS programs for creating, analyzing, displaying, and managing computerized maps in a vector format. It organizes geographic data by using a relational and topological model. This format facilitates the handling of the two generic classes of spatial data: (1) location data describing the location and topology of point, line, and polygon-area features and (2) attribute data describing the characteristics of these features. ARC/INFO represents map features by sets of lines (arcs) and label points and as relationships between connected or adjacent lines and points. The relationships used to represent the connectivity and contiguity of these features are referred to as topology. Topology is a mathematical procedure for explicitly defining these spatial relationships. It is used to store three spatial relationships for each map feature: area definition, contiguity (the identification of polygons that touch each other or connect), and connectivity (the identification of interconnected arcs).

ARC/INFO is composed of two subsystems: ARC and INFO. ARC, the x, y coordinate-handling software, is the main program environment in ARC/INFO and provides the extensive capabilities of the GIS system. ARC is used to automate, update, and edit spatial data and to manipulate the data through analytical operations such as buffering, map overlay, transformation, and coordinate projection. ARC handles the display of the map information. INFO is a complete Relational Data Base Management System for managing map attribute (thematic) data associated with geographic features in map coverages. All ARC/INFO attribute files are stored in INFO-readable formats. This format allows INFO to be employed for processing a coverage's thematic data.

In ARC/INFO, a coverage is the basic unit of information, and it represents a single map or theme of geographically referenced information. It is analogous to a digital version of a single map-sheet layer, or map separate, in conventional cartography and generally describes only one type of map feature, such as roads, streams, geologic rock units, or landownership tracts. A coverage defines the locational data (defined by coordinates and topological relationships with others) and includes thematic attributes (defined as a set of named variables or items) for map features in a geographic area. By varying the types of features contained in a coverage and the thematic items associated with the features, the coverage can be used to represent many types of map information. The coverage serves as a unified framework for the representation of geographic information in ARC/INFO.

APPENDIX B. TIN MAPPING PROGRAMS FOR ARC/INFO

TIN is the set of software programs used to store, manage, and analyze three-dimensional surfaces for ARC/INFO. TIN stands for Triangulated Irregular Network—a set of adjacent, nonoverlapping triangles used to represent the facets of the Earth's surface. A TIN structure is created from a set of irregularly spaced points having x, y coordinates and z values such as elevation or subsurface depth. Because the TIN data structure includes topological relationships between points and their close neighbors (that is, which points define each triangle and which triangles are adjacent), it allows the user to generate surface models.

TIN is integrated with the rest of the ARC/INFO system. It provides data conversion, modeling, and display capabilities for terrain and other types of surfaces, as well as conversions to and from standard ARC/INFO coverages.

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Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7.5- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales; they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7.5-minute quadrangle photogeologic maps on planimetric bases that show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

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Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases for quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolored or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; principal scale is 1:24,000, and regional studies are at 1:250,000 scale or smaller.

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