

GIS for Subsurface Modeling

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Draft May 4, 2003

Prepared for ESRI Book Publication entitled: *Subsurface Modeling With GIS*

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Summary

Subsurface geologic modeling is a complex task for geographic information system (GIS) technology. However, the spatial nature of geo-objects always drives GIS to be part of the modeling systems. The traditional activities in which GIS is involved in geosciences are data management, visualization, spatial analysis, and decision support. Current developments allow the full GIS capabilities on a desktop computer with full integration of the industry-standard relational database management system (RDBMS), geostatistical functionality, 3D visualization, 3D geoprocessing capabilities, and Web-based mapping. These make GIS more attractive for comprehensive geosciences needs. Modern GIS is built on an open standard technology that ensures GIS can be integrated with specialized solid 3D geosciences programs to solve complex geologic problems.

Introduction

Subsurface geologic modeling is a difficult task for GIS. There are several reasons for this, for example, (1) a GIS is merely a general software package that handles spatial data, (2) the limitation of subsurface data requires data exploratory interpolation tools that traditionally are not a part of a GIS, (3) the requirement of real 3D analysis and visualization demanded by petroleum and mining companies is not available from most GIS packages, and (4) the complexity of the geo-objects themselves.

However, the spatial nature of geo-objects as the object of modeling always drives GIS to be part of the modeling systems. Traditionally the main activities in which GIS was involved in geosciences projects were in the data management, visualization, spatial analysis, and decision support system. The current GIS developments allow wider and deeper contributions of GIS. This paper describes the current GIS technology standards that can be applied for subsurface geo-objects modeling and the development trends in the near future that make GIS more attractive for satisfying the complex needs of geosciences.

Core GIS Activities for Geosciences

To know how GIS can be applied in geosciences, especially in subsurface modeling, consider what geoscientists think about GIS. Among many geoscientists having special interest in GIS, Dr. Graeme Bonham-Carter (Geological Survey of Canada) and

Professor Keith Turner (Colorado School of Mines and Delft University of Technology) may be the most well-known geoscientists who, for decades, have been promoting GIS for geosciences applications. Following are their views about GIS.

Bonham–Carter works mainly with surface data for *mineral potential mapping*, but much of his concept is applicable for subsurface projects as well. Bonham–Carter (1994, 2000) stressed what can be done by GIS for geosciences rather than complaining about what cannot be done by GIS. There are six core activities of GIS that can be applied in geoscience applications: (1) *data organization* (involving data modeling, data compilation, and database construction), (2) *data visualization* (producing data views and maps and graphically evaluating spatial patterns), (3) *spatial data search (query)*, (4) *combining (integration)* of diverse data types, (5) *data analysis*, and (6) *prediction*, particularly to support decision making based on multiple factors of spatial information.

GIS has been particularly important in geosciences for data collection, organization, and distribution of geologic data and maps. Geosciences projects often maintain many types of data sources (geology, geophysics, geochemistry, wells, etc.) in which GIS is an invaluable tool for integration for many different data types. Visualization is another GIS activity that is extensively used in geosciences applications. This includes making maps on screen, producing hard-copy maps, and delivering maps. The spatial data search, or query, is a major advantage of using GIS compared to other types of software such as computer-aided design (CAD). The spatial query capability is enabled because GIS maintains a link between spatial features and associated nonspatial attributes, although they may reside in different tables. GIS uses the commonality between multiple layers to search their relationships. This is done through its ability to combine different map layers and observe them simultaneously to discover their relationship. This work leads to the hallmark of GIS functionality: *spatial analysis*. Spatial analysis in GIS is mainly used to uncover associations between data sets that are otherwise unknown. Exploring spatial association between data layers is ultimately used for prediction of suitable areas for a specific target. The prediction is based on mathematical and statistical models of many types. The modeling can be divided into two major groups: *data driven* and *expert-driven* methods.

Keith Turner (1989, 2000) on the other hand proposes the development of a new branch of GIS specialized for 3D modeling for geosciences applications called the *Geoscientific Information System (GSIS)*. The reason is that GIS is mainly dealing with 2D modeling that is not appropriate for geosciences applications. The GSIS is mainly differentiated from GIS by its three-dimensional spatial representation, either by using *volume elements* or *voxels* (3D version of raster) or *surface representations* (3D version of TIN).

Current Standard of Desktop GIS for Subsurface Modeling

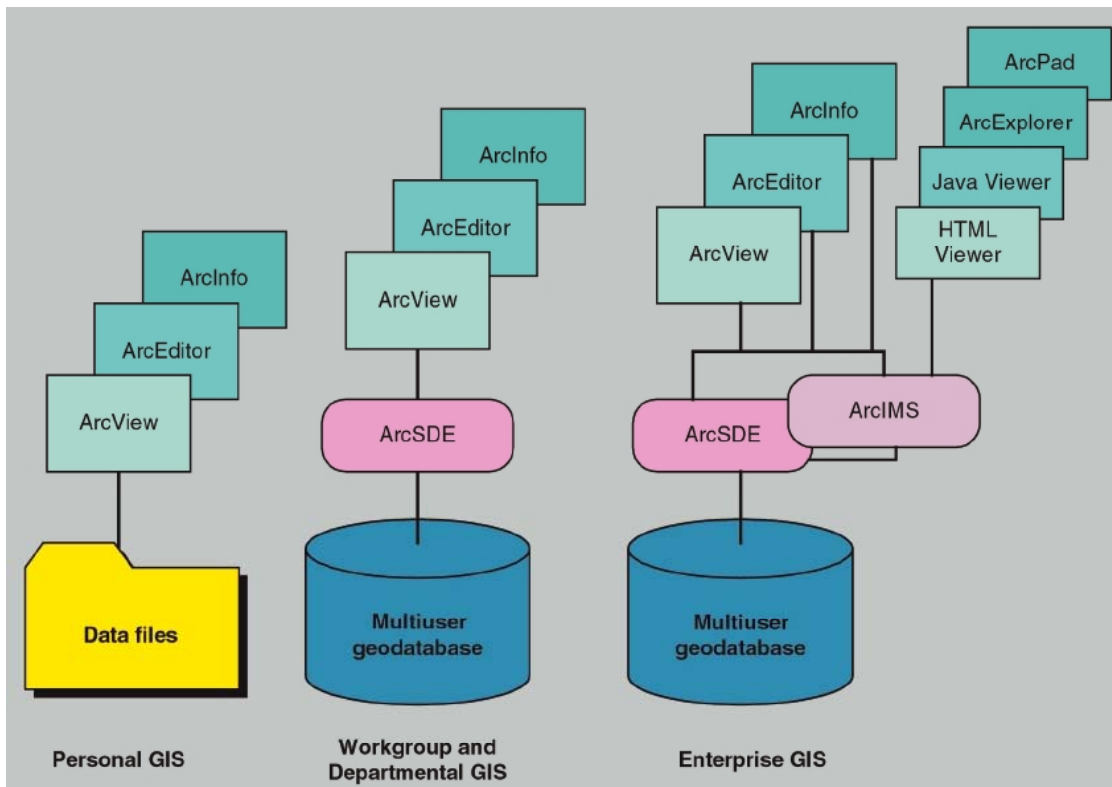
The current GIS technology applicable for subsurface geosciences applications is best described at a certain level located among Bonham–Carter's and Turner's ideas. The modern GIS is not yet based on a 3D spatial representation, but it has achieved a standard that extends the traditional 2D modeling into more complex tasks that bring it closer to geosciences needs.

The current GIS standards for geosciences applications are characterized by the following criteria: (1) it is built on nonproprietary object-based components, such as Component Object Model (COM) and CORBA; (2) it uses industry-standard database systems; (3) supports full functionality on a desktop GIS; (4) opens for further development and is highly interoperable with other systems; and (5) supports Web-based mapping. The GIS with these specifications allows data sharing with other systems and integration with specialized programs for geologic modeling (seismic interpretation, geophysical data processing, etc.). The object-based components also provide flexibility when configuring a GIS system since it is *modular* and *scalable*. It is modular in the sense that you acquire the system in pieces, and it is scalable since it can be deployed on an individual desktop or across a globally distributed network of people. The desktop GIS for geosciences should have full GIS functionality rather than only capability for display and query of spatial data. Internet mapping is important, especially for earth resources companies whose operation areas are located in many countries.

The ArcGIS family from ESRI fulfills these criteria. It is designed as a scalable system that can be deployed in every organization, from an individual desktop of a geologist to a globally distributed network of a petroleum company. In previous GIS products, the desktop GIS (for example, ArcView 3.x) was totally different from a full GIS such as ArcInfo. They were built on different technologies, they use different programming languages, data formats, and so forth. The desktop GIS in the past was used to display and query spatial data and was limited in complex functionality of the full GIS. The new breed of GIS is built on the same platform for all levels of functionality. For example, ArcGIS is built on the same platform for all packages, but they can have different functionalities depending on the types of license used. In ArcGIS 8 there are three levels of licensing: *ArcView*, *ArcEditor*, and *ArcInfo*. ArcInfo is the most powerful of all. Because ArcGIS uses common software application, data formats, and communication methods, a macro, for example, written with ArcView can be run using ArcInfo. All licenses also have the same three common applications: *ArcCatalog*, *ArcMap*, and *ArcToolbox*. ArcCatalog lets you find, preview, document, and organize geographic data and create a sophisticated geodatabase to store the data. ArcMap is the application for you to create and interact with maps, in which you can view, edit, and analyze your geographic data. ArcToolbox is a set of geoprocessing tools that give you the power of ArcInfo Workstation in a handy toolbox.

As ArcGIS is scalable, it can be deployed in different ways, depending on the complexity of your needs. A consultant geologist working for his/her natural hazard assessment project may use ArcGIS as a single user mapping and analysis tool. A research laboratory or a mining exploration department may use what is called a departmental GIS. This system is developed to support a key function of the department. An enterprise GIS of a mining company, for example, spans departments in its organization. These large systems support multiple functions from exploration and production to strategic planning.

Figure 1
Scalable ArcGIS Family



The key features of current GIS technology that directly benefit subsurface applications are as follows:

1. Industry-Standard Database and Intelligent Data Model

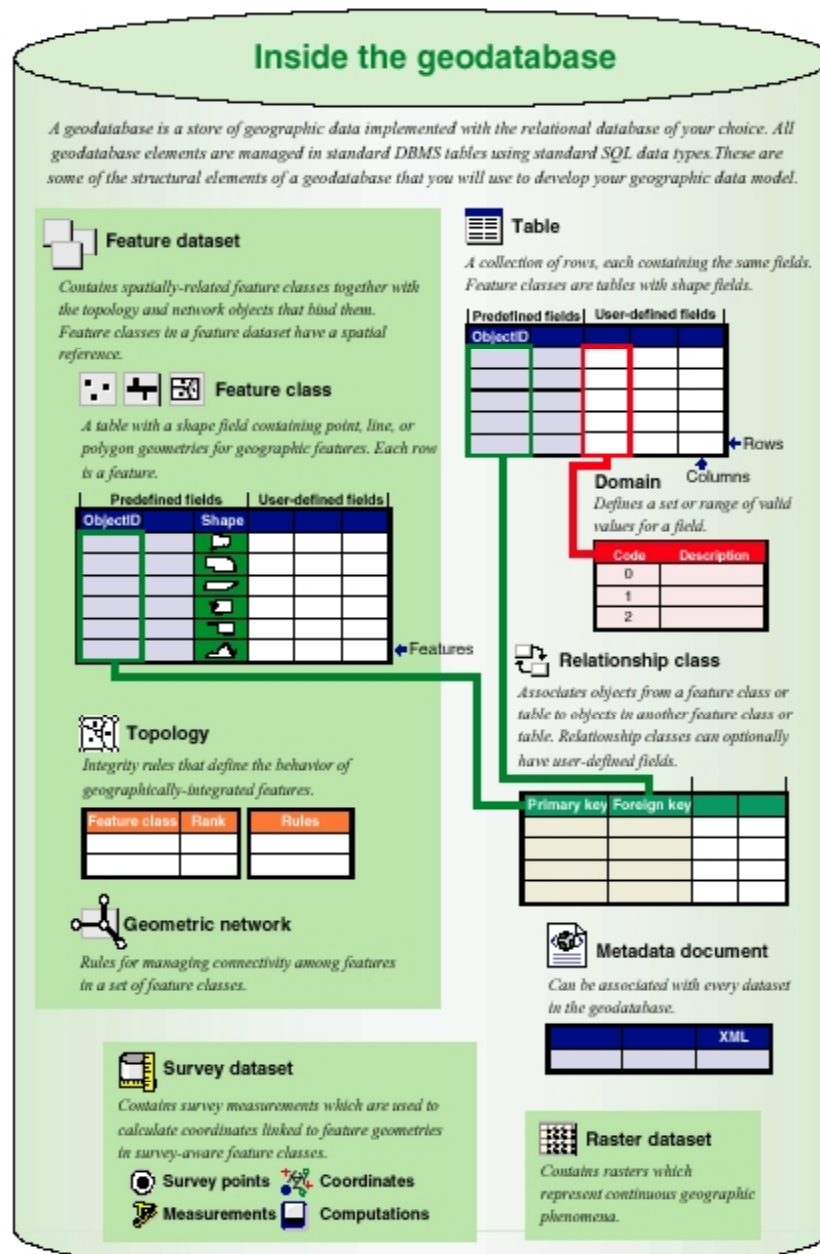
Using the industry-standard relational database management system enables the GIS team to directly use the corporate database within the management group. The GIS will also benefit from the development of the database management systems (DBMSs) by developers. The RDBMS is implemented in ArcGIS by *geodatabase*. The geodatabase is the native data format for ArcGIS that represents geographic features and attributes as objects and is hosted inside an RDBMS (Kennedy, 2001). The geodatabase supports a model of topologically integrated feature classes, similar to the coverage model, but it

also extends the coverage model with support to complex networks, relationships among feature classes, and other object-oriented features (MacDonald, 2001). The geodatabase brings a physical data model closer to its logical model such as boreholes, geologic maps, and geologic structures (previous data models such as the ArcInfo coverage aggregated these objects into homogeneous collections of points, lines, and polygons with generic behavior). The geodatabase supports the special behavior for each feature (Zeiler, 1999). A personal geodatabase is stored in Microsoft Access and is used for small- to medium-scale projects. Enterprise geodatabases are stored in IBM DB2, Informix, Oracle, or Microsoft SQL Server and are accessed through ArcSDE. The enterprise geodatabase handles huge amounts of data sets. Subsurface projects usually demand an excessive amount of spatial data storage. Putting all types of data (raster, vector) into a single container means that data integrity is maintained (*load once—read many*). This is the key of an enterprise GIS.

The geodatabase offers many advantages as follows: (1) all data (vector, raster, CAD, etc.) is stored together in an industry-standard RDBMS that assures data integrity, accuracy, and correctness; (2) allows multiuser access to continuous databases through the use of versioning and long transactions; (3) supports intelligent features, rules, and relationships; (4) the geodatabase data model supports a rich collection of objects (rows in a database table) and features (objects with geometry); (5) supports advanced capabilities, such as geometric and logical networks, and complex polylines; (6) geodatabases can be accessed via the standard menus and tools in ArcGIS, but programmers can also use the ArcObjects, OLE DB, and SQL application program interfaces (APIs) data access capabilities that are built using industry-standard APIs.

ArcGIS 8.3 allows ArcEditor and ArcInfo users to employ disconnected editing capabilities to work with a local or remote version of an enterprise geodatabase in a checkout/check-in environment. Users can work independently of the main database with options to reconcile edits and update the main database. This allows a geologist to work in the field, drilling site, or base camp locally without network constraints. When the geologist returns to the office and checks data in, only updates, deletions, and inserts are merged with the parent version of the database, thus improving the efficiency and integrity of the data. Disconnected editing technology also gives geoscientists the ability to readily distribute and share data from the main database with their colleagues in other sites.

Figure 2
Inside the Geodatabase



2. Web-Based GIS Mapping

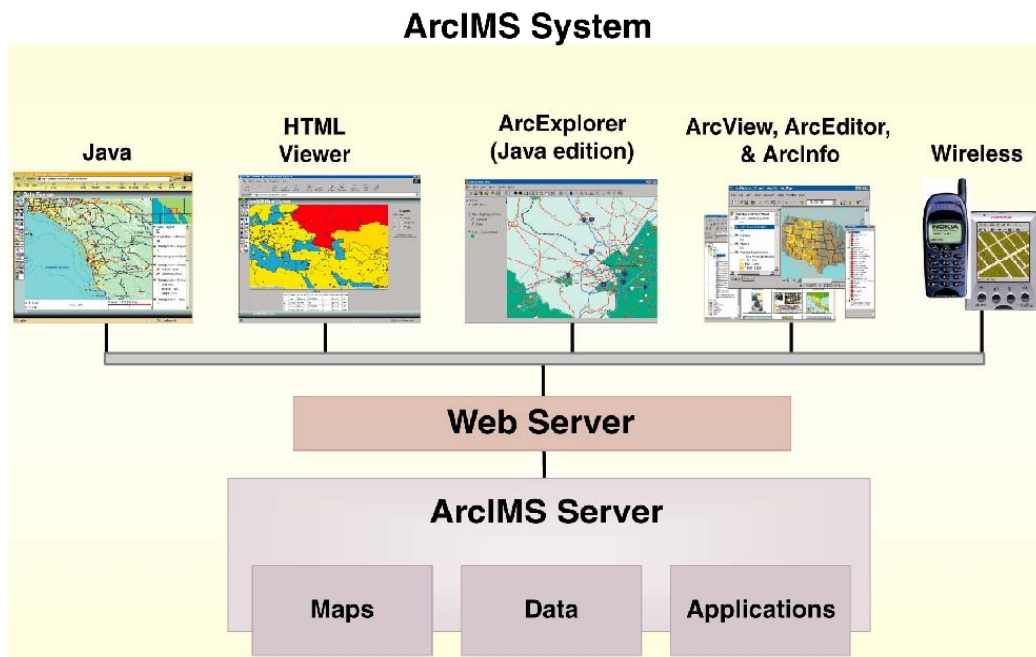
Internet-based GIS allows earth resource enterprises to centrally build and deliver a wide range of exploration data, GIS maps, and applications to geoscientists in different offices or sites on the World Wide Web. Fried (2000) showed how the Internet can be used to manage petroleum exploration and production data in order to make more efficient interconnections among team members of a project. Several advantages using Web

technology include the ease of use (most geoscientists and managers are more familiar with the Internet interface than GIS functionality) and minimal client hardware and software requirements.

In ArcGIS, Web-based mapping is made possible through ArcIMS. It extends a Web site by enabling it to serve GIS data and applications. ArcIMS works with a wide range of clients such as ArcGIS Desktop, HTML and Java viewers, ArcPad, wireless devices, and MapObjects for Java clients. ArcIMS runs in a distributed environment and consists of both client and server components. When an ArcIMS client sends a request to a server, the ArcIMS server processes and responds to the request. A wide range of GIS services is available through ArcIMS. The most common ArcIMS services deliver interactive maps to many types of clients. The map is delivered to the client in any of three ways: as an image, as streamed features, or as an ArcMap Image Service. A new ArcMap Service streams images from an ArcMap document to the requesting client. Feature streaming enables more advanced clientside tasks.

Metadata catalog is a catalog that references your data holdings and information sets and publishes them as a search service using ArcIMS. This provides an open search mechanism for geoscientists to purchase subsurface data sets such as geophysical data from a clearinghouse.

Figure 3
Web-Based GIS Architecture in ArcGIS Technology



3. Industry-Specific Standard Data Models

Many industry-specific data models have been built within the ArcGIS platform in order to simplify the process of implementing projects and to promote standards within the user communities. These models support ESRI's goal to support many different vertical industries, including earth sciences, with one GIS platform. ArcGIS data models provide ready-to-use nonproprietary frameworks for modeling and capturing the behavior of real-world objects in a geodatabase. These data models provide "quick start" solutions that optimize performance and establish industry standards that improve data sharing.

Several data models are already available for earth sciences including the petroleum, hydrography and hydrology, geology, and marine data models (see <http://support.esri.com/datamodels>). The ArcGIS petroleum data model is adapted from the Public Petroleum Data Model (PPDM) (<http://www.esri.com/industries/petroleum>), and it now supports the spatially enabling petroleum well database. The hydrology and hydrography data model (Arc Hydro) is developed by ESRI and the Center for Research in Water Resources (CRWR), University of Texas at Austin. It still deals mainly with the surface water system, but the ground water data model is in development. Check the latest development at <http://www.crwr.utexas.edu/giswr>. The marine data model is maintained by the Oregon State University (<http://dusk.geo.orst.edu/djl/arcgis>). This model covers both physical and biotic marine data objects. The subsurface data model is available as marine survey data and a model for the 2.5D surface from the survey data. This model also considers how marine and coastal data might be more effectively integrated in 3D space and time.

The geology data model is being developed after a meeting in February 2002 in Redlands, California, on developing a common data model for geological information. The participants of this meeting were the British Geological Survey (BGS), the Netherlands Institute of Applied Geoscience (TNO), the United States Geological Survey (USGS), the Geological Survey of Canada (GSC), and ESRI. The challenge for these major geologic mapping agencies is to find a way to catalog, store, and retrieve large volumes of current and historical geological data sets.

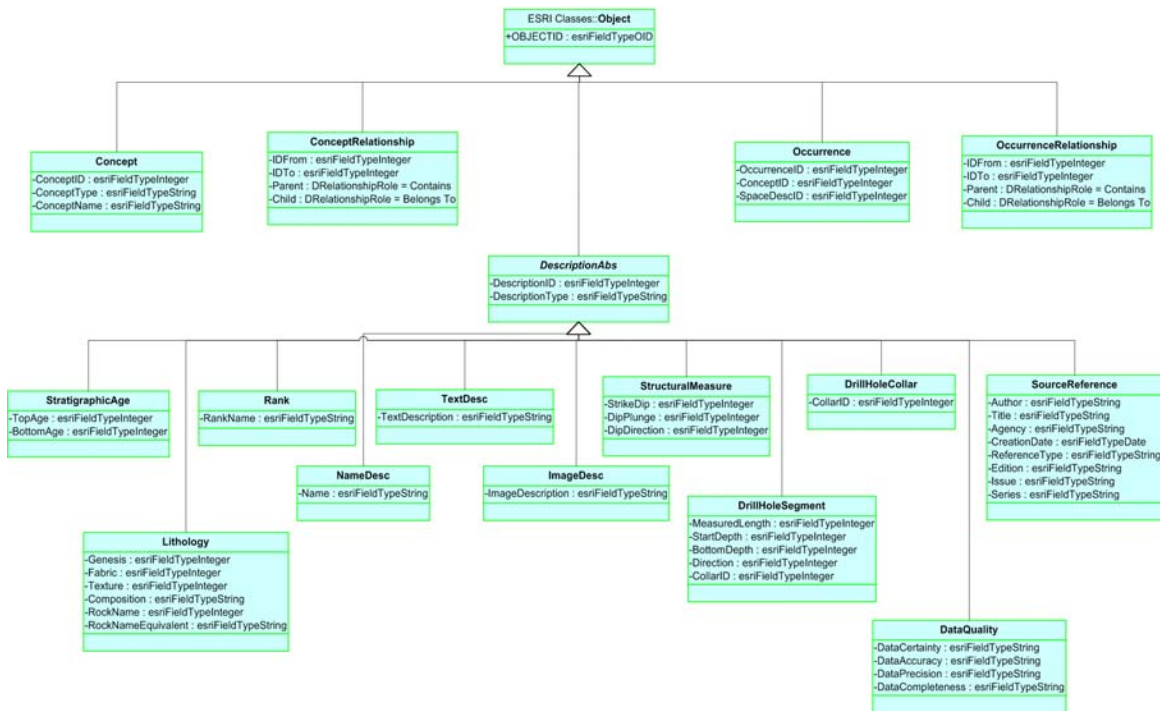
A group of people from USGS and GSC has been working on a North American Data Model for geology to find a way to solve these problems (<http://geology.usgs.gov/dm/>). As this effort evolved over the last several years, the ArcGIS Geology Data Model group investigated ways to implement the model with commercial software. So the purpose of this data model is to take some of those ideas and demonstrate how to implement them with ArcGIS.

The geology data model is different from other ArcGIS data models (Grisé and Brodaric, 2003). In most cases, ESRI is working in an industry/discipline to get agreement on a common set of terms and concepts, then ESRI provides a template for implementing that set of concepts. In the geology case, the situation is much different because the model must accommodate many different geologic terms and concepts in a single database. As a result, the design is simple, but the data organization is more convoluted than many

other data models. Check the latest development at the Web site (<http://support.esri.com/datamodels>).

The first draft of the geology data model is currently available for public use. It is a simple, compact data model that has been designed to contain a broad array of geological information. As such, direct access and use of this data model for a specific project is not recommended. A goal of this project is to encourage development of applications and the use of schema extract tools to make the contents of a geoscience data repository accessible to project teams and mapmakers.

Figure 4
Geology Data Model



4. Geostatistical Analysis Tools

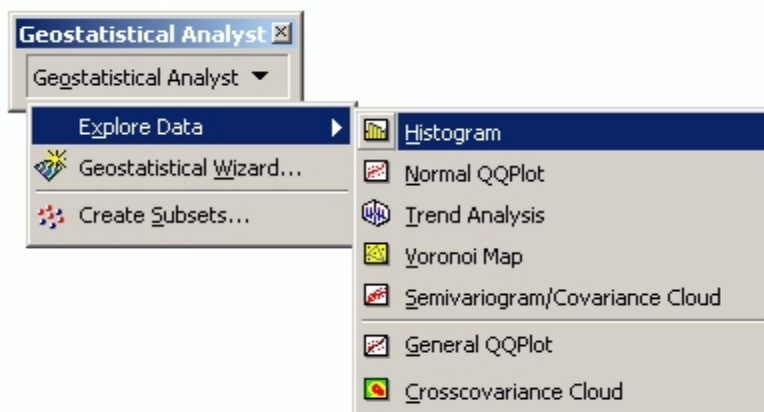
The geostatistical analysis package has perhaps the only GIS functionalities that were originated from geoscience (mining industry), and it is already integrated into GIS for geosciences applications. To not be confused about the term, in this paper geostatistics is considered a branch of statistics that deals with *regionalized variables* (Clark, 1979; Bonham–Carter, 1994; Houlding, 2000). A regionalized variable is a quantity whose value changes with spatial location and whose behavior is somewhere between a truly random variable and one that is deterministic. Its behavior is studied through *semivariogram* that in turn is used in *kriging*.

Only recently, ESRI developed new geostatistical tools as an extension to its GIS. The ArcGIS Geostatistical Analyst is revolutionary for geoscientists because it is the first kind of ESRI GIS technology that is directly built for the geosciences applications. It bridges the gap between *geostatistics* and GIS. Such a marriage of technology between a GIS and geostatistics holds special promise dealing with the common situations of limited data availability in subsurface sampling and more effective decision making for geoscientists (Coburn and Yarus, 2000). The key role of Geostatistical Analyst is to provide advanced surface modeling tools, either using *deterministic* or *geostatistical* methods (Johnston et al., 2001). The new surfaces generated with Geostatistical Analyst can subsequently be used in modeling and visualization using other ArcGIS extensions such as Spatial Analyst and 3D Analyst.

The general steps to build a surface from point data using Geostatistical Analyst are (1) data exploratory, (2) fitting a semivariogram model, (3) performing diagnostics to understand how well the model predicts the unknown values, and (4) comparing several models to find the better predictions of unknown values.

Data exploration is done to look for obvious errors in the input sample data that may drastically affect the result. It is accomplished by examining the data distribution, global trends, and so forth. The most common way is by creating a *histogram*. The best interpolation surface results from normally distributed data. If the data is skewed, you should transform it to make your data normal. Another tool is *QQPlot*, where you can compare the distribution of your data to a standard normal distribution. The closer the points are to creating a straight line, the closer the distribution is to being normally distributed. The *Voronoi Map* tool is used to analyze the stationary and spatial variability of a data set. *Trend Analysis* can be used to see the global trends in your data. If a trend exists, it is the nonrandom (deterministic) component of a surface that can be represented by some mathematical formula. You may want to remove the trend and model the residuals.

Figure 5
Geostatistical Tools in the ArcGIS Geostatistical Analyst Extension



Semivariogram/Covariance Cloud is used to conduct spatial autocorrelation and directional influence analysis to determine the best fit for a model that will pass through the points in the semivariogram. The semivariogram can be either uniform for all directions (*isotropy*) or directional (*anisotropy*). The General QQPlot tool is used to explore whether two data sets have the same distributions. The Crossvariance cloud tool is used to understand the cross-covariance between two data sets. Cross-validation gives us an idea of how well the model predicts the unknown values. This gives an informed decision about which model provides the most accurate prediction.

Figure 6
Trend Analysis Applied on a Gas Reservoir of an Oil Field
(Source: John Calkins, ESRI)

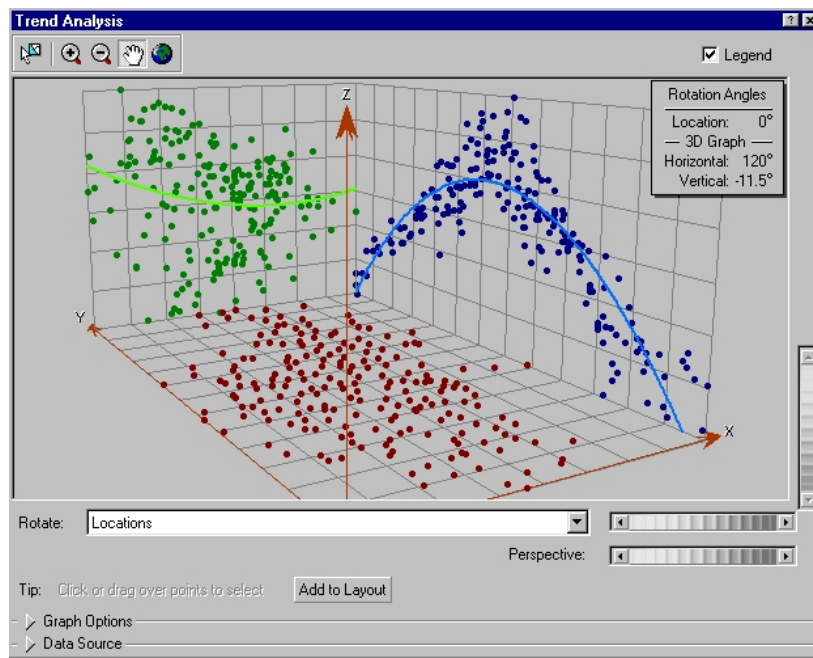
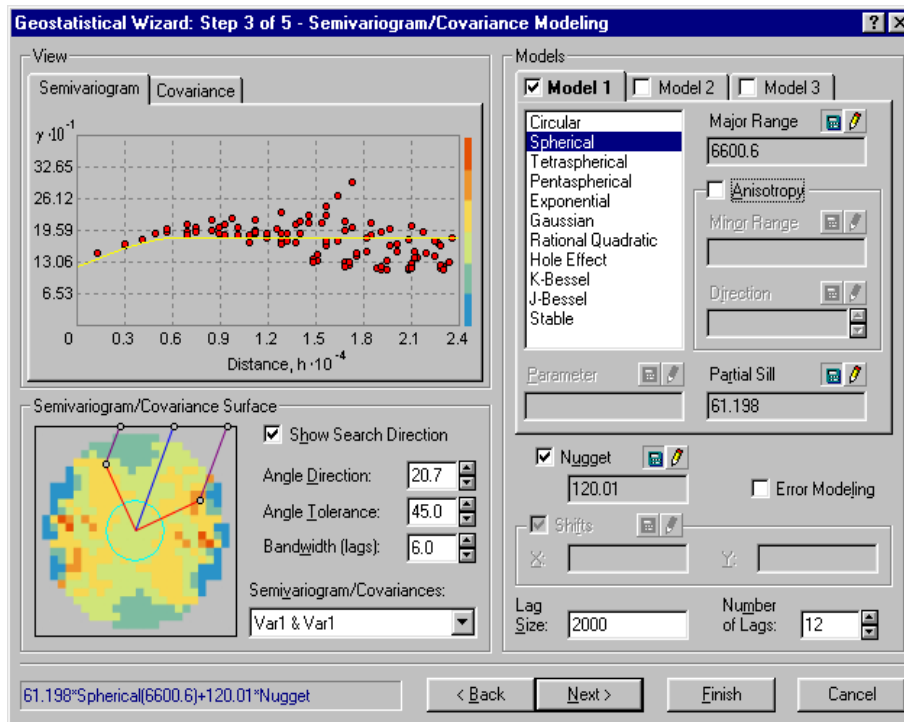


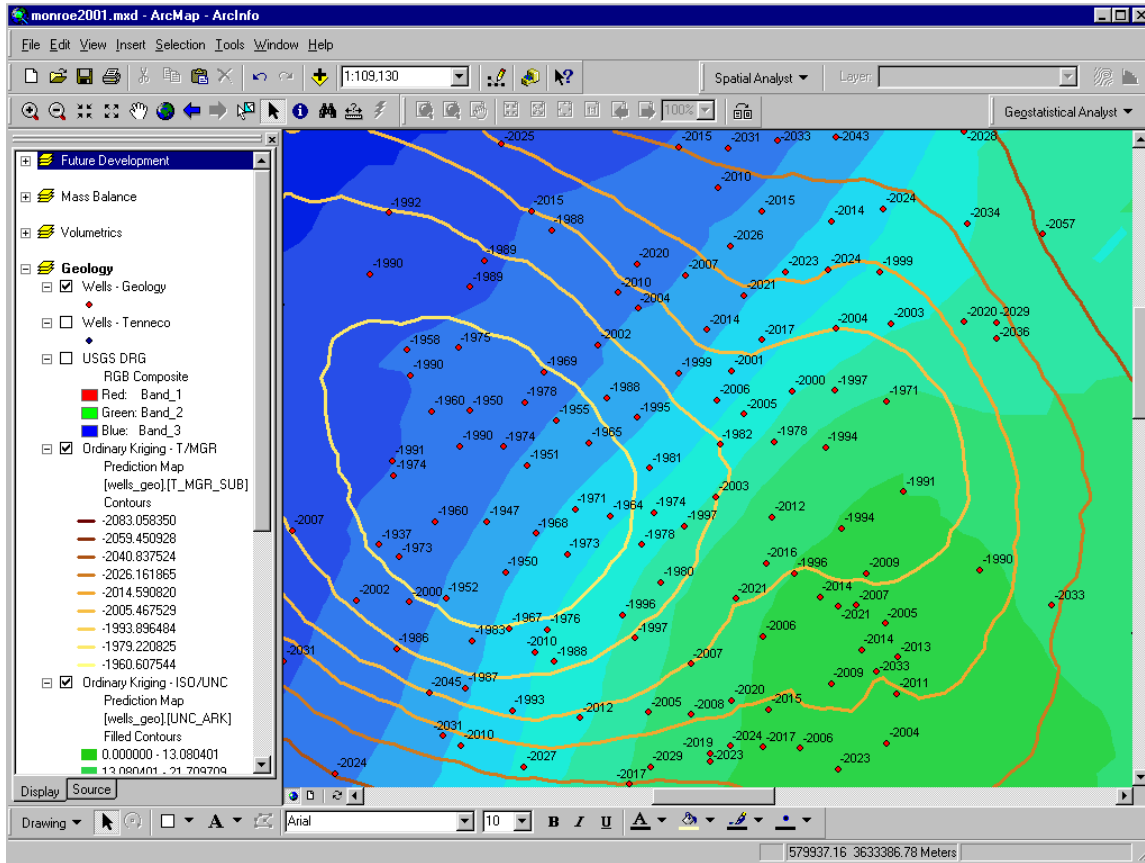
Figure 7
Semivariogram Model for an Oil Field
 (Source: John Calkins, ESRI)



After exploring the data, the next step is to interpolate sample points to create a continuous surface. The interpolation techniques can be divided into *deterministic* and *geostatistical* methods. The deterministic technique uses mathematical functions for interpolation. The geostatistical technique, on the other hand, relies on both statistical and mathematical methods, which can be used to create surfaces and assess the uncertainty in predictions.

Geostatistical methods are based on statistical models to predict the surface as well as to provide some measure of accuracy of the predictions. This method must first calculate the empirical semivariogram for the prediction using kriging. From the kriging weights, you can calculate a prediction of unknown values and calculate probability and quantile maps for a predetermined critical level. Kriging is also used to calculate the standard error associated with predicted values. The most rigorous way to assess the prediction quality is to compare the predicted values with the real values. This is done through creation of subsets of data sets: one subset for modeling and prediction, another for validation. The final step, if desired, is to produce several models in which the predictions can be compared using cross-validation statistics to select the best one.

Figure 8
Two Surfaces: Structure (Contour) and Paleostructure (Filled Color) Built From Wells Data for a Characterization Study of a Gas Reservoir
 (Source: John Calkins, ESRI)



5. 3D Analysis Tools

The majority of GIS packages do not provide solid 3D analysis tools for geosciences applications, although the available tools are improving from time to time. There are several GIS packages that are specifically designed to handle 3D geological data, such as *GOCAD* and *Stratamodel*, but they are not as strong as the 2D system for dealing with attribute data (Bonham–Carter, 2000). Other GIS programs such as ArcGIS 3D Analyst, work on *3D display* or *2.5D GIS* according to Van Driel's classification (Raper, 1989).

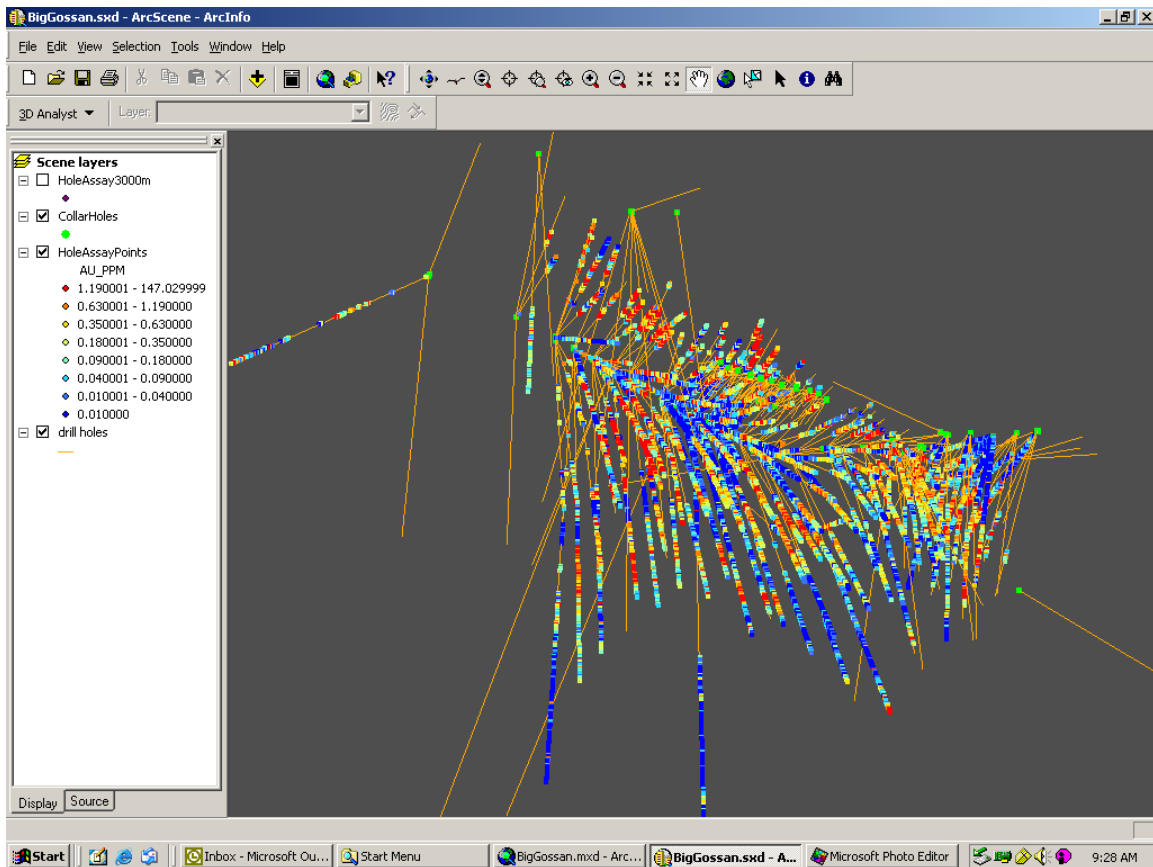
The ArcGIS 3D Analyst extension enables users to effectively visualize and analyze surface data. The core of the 3D Analyst extension is the ArcScene application that provides the interface for viewing multiple layers of three-dimensional data and for creating and analyzing surfaces. There are two surface models used: *TIN* and interpolated *raster* (Bratt and Booth, 2002). A raster interpolation from point data can be done using several available techniques: *inverse distance weighted*, *spline*, *kriging*, and *natural neighbors*. The *trend analysis* is only available through customization or by Geostatistical Analyst, which provides more sophisticated tools for data exploration.

Displaying a surface in 3D Analyst can be done in several ways. A raster surface can be displayed in 3D by setting a base height using a constant or getting its heights from a surface or TIN. The continuous values of a raster are more suitable to display by grouping them into a number of classes or by stretching the values to enhance contrast. The values use either a continuous grayscale or color ramp visualization. The symbology for TIN faces can be done by grouping into classes using certain classification techniques such as natural breaks and quantile (Bratt and Booth, 2002). Both raster and TIN surfaces can be displayed as a shaded and transparent layer in scenes and maps.

In addition to tools for viewing surfaces, 3D Analyst provides surface analysis tools to get more information on a surface. Contour lines can be derived either from a raster or a TIN. A TIN model can be derived from a raster model, and vice versa. The *Area and Volume Statistics* tool is beneficial for geoscientists to calculate 2D area, surface area, and volume. All calculations are done relative to a given reference plan. The 3D Analyst also provides tools to convert surface into vector data for analysis with other vector data sets. Finally, 3D Analyst provides a tool to create a 3D feature.

The strongest point of using 3D Analyst for subsurface characterization is that you can directly use benefits of other GIS functionalities that are available in ArcGIS. These include the link between 3D features and their attribute tables, linear referencing system, dynamic segmentation, and 3D geoprocessing. The intelligent GIS innovation such as linear referencing and dynamic segmentation can directly be applied on 3D features such as boreholes. The following figure shows that the boreholes can be represented as routes that have X, Y, Z, and M domains. The M domain represents the measure length and is used to spatially register the holes with their attribute data (lithology, ore grades, etc.). In this case, the grade of gold (Au) is drawn using the intelligent query tool of GIS. This case shows how a generic GIS innovation, such as linear referencing, can be applied for 3D subsurface modeling.

Figure 9
Displaying 3D Borehole Data Using ArcGIS 3D Analyst
(Data Courtesy PT. Freeport Indonesia)



ArcScene is used to view the 3D model interactively. Navigating through a scene can be done in several ways including using the Fly tool in which you investigate the view by flying through it. A 3D bookmark can be used to save a particular camera perspective. You can also interactively select features that you want to be displayed in the scene. A scene can be exported into a 2D image or a 3D virtual reality modeling language (VRML). Finally, you can make animations from the scene that can be replayed. An animation may also be exported as an Audio Video Interleave (.avi) file that can be played by a third party video player and include its distribution through the Internet.

6. Geoprocessing and Spatial Analysis Tools

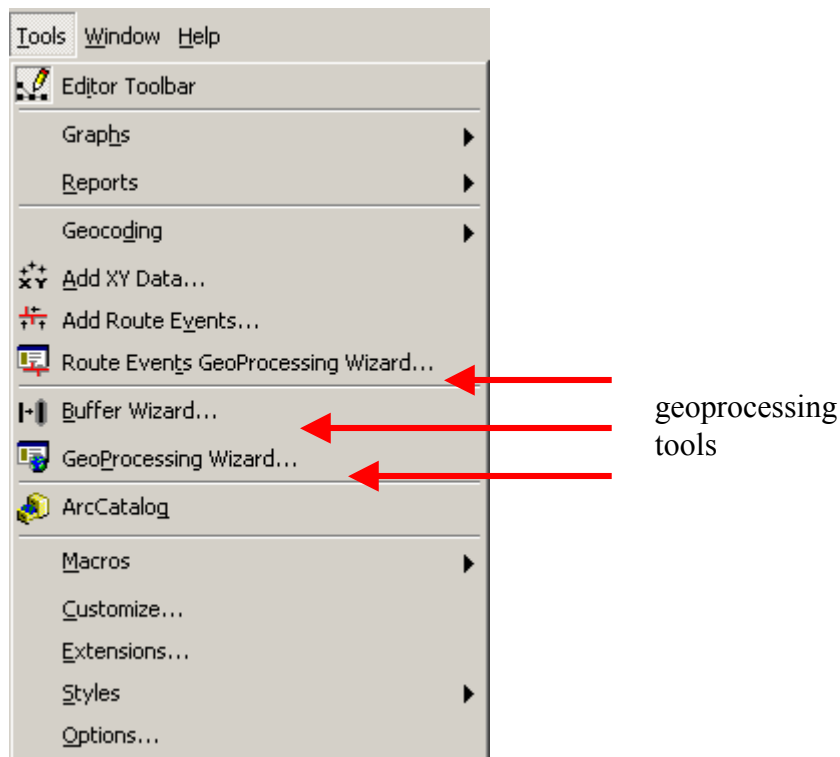
Spatial analysis is the hallmark of any GIS, although it is not exclusively attached to GIS only. Bonham–Carter (1994, 2000) indicated other kinds of software that also deal with spatial analysis such as computer-aided design, image processing, database management system, surface modeling software, 3D modeling, and statistical packages. But, more than other packages, GIS uses both the spatial and nonspatial data to solve the problem. GIS is also capable of observing multiple data layers simultaneously to discover the

spatial relationship among data sets and then use the evidence for predictions and support of decision making.

ESRI defines geoprocessing as the creation or modification of data, which is typically spatial in nature, by a function that has one or more parameters. In this manner, geoprocessing functions include spatial analysis functions (overlay, buffer, slope), data management functions (add field, copy, rename), and data conversion functions. In this definition there are abundant geoprocessing tools in ArcGIS 8 that are available in different places and can be accessed in different ways. The standard geoprocessing tools use vector operations, while raster-based geoprocessing tools are available through the ArcGIS Spatial Analyst extension.

The main entry for compiled vector-based geoprocessing tools is located under the Tools option of ArcMap. Typical operations of vector analysis include the creation of *buffer zones* surrounding a feature and *multiple layers operations*. The latter is accessible through the GeoProcessing Wizard that allows operations, such as intersection, merge, clipping, unity, and contained operations, between two feature classes.

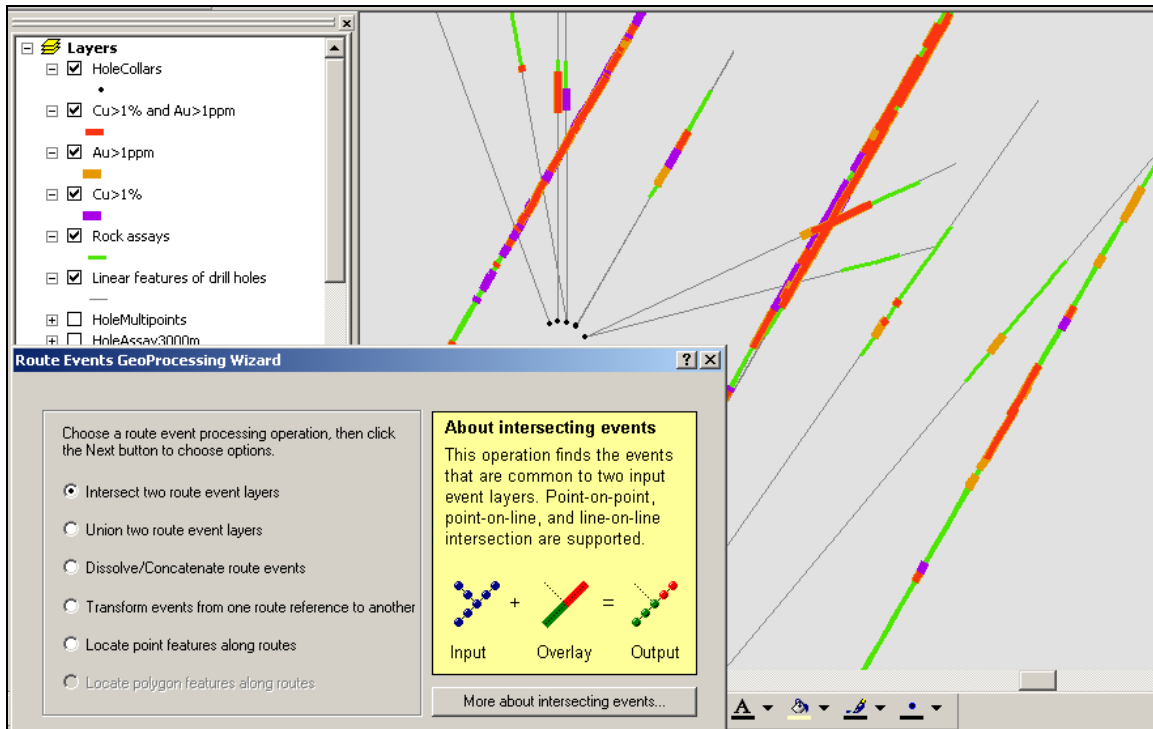
Figure 10
Vector-Based Geoprocessing Tools Within ArcGIS 8



ArcGIS extends its geoprocessing capabilities to *route events*. In the previous section it is shown how boreholes can be represented as 3D routes with X, Y, Z, and M dimensions. Lithology and rock assays occur along the hole routes and are thus examples of route events. Using the new *Route Events Geoprocessing Wizard* within ArcGIS 8.3,

you can extend the traditional spatial analysis into a new dimension: *3D geoprocessing*. Geoprocessing of event data enables analysis such as point-on-route, polygon-on-route overlay, or route-on-route. These geoprocessing tools work not only on 2D features, but also in 3D features such as petroleum and mining borehole data sets. The following example shows how this tool can be applied to search the parts of the drilled ore bodies that contain high grades of Cu and Au. This is done first by creating two route events (Cu and Au events), then making queries for each event (Cu>1% and Au>1ppm), and conducting the Route Events Geoprocessing Wizard using the *intersect tool* between two route events. This operation can also be done for different types of events such as looking for a relationship between high grade of Cu with lithology types. These 3D geoprocessing results can be displayed in 3D using ArcGIS 3D Analyst.

Figure 11
Three-Dimensional Geoprocessing on Borehole Data Sets



Although vector-based spatial analysis already provides various tools of geoprocessing, the richest modeling environment is available within a raster-based GIS. This is the major strength of raster-based GIS compared to vector-based counterparts. Not surprisingly, several GIS packages developed for university research are built using raster-based technology such as the Ilwis by ITC Holland and IDRISI by Clark University. The geoprocessing in raster GIS is done through *map algebra* or *cell-by-cell calculation*. Raster-based GIS makes integration with remote sensing processing easier.

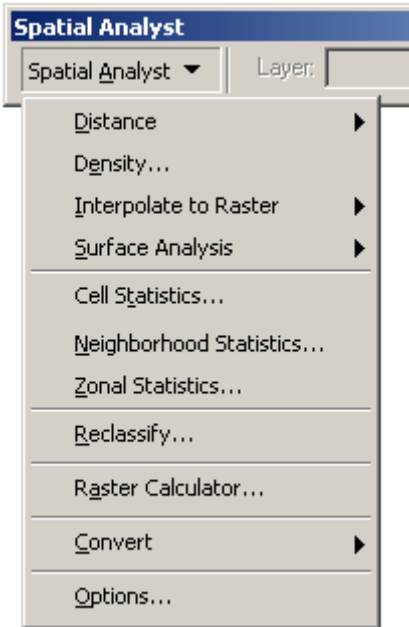
Modeling using raster-based calculation can be done on a *single map* or *multiple maps*. Single map analysis usually deals with *reclassification* and *spatial neighborhood calculation* on a map. Multiple map analyses use two or more map layers (generally

called *evidence maps*) to build a model. Mineral potential mapping and natural hazard assessments are typical examples for geosciences applications (e.g., Bonham–Carter, 1994), although examples in subsurface petroleum application are also found (e.g., Paulus, 2000).

In many types of GIS modeling using multiple available maps, you can divide them into two main categories: *knowledge driven* and *data driven* (Bonham–Carter, 1994). The knowledge-driven models use the expert estimation (based on conceptual model) to set the parameters (e.g., evidence maps used, the weights applied for each evidence). Knowledge-driven models include the *Boolean*, *index overlay*, and *fuzzy logic*. The data-driven methods, on the other hand, use the statistical calculations from training data to establish the model parameters. Various evidence maps are then combined using models such as *logistic regression*, *weight of evidence*, or *neural network*. It is preferable that data sets are divided into two sets: *training* and *validation* data sets. The training data set is used to get model parameters such as weights of evidence. The rest of the data set is used to validate the model(s). The readers should refer to the textbook of *Geographic Information Systems for Geoscientists: Modelling With GIS* (Bonham–Carter, 1994) for the details of these techniques. This book is widely used in graduate courses in economic geology, natural hazard studies, and other related geosciences courses in many universities.

ESRI's ArcGIS also provides the raster-based modeling through the ArcGIS Spatial Analyst extension. Spatial Analyst provides a broad range of powerful spatial modeling and analysis features including the following tools: (1) convert features (point, line, or polygon) to rasters; (2) create raster buffers based on distance or proximity from features or rasters; (3) generate density maps from point features; (4) create continuous surfaces from point features; (5) derive contour, slope, viewshed, and aspect maps and hillshades of these surfaces; (6) perform map algebra—Boolean queries and algebraic calculations; (7) perform neighborhood and zone analysis; (8) carry out discrete cell-by-cell analysis; (9) perform grid classification and display; (10) use data from standard formats including TIFF, BIL, IMG, USGS digital elevation model (DEM), Spatial Data Transfer Standard (SDTS), Digital Terrain Elevation Data (DTED); and many others.

Figure 12
Tools Available Within ArcGIS Spatial Analyst



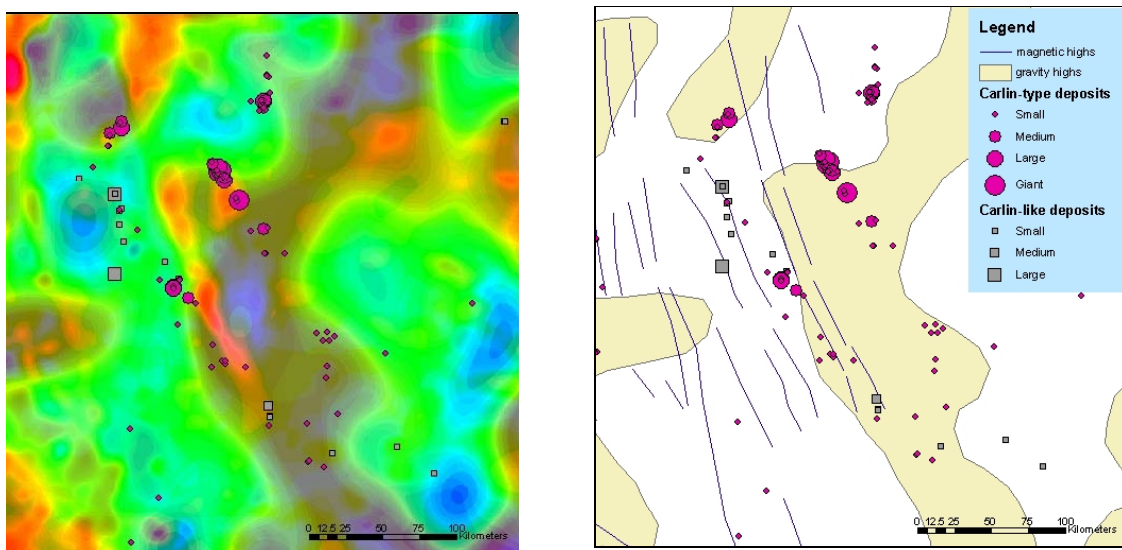
The raster calculation using the *Raster Calculator* tools can be done through typing *Map Algebra syntax* using *operators* and *function*, setting up selection queries, or typing ArcGIS Spatial Analyst function syntax. Inputs can be raster layers, shapefiles, coverages, tables, constants, and numbers. The *mathematical functions* are applied to the values in a single input raster. There are four groups of mathematical functions: Logarithmic, Arithmetic, Trigonometric, and Power. The *mathematical operators* apply a mathematical operation to the values in two or more input rasters. Three groups of mathematical operators are available in the Raster Calculator: *Arithmetic*, *Boolean*, and *Relational* (McCoy and Johnston, 2002).

Although the tools for map calculations are available for geoscientists, you should not use them as a "black box." Especially in the subsurface applications, you should consider carefully before deciding to use map calculation techniques. Because the map calculation is a quantitative technique, it requires that all evidence maps be reclassified into quantified and discrete classes. In fact, most subsurface evidence maps are surfaces created by interpolation from point data. It is important to stress here that these surfaces are continuous phenomena in which their values have a wide range and change gradually in space. Delineating the boundary of geophysical anomalies, for example, is a transformation process from continuous fields into discrete objects. Picking the threshold lines among the created discrete classes is an approximate and subjective process, which therefore introduces a certain degree of error. Geoscientists must also be aware of the nonunique relationship between geologic phenomena and geophysical anomalies. For example, porphyry copper deposits can either be associated with high magnetic feature (hypogene Cu mineralization within magnetite-rich acidic stocks) or low magnetic feature (supergene Cu blanket in which magnetite is already oxidized). Finally,

geophysical fields captured by their sensors come from continuous depth levels below the earth's surface. Meanwhile, a GIS map calculation is done on a 2D plane. Subsurface features represented by geophysical images can shift considerably from their vertical surface projection, even though they may not continue up to the earth's surface.

An example below shows the difference between representing geophysical images as geographic continuous fields versus discrete objects. The geophysical images used are the intermediate wavelength gravity anomaly displayed with magnetic anomalies after 5 km upward continuation filtering. On the left we display the images as continuous fields using ArcGIS 8.3 and the transparency tool. On the right is shown discrete feature classes (polygon and polyline) interpretation from the geophysical images for further spatial analysis (buffering, map calculations, etc.). The author leaves the discussion here and lets the readers judge which one serves their own purposes better.

Figure 13
Comparison Between Geophysical Images as Continuous Fields (left)
Discrete and Objects (right)



Transformation into discrete objects is required for quantitative statistics and raster-based map calculations.

Besides the raster-based map algebra tools, ArcGIS Spatial Analyst also provides other tools dealing with vector data such as creating a density map and generating a surface from point data. The surface generation can be done through Inverse Distance Weights (IDW), trend surface, spline, and kriging interpolation methods. More advanced surface generation is available through Geostatistical Analyst. Another tool that gives benefit to geosciences applications is the *Cut/Fill* tool. This tool enables users to create a map based on two input surfaces: *before* and *after* that represent the areas that have been modified by the addition or removal of surface material. With little innovative thinking, Price (2002) used this tool to easily calculate the volume of lake bottom sediment of the Powers Lake in Burke and Montrail Counties in North Dakota. Rather than creating

multiple topographic surfaces typically required for cut/fill calculations, he created a mask polygon of the lake boundary and the isopach map of the mud thickness. Both maps are converted into raster maps, but the lake polygon mask is assigned zero for all values. Then applying Cut/Fill calculation on both maps, he produced the volume of the mud sediment.

7. Open Standard With Other Specialized Programs

A significant weakness of GIS for subsurface modeling is that GIS does not support *solid 3D modeling*. For this purpose, GIS must be open for further development for specific projects or for integration with other specialized programs. The key for this is the standardization and interoperability of a GIS. ESRI has developed its product based on open standards to ensure a high level of interoperability across platforms, databases, development languages, and applications. An open GIS system allows for the sharing of geographic data, cooperation of different GIS technologies, and integration with other non-GIS applications. An open GIS also exposes objects to allow for the customization and extension of functional capabilities using industry-standard development tools.

The integration between generic ArcGIS applications and specialized subsurface programs can be done in several ways. First is by standardization of data formats. For example, the shapefile is a famous spatial data format that allows data sharing among applications. For raster data, a format such as geoTIFF can be used to share interpreted geophysical images from specialized software to a GIS. The second approach of integration is by creating a direct extension to ArcGIS. The core technology of ArcGIS is *ArcObjects*, which is a collection of COM features. You can customize these applications using a common Visual Basic for Applications (VBA) environment. The customization can vary from creating a script for a specific task to highly customized and stand-alone applications based on the ArcObjects software components. Developers have a choice of development environments when using ESRI software including VB, C++, .NET, and Java (J2ME, J2SE, J2EE, ASP/JSP). ESRI is committed to concentrate on the development of the core GIS technology, while it lets developers build customizations and extensions for a specific industry including subsurface applications. Table 1 shows several ways of integration between ArcGIS and several specialized geoscientific applications.

Table 1
Integration Between Generic ArcGIS and Specialized Programs

Company/ Developer	Name of Package	Application	Way of Integration to GIS
Earthsoft	EQuIS	Environmental analysis	An extension to ArcView and ArcGIS
	GMS	Groundwater modeling	Shapefile, .e00, and through EQuIS interface
Rockware Inc.	RockWare suite of applications	Geologic modeling	Shapefile and interface through EQuIS
OpenSpirit	OpenSpirit Shapes Utility and the OpenSpirit ArcView Extension	Seismic interpretation	Publishing seismic, well, and horizon to shapefile and through an extension
Geosoft Inc.	Oasis Montaj	Geophysical data interpretation	GeoTIFF image format

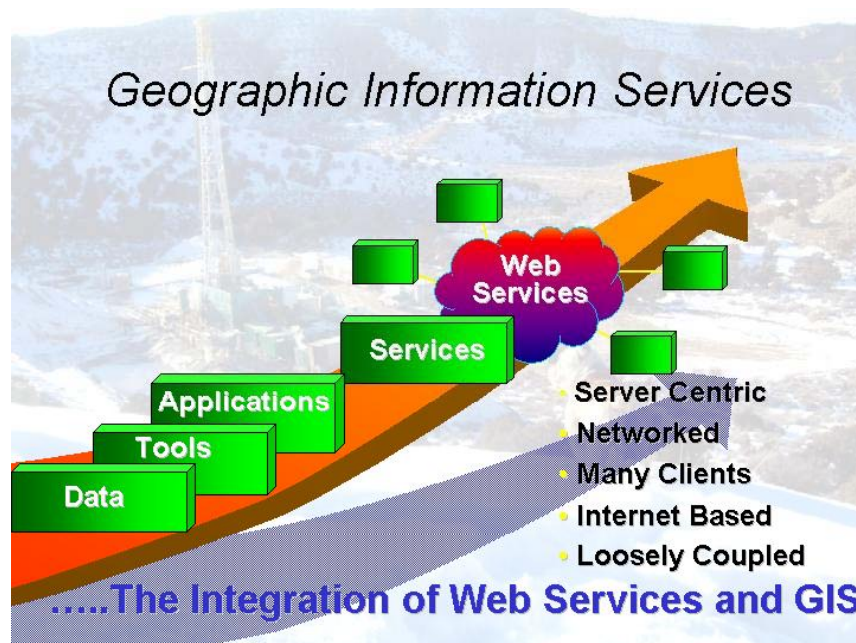
ArcGIS 9: Web Services and Centralized Geoprocessing Tools

The new ArcGIS 9 family concentrates on the development of Web services as a new framework of technology and standards for computing. Web service standards are the first attempt at building a foundation through which computers and devices interact to form a greater computing whole, accessed from any other device on the network. The use of Web services (a connecting technology) coupled with GIS (an integrating technology) can efficiently support various information and can be dynamically queried and integrated.

Web services allow each GIS vendor to build and distribute its own GIS products using the best available technology and methods, while at the same time enabling the technology to interoperate with a wide range of external systems without compromising the design and implementation of the core technology. This Web services architecture provides a new and promising solution for implementation of complex collaborative applications needed in a distributed GIS. The integration of GIS and Web services means that GIS will be more extensively implemented, and geologists can take data, mapping, and geoprocessing from many servers and integrate them using a common Web service-based environment.

The GIS metadata and a GIS catalog portal play a critical role in the Web service technology. A GIS catalog portal provides the ability to search a catalog that references numerous GIS holdings such as geographic data, Web mapping services, data collection activities, references, and contact information. Geoscientists are now able to perform searches in real time on GIS metadata through the GIS catalog portal. Search criteria can be based on content type, geographic location, or a date range. Maps can be viewed in the Web browser or with free GIS software such as *ArcExplorer*. Downloading data can be done through feature streaming or FTP services for large data sets.

Figure 14
Web Services GIS Architecture in ArcGIS 9



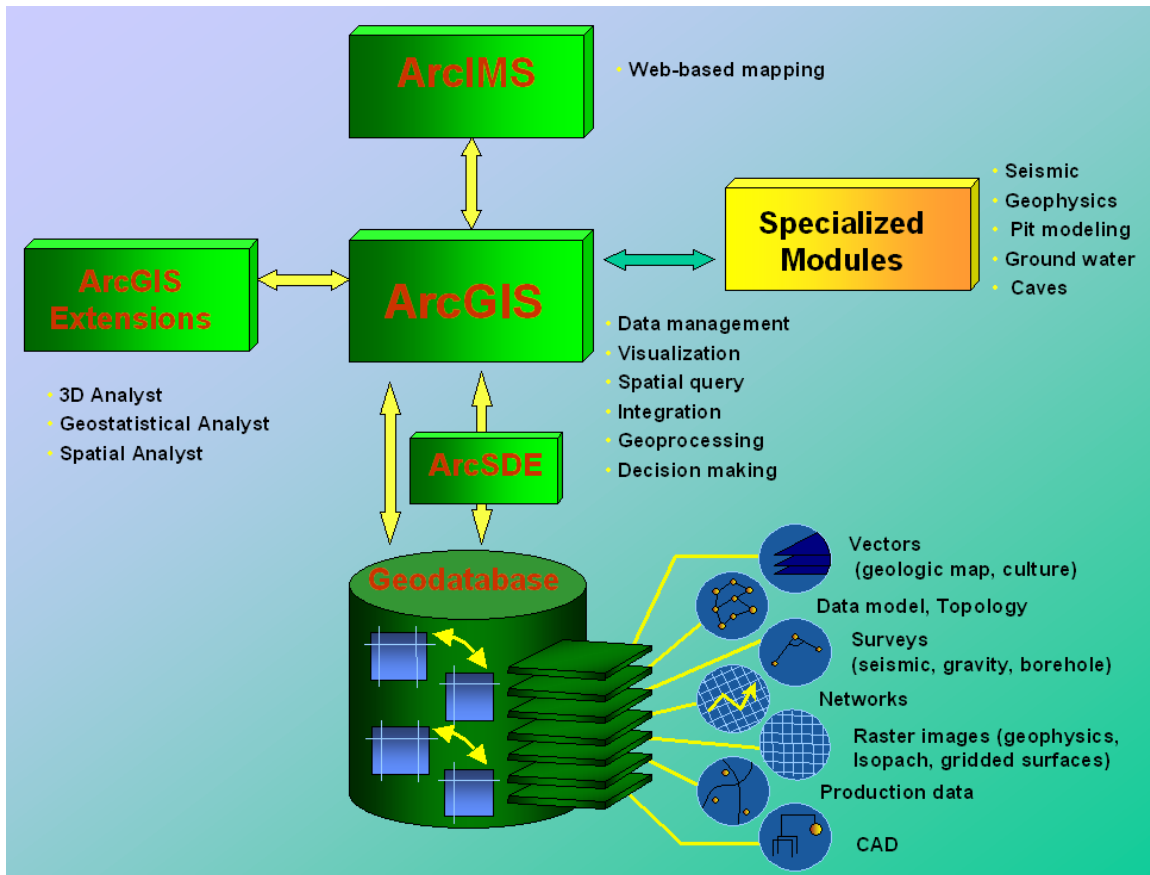
ArcGIS 9 also provides a number of improvements for 3D GIS and adds the capability to visualize multiscale global data in 3D using a new application, *ArcGlobe*. *ArcGlobe* allows users to view and analyze large amounts of GIS data seamlessly and with extremely fast display speeds. The new geoprocessing tools are another big improvement. ArcGIS 9 provides a unified framework for geoprocessing. The new ArcGIS geoprocessing environment has approximately 500 geoprocessing tools for processing all types of data. Tools are organized in toolboxes, which exist in folders and geodatabases. ArcGIS extensions add more geoprocessing tools that work like any other tool so all geoprocessing functions in ArcGIS behave and look the same, with only their parameters and execution being unique. The number of functions will vary depending on the software license used. Users have a choice of four different methods for performing geoprocessing: *ModelBuilder*, *dialog boxes*, *command line*, or *scripts*. To perform complex geoprocessing tasks involving multiple functions, create a new model tool and link processes together in a visual diagram using *ModelBuilder*. For single geoprocessing tasks, use tool dialog boxes found in toolboxes or use the command line. To perform the same function many times on different data sets, use or create a tool derived from a script.

Conclusion

The current GIS technology has appropriate tools for subsurface geosciences applications in addition to its traditional functionality. These tools include data management based on industry-standard RDBMS, Web-based mapping, geostatistical and surface modeling

tools, 2.5D visualization, and 3D geoprocessing. While these capabilities can fulfill most requirements for subsurface characterization, solid 3D modeling can only be achieved through integration of GIS and a specialized 3D program. Modern GIS is built on open, standard technology that ensures a high level of interoperability across platforms, databases, development languages, and applications. This enables a specialized geo-object modeling package to be attached to a core GIS system easily.

Figure 15
Integrated ArcGIS 8 Solution for Subsurface Modeling



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