



Automated geological modeling with ArcGIS Engine: a methodological framework for surface and subsurface data integration

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Abstract

The integration of surface and subsurface spatial data remains a fundamental challenge in geoinformatics, as conventional GIS platforms excel in three-dimensional (3D) geographical modeling but lack robust capabilities for representing complex subsurface geological structures. To bridge this gap, this paper presents a methodological framework for automated geological modeling that enables the fusion of geographical and geological models within a unified GIS environment. The framework extends ArcGIS by decomposing and reorganizing the 3D geological modeling workflow using object-oriented methods, thereby integrating geological modeling schemes into the ArcGIS platform. The methodology centers on extending ArcGIS's basic geometric data structures to define key geological object data structures, and on designing and integrating core algorithms based on these structures for accurate positioning and high-resolution representation of geological bodies, with an emphasis on automation, reusability, and interoperability. Based on these designs, a 3D geosciences modeling software prototype was developed and implemented using ArcGIS Engine components and Visual Studio C#. The proposed framework facilitates the integrated modeling of 3D surface and subsurface data, offering a systematic solution to the longstanding challenge of multi-source spatial data integration in GIS environments. A case study of coalbed methane 3D modeling in the Qinshui Basin demonstrates the applicability of this methodology, with quantitative validation against 189 borehole measurements showing high geometric accuracy (RMSE=0.0936 m), pointing to its potential for broader applications in digital twins, urban planning, and natural resource management.

Keywords 3D geological modeling · Surface objects · Subsurface objects · Data integration · ArcGIS Engine

Introduction

The Earth is a continuous three-dimensional (3D) space, and for some applications, 3D geosciences models should integrate both surface and subsurface spatial objects. For a long

time, GIS software such as ArcGIS, MapInfo, and Google Earth has mainly focused on modeling 3D aboveground entities of geographic space, including surface landscapes, buildings, and their attachments (Reitz and Schubiger-Banz 2014; Razali et al. 2019). Although GIS has a good 3D representation ability for aboveground entities, such as geometric structures, spatial relationships and attributes, its modeling ability for 3D underground entities is weak (Velasco et al. 2013). At the same time, 3D geological modeling software, such as Petrel, GOCAD, Surpac, Micromine and Datamine, etc., focus mainly on underground entities. For instance, they are applied to the 3D representation of exploration projects for oil and gas and mining resources as well as water resources and underground storage of fluids (gas, hydrogen, disposed produced water/brine). These "static" geological models serve as the basis for further dynamic modeling of fluid flow and geomechanical phenomena (e.g., fracturing, seismicity). Dynamic models inform decisions on, for example, the placement of wells

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which is also constrained by surface features (roads, buildings, power lines, etc.). However, these "static" geological models are unrelated to aboveground features and information. Therefore, a software platform able to integrate all spatial objects on the surface, aboveground and underground according to their spatial position, would be very useful for 3D management (e.g., digital twins) of cities, mines, oil and gas fields, groundwater resources, and other applications.

The research on 3D surface and aboveground modeling in GIS software is relatively recent, beginning in the early 1990s (Giertsens and Lucas 1994; Ranzinger and Gleixner 1997). With the rapid development of 3D GIS technology, GIS software can better realize automated or semi-automated 3D geometric structure modeling of spatial entities such as topography, buildings, roads, and landscapes (Prechtel 2015; Subiyanto et al. 2019). At the same time, with the continuous development of 3D geological modeling technology, the construction of 3D geological models is becoming more and more detailed (Liang et al. 2021). In addition to building 3D geological structure models, it is also necessary to create high-resolution attribute models to reflect the internal heterogeneity of geological bodies (Høyer et al. 2019). The building of such models is very laborious. The current excellent 3D surface modeling capabilities of GIS software could be harnessed to develop software functions that can quickly build 3D geological (including structure, geobody geometry and property attribute) models, as well as create 3D surface and DEM models, remote sensing images, and underground engineering models. These spatial entities could be combined to form a multi-level comprehensive 3D model to enable the integrated management and visualization of aboveground and underground data. This represents a key direction for current GIS software development.

Due to the general-purpose nature of GIS software and the inherent complexity of geological objects, subsurface 3D geological modeling remains a challenging task for GIS, particularly for automated modeling (Feng and Mao 2015). ArcGIS software (ESRI) is one of the most widely used geographic information system software in the world today relative to capability and number of users (DeVasto et al. 2012). ArcGIS includes 3D terrain modeling and 3D visualization of surface objects, and provides a rich component library for users to carry out secondary development (Song et al. 2019). Developers can design underground data structures and use its related components to quickly model 3D geological bodies, visualize them and conduct a variety of analyses. This toolkit provides a basis for extending the 3D geological modeling capabilities of GIS software (Song et al. 2013).

Recently, open-source Python libraries such as GemPy (De la Varga et al. 2019), LoopStructural (Grose et al. 2021), and ArchPy (Schorpp et al. 2022) have enabled

geological modeling in open GIS environments such as QGIS. These libraries provide flexible, algorithm-driven solutions for implicit geological modeling and uncertainty quantification. However, a similar extension for ArcGIS that leverages its native data structures (e.g., MultiPatch) and secondary development framework (ArcGIS Engine) has remained underexplored. While QGIS-based solutions offer open-source accessibility, they often require manual integration and lack the seamless aboveground-subsurface visualization that ArcGIS natively provides. To bridge this gap, this study presents a methodological framework that extends ArcGIS's inherent 3D geological modeling capabilities, enabling integrated surface-subsurface modeling within a single GIS-environment.

This paper presents an automated workflow for 3D geological modeling that integrates surface and subsurface data within the ArcGIS environment. The proposed approach can be implemented through custom development using the ArcGIS Engine, extending the standard ArcGIS Desktop functionality. First, we propose an integration strategy for surface and subsurface geospatial data using the terrain surface as the interface to connect aboveground and underground entities. Second, we extend ArcGIS's basic geometric data structures to define key geological object data structures based on MultiPatch features, and design core algorithms for accurate positioning and multi-scale representation of geological bodies. Finally, using ArcGIS Engine components and Visual Studio C#, we develop a 3D geological modeling software prototype. And a case study of 3D coalbed methane modeling in the Qinshui Basin is conducted using real-world data, demonstrating the method's good performance in both modeling and visualization.

Methodology

Strategy for surface and subsurface data integration

Using the terrain surface as an interface, geospatial objects can be divided into two categories and three levels in the vertical direction. Surface and subsurface spatial objects include three levels: aboveground entities, ground surface, and underground entities, respectively (Chen et al. 2018). Table 1 lists the main categories of geospatial objects.

Over the past 30 years, most 3D GIS research focused on 3D surface modeling, such as terrain (Florinsky and Filipov 2019), buildings (Noor et al. 2020), trees (Park et al. 2021) and vegetation (Gibbs et al. 2019), while less attention was given to 3D underground modeling. This is also the case for advanced ESRI ArcGIS products. ArcGIS is powerful in surface modeling, but it is weak in geological modeling. Therefore, to achieve the geospatial data integration

Table 1 Categories of geospatial objects

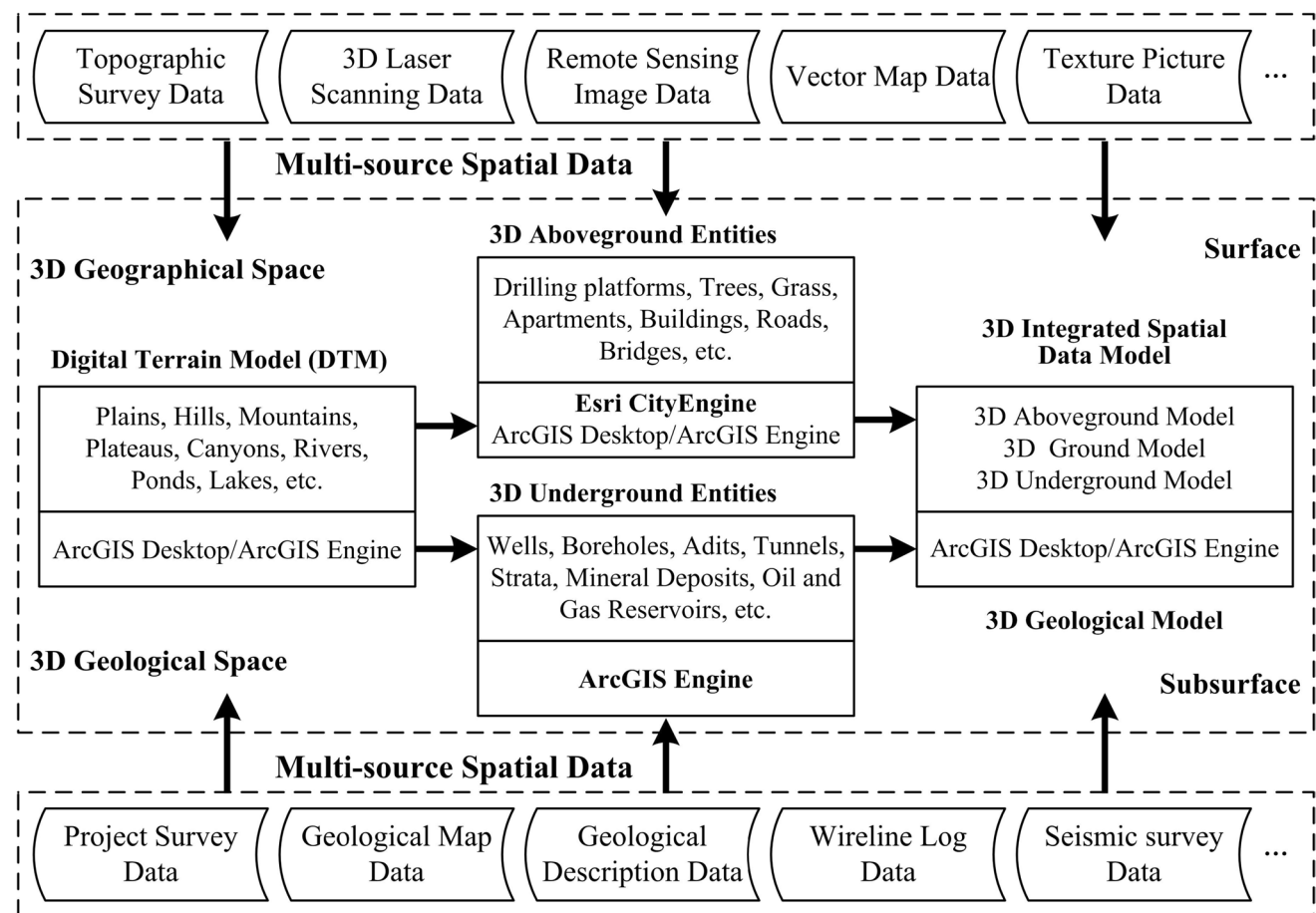
Surface	Geographical spatial objects	Above-ground entities	Drilling platforms, trees, grass, apartments, buildings, roads, bridges, etc
		Ground surface	Mountains, hills, rivers, lakes, etc
Subsurface	Geological spatial objects	Under-ground entities	Wells, boreholes, adits, mine tunnels, underground pipes, strata, mineral deposits, oil and gas reservoirs, etc

of surface and subsurface with ArcGIS, it is necessary to expand its capabilities to realize 3D geological modeling. Based on multi-source geospatial data from ground and underground surveying, the data integration strategy of this application is shown in Fig. 1. Detailed 3D aboveground entities and terrain features are represented by using ArcGIS software products, and high-resolution 3D geological models can be built by developing the ArcGIS Engine. Firstly, terrain and remote sensing data are used to create a Digital Terrain Model (DTM), referring to the ground vector maps and prospecting projects, which is a bare ground surface devoid of any objects, such as plants and buildings,

but it serves to connect the surface and subsurface entities. Based on DTM, vector maps, remote sensing images, and texture pictures, a high-resolution 3D aboveground model is constructed by using ArcGIS Desktop, ESRI CityEngine, or ArcGIS Engine, including buildings, bridges, trees and vegetation. In a similar fashion, high-resolution 3D prospecting projects and geological bodies can be built automatically by developing ArcGIS Engine components, such as wells, strata and reservoirs. Finally, the 3D geospatial data integration of surface and subsurface entities is accomplished by using ArcGIS Desktop or ArcGIS Engine software platform.

Methodology for automated 3D geological modeling

3D geological modeling is essential for GIS to achieve 3D integration of surface and subsurface data. However, geological modeling is more challenging than surface modeling because subsurface objects are not visible from the ground surface and defining them requires the interpretation of sparse data collected from different techniques (geophysical logs, seismic surveys). ArcGIS Engine provides an effective way to achieve 3D geological modeling using existing

**Fig. 1** Integration strategy for surface and subsurface geospatial data based on ArcGIS products

components and by developing more complex 3D modules to describe geological features.

ArcGIS engine

ArcGIS Engine is a complete library of embeddable GIS components for developers to build custom applications (Liang, et al. 2007; Koo et al. 2018). Its software developer kit (SDK) provides visual components, tools, and object application programming interfaces (APIs) for developers to view multiple layers of 3D data and to visualize, create, and analyze 3D geospatial objects (Hou et al. 2020). However, although 3D point, polyline, polygon, surface (TIN or GRID) features of ArcGIS can be used to characterize common surface objects, it is more difficult to represent complex collections of subsurface objects.

MultiPatch features

ArcGIS products do not directly provide complex 3D modeling tools for irregular underground objects, and usually MultiPatch is necessary to achieve 3D geological modeling (Xu et al. 2009). The MultiPatch data format is a GIS industry standard developed in 1997 (ESRI 2008). MultiPatch stores a collection of patches representing the boundary of a 3D object as a single row in a database, as is the case for points, polylines and polygons in ArcGIS Desktop (Shen et al. 2013). However, due to its complexity, MultiPatch features are not

usually created with ArcGIS Desktop directly, but using geo-processing tools, importing 3D models (such as 3D Max, SketchUp, CityEngine, etc.), and developing fit-for-purpose software with ArcGIS Engine. Patches store texture, color, transparency, and geometric information representing parts of a feature. The geometric information stored in a patch may be triangles, triangle fans, triangle strips, or rings (Fig. 2). A single MultiPatch of geological objects may comprise a combination of one or more of these geometries (Sun et al. 2011).

Basic elements of geological model definition

Complex geometric shapes can be created by combining the much simpler shapes. Similarly, complex geological objects can be characterized by some simple MultiPatch features. Thus, defining and creating the essential elements of a geological model based on the fundamental geometries of MultiPatch features, such as triangles, triangle fans, triangle strips and rings, is the key for realizing automated 3D geological modeling with ArcGIS Engine.

A geological model is split into model elements by using the object-oriented method: elements are defined according to spatial relationships and attributes. A basic model element which includes information on geometry, and style can depict a simple geological object. According to the model purpose, the 3D geospatial objects are flexibly fitted and interpreted at different scales by combining component model elements (Fig. 3).

Fig. 2 Basic geometries of MultiPatch features

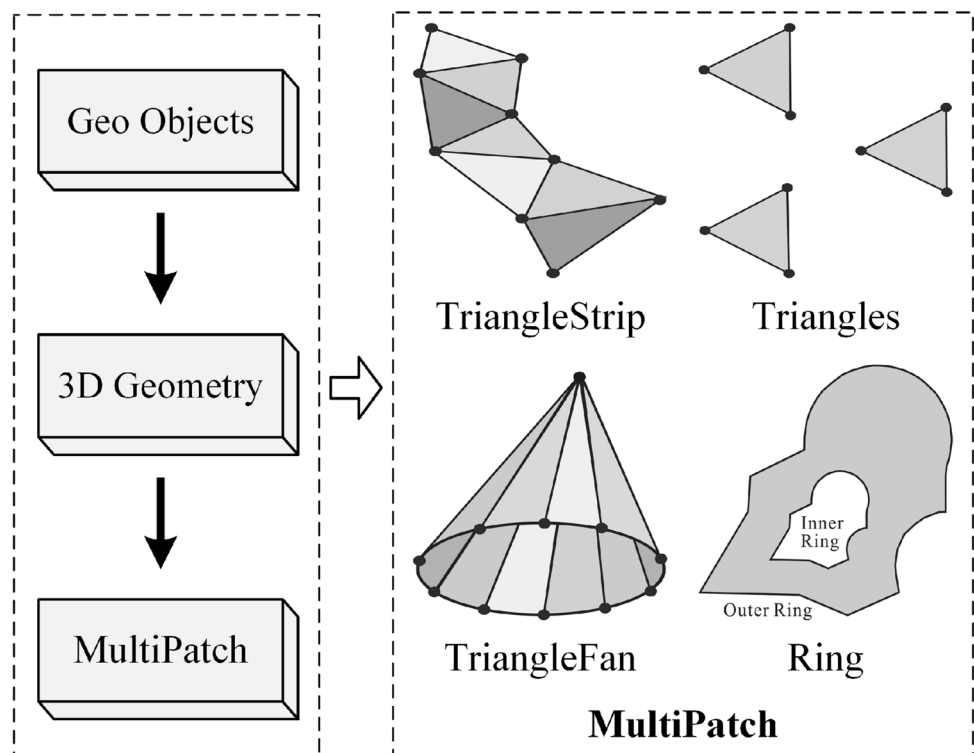
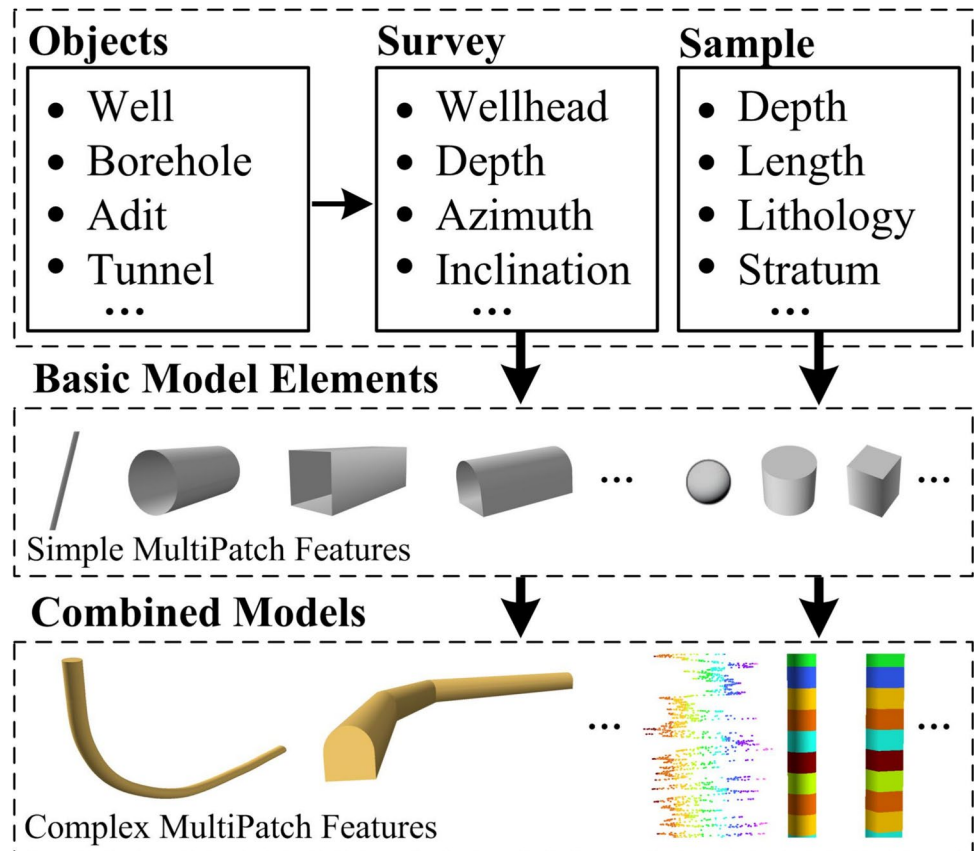


Fig. 3 Example for the definition of basic MultiPatch elements for a geological model



Automated modeling workflow and core techniques

In this work, "automated" refers to batch processing and geometry generation once input data and parameters are provided. Users must predefine the stratigraphic column, select interpolation algorithms, and set voxel resolution. This semi-automated design balances efficiency with flexibility. Based on this principle, automated modeling can reduce the complexity of 3D geological modeling, reduce the workload, and improve the work efficiency for geologists (Lyu et al. 2021). It is an effective way to quickly achieve integrated modeling for 3D surface and subsurface data based on GIS software.

This research uses ArcGIS Engine components and Visual Studio C# as the software development platform, and uses an object-oriented approach to decompose, optimize and reorganize the work steps of 3D geological modeling. Based on the designed MultiPatch geological data structures, functional software modules are developed, and the system functions are integrated to realize automated 3D geological modeling. The main functional framework and workflow of the system are shown in Fig. 4.

The core techniques of this research are the precise positioning of geological descriptions, core samples and wire-line logs, as well as the flexible use of MultiPatch geological

structures and multi-scale spatial representation of geological objects, which are included in the following three tasks:

- Automated high-resolution well modeling.** Core sampling, geophysical logging, or geological descriptions are part of the well data. The construction of a drilling database as well as the standardization, organization and management of these data are the foundation for automated 3D geological modeling. Exploration (and production) well data record the spatial location in 3D of geological bodies (rock layers, rock masses, ore bodies, etc.) and their detailed geological properties along each well. Therefore, the drilling database should contain drilling trajectory surveying records, such as well coordinates, diameter, inclination and hole depth, core sample and geophysical logging data, and include geological descriptions and core catalogue data, such as stratigraphic horizons, lithology, etc. These data can support the precise positioning and high-resolution representation of the wells' geological reports and core sample features. The stratigraphic and lithological sequences are pre-established by geologists during the drilling database construction phase. As formalized in the stratigraphic pile concept (Calcagno et al. 2008; Schorpp et al. 2022), each layer is assigned a unique

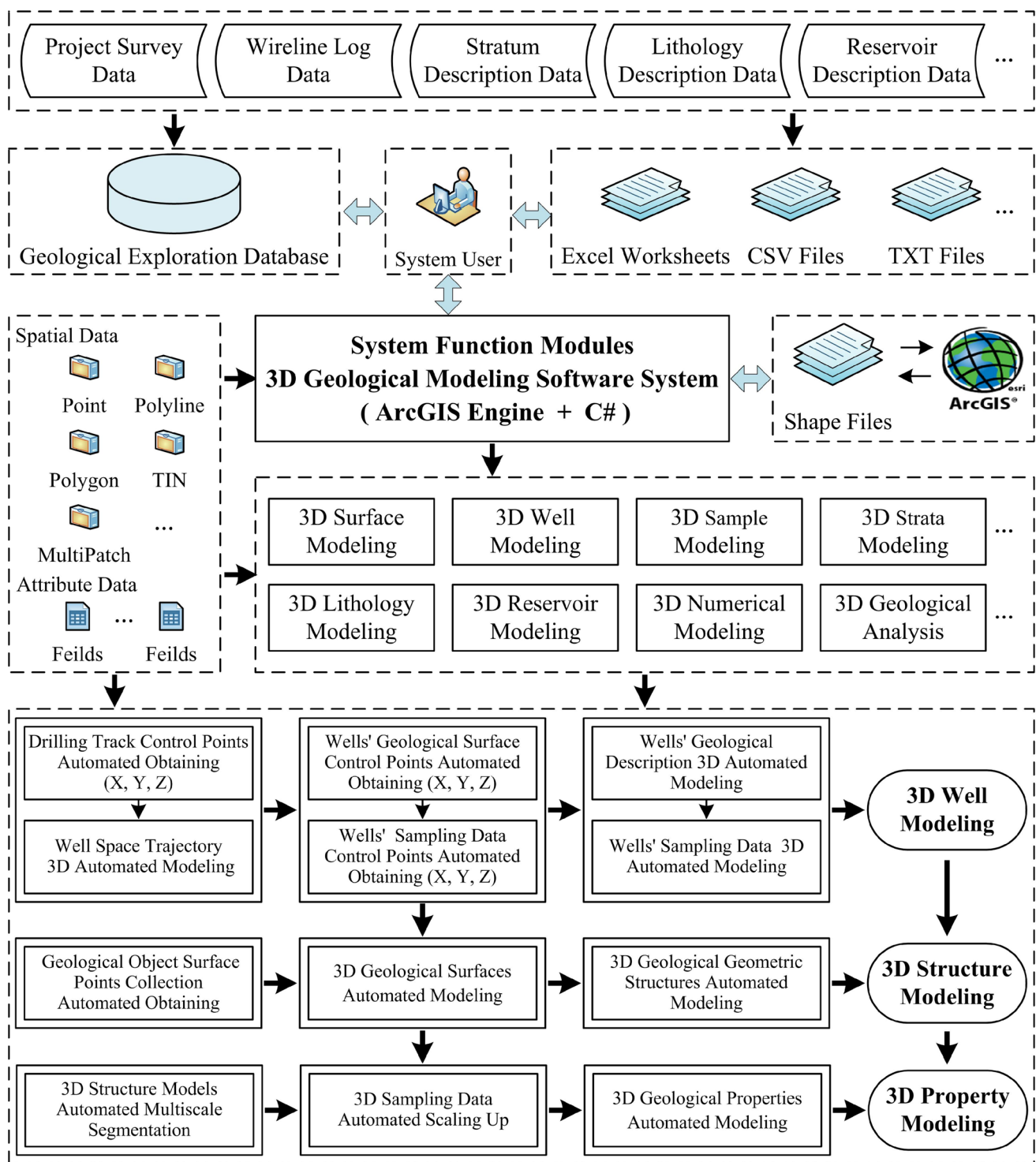


Fig. 4 Framework and workflow of 3D geological objects auto-modeling system based on ArcGIS Engine

hierarchical code according to a predefined stratigraphic and lithological column (if a layer is absent, the starting and ending positions of drilling for that layer are the same, and the thickness is set to zero). This ensures that the layer sequence within each well is correctly

ordered and correlated without inversion. These codes also serve as the basis for correlating equivalent layers across different wells during subsequent surface interpolation. Thus, by reading the well information in the drilling database, computer algorithms can be used to

automatically create well models, including 3D spatial models of well trajectory, samples, stratum and lithology, etc..

- (b) Automated extraction of control points and 3D geological structure modeling. In sedimentary environments, sedimentary strata or rock formations can be modeled by creating distinct stratigraphic surfaces, and the control points of top and bottom surfaces can be extracted from well models automatically. Triangulated geological interfaces are created as a multi-layer TIN model from the geological surface control points. The TIN (Triangulated Irregular Network) is a vector-based representation constructed using the Delaunay triangulation algorithm, which is the standard method in ArcGIS for creating triangulated networks from scattered points. To ensure that the resulting TIN surface passes exactly through all geological surface control points (i.e., the well intersection points), these points are added as vertices to the TIN mesh prior to triangulation. If a smoother or more detailed TIN surface is required, additional control points can be densified at regular intervals based on the existing geological surface control points (e.g., inverse distance weighting, minimum curvature, kriging). For locations between control points, the elevation is determined via linear interpolation across the TIN facets. Following the principles of hierarchical geological modeling (Calcagno et al. 2008; Schorpp et al. 2022), each stratigraphic or lithological interface is generated based on well control points or the densified control points. By comparing the elevation values of adjacent geological surfaces at any given XY location, the spatial contact relationships (i.e., the superposition relationship of each layer, including erosional contacts where younger surfaces cut across older ones) are automatically determined. If the automatically generated relationships do not satisfy the geological interpretation, geologists can manually adjust the TIN surfaces by editing nodes, adding constraints, or locally re-interpolating the affected surfaces using ArcGIS's TIN editing tools. Once the multi-layer DEM model meets the modeling requirements, using the designed MultiPatch data structures and algorithms, the 3D geological geometric models are constructed with the constrained boundaries, such as stratum, rock formations and coal seams.
- (c) Automated creation of multi-scale voxel blocks and 3D geological properties modeling. The various properties of the geological bodies (such as lithology, coal quality, porosity, permeability, gas content, etc.) are heterogeneous in 3D space and can be quantitatively characterized by high-resolution multi-scale voxels (Wang et al. 2017). 3D voxel blocks may be cubic, regular

cuboid, irregular cuboid, tetrahedron, and so on. Usually, 3D voxel blocks are defined as multi-scale cubes or cuboids based on MultiPatch features in the ArcGIS Engine to fill the 3D geological bodies. The spatial geometric framework of 3D geological bodies, such as strata or lithological layers, is constructed through the workflows described in Sects. "Automated modeling workflow and core techniques"(a) and 2.2.4(b). Within the spatial extent of each stratigraphic or lithological unit defined by this geometric framework, the 3D geological body model is discretized into voxels. The attribute values for filling these voxels are derived from actual geological sampling data (e.g., borehole assay data) stored in the database or from interpretation results provided by geologists. These data are located in 3D space along well trajectories and are linked to voxel blocks through spatial topological relationships. The sampling points contained in each voxel block are automatically obtained accordingly, used to calculate the property values of that voxel block, and then used to fill other voxel blocks without sampling data through 3D spatial interpolation algorithms selected according to geological principles, thereby achieving the 3D spatial distribution simulation of geological properties and completing the 3D numerical modeling of geological bodies.

To provide a clear overview of the automation level of each step, Table 2 lists all steps in the proposed modeling workflow, indicating which are fully automated and which require human intervention (semi-automated).

Finally, 3D geological analysis functions for 3D geological geometric models and 3D geological property models can be developed based on ArcGIS Engine and C#, such as virtual drilling analysis, geological section analysis, and spatial field analysis.

Algorithms for geological data accurate positioning and multi-scale representation

Well trajectory and precise geological data positioning

The positioning method of geological objects in 3D space is different from that of geographic entities, and the calculation parameters and calculation algorithms are more complicated. The 3D well path is recorded by measured depth (MD), inclination, and azimuth while a well is being drilled (Fig. 5a), and the 3D spatial coordinates of each point along the well trajectory can be calculated based on directional parameters (Fig. 5b).

Table 2 Automated and semi-automated steps in the modeling workflow

Workflow	Step	Step Description	Automation type	Human intervention
Data preparation	1	Digital data processing and cleaning of exploration data (digitization, standardization, quality control)	Semi-automated	Geologists
	2	Defining stratigraphic column and assigning hierarchical codes to each layer in database	Semi-automated	Geologists
	3	Reading geological exploration database (Excel/CSV/TXT)	Fully automated	No
	4	Extracting drilling track control points (X, Y, Z) from well database	Fully automated	No
3D Well modeling	5	Automated 3D well trajectory modeling from well database	Fully automated	No
	6	Automated 3D sampling data modeling (core samples, logs) from well database	Fully automated	No
	7	Automated 3D stratigraphic and lithological modeling from well data	Fully automated	No
3D structure modeling	8	Automated extraction of geological surface control points from well models	Fully automated	No
	9	Interpolating TIN surfaces from control points	Fully automated	No
	10	Automatically determining spatial contact relationships by comparing surface elevations	Fully automated	No
	11	Manually adjusting TIN surfaces (automatically generated relationships are unsatisfactory)	Semi-automated	Geologists
	12	Constructing MultiPatch geometries for strata, rock formations, and coal seams (3D structure models)	Fully automated	No
3D Property modeling	13	Selecting voxel resolution	Semi-automated	Geologists
	14	Automated multi-scale segmentation of 3D structure models into voxels	Fully automated	No
	15	Automated scaling up of 3D sampling data to voxel blocks	Fully automated	No
	16	Assigning attribute values to voxels from sampling data	Fully automated	No
	17	Selecting interpolation algorithm and interpolation parameters for voxels without sampling data	Semi-automated	Geologists
	18	Executing spatial interpolation to fill voxels without sampling data (3D properties modeling)	Fully automated	No
3D spatial analysis	19	Generating virtual drilling analysis, arbitrary sections, spatial field analysis, etc	Semi-automated	Geologists

There are several methods used by the oil and gas industry to calculate well trajectories, i.e., the tangential method, the average angle method, the radius of curvature method, and the minimum curvature method (Atashnezhad et al. 2014). Among all, the minimum curvature method (Smith and Wessel 1990) is the most accurate method for calculating northing and easting offsets, and it is the most accepted method and practically used universally by the oil and gas industry. As shown in Fig. 5b, the drilling path BE is assumed to be an arc segment, the coordinates of the starting point B are (x_b, y_b, z_b) , and the coordinates of the next inflexion point E can be calculated by using the minimum curvature method.

Equations (1) and (2) calculate the change in angle and the ratio factor of curvature between two points in 3D space:

$$\beta = \cos^{-1} [\cos(\alpha_2 - \alpha_1) - (\sin \alpha_1 \sin \alpha_2 \times (1 - \cos(\varphi_2 - \varphi_1)))] \quad (1)$$

$$RF = \frac{2}{\beta} \tan\left(\frac{\beta}{2}\right) \quad (2)$$

where β is the dogleg angle (in radians), RF is the curvature ratio factor, and α_1 α_2 φ_1 φ_2 are the inclination angles and azimuth angles of point B and point E, respectively.

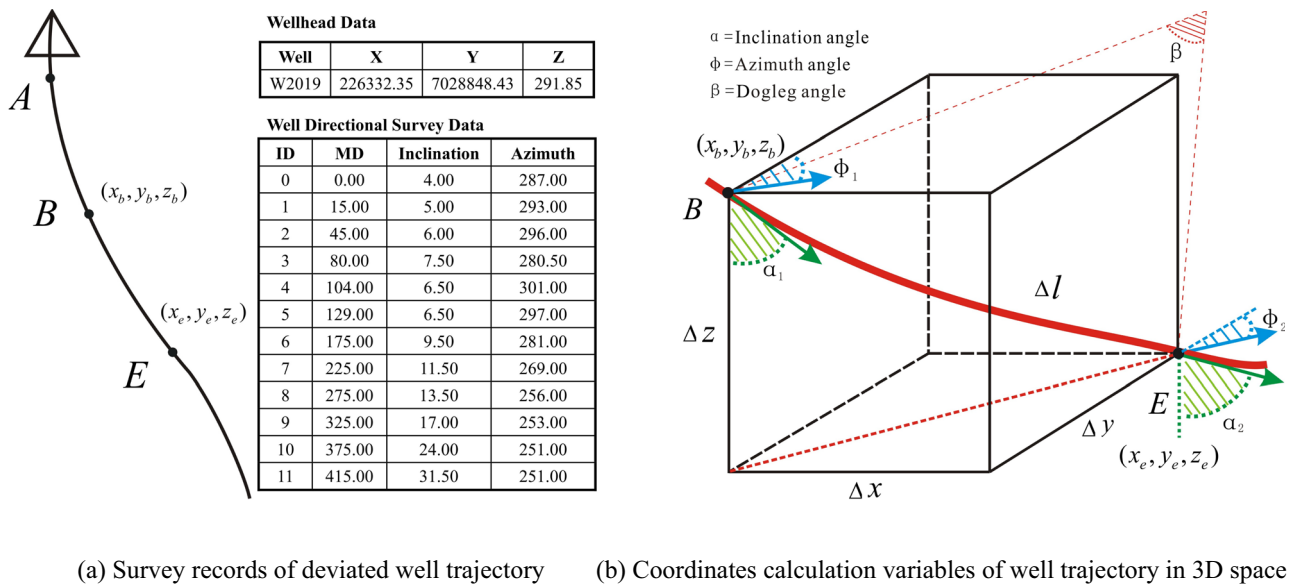


Fig. 5 Principle of accurate 3D spatial positioning for complex wells

Equations (3)–(5) calculate offset distances in three specific directions between point B and point E in 3D space (i.e. to X, to Y and Z).

$$\Delta x = \frac{\Delta l}{2} [\sin \alpha_1 \sin \varphi_1 + \sin \alpha_2 \sin \varphi_2] \times RF \quad (3)$$

$$\Delta y = \frac{\Delta l}{2} [\sin \alpha_1 \cos \varphi_1 + \sin \alpha_2 \cos \varphi_2] \times RF \quad (4)$$

$$\Delta z = \frac{\Delta l}{2} [\cos \alpha_1 + \cos \alpha_2] \times RF \quad (5)$$

Here, Δl is the difference in measured depth between point B and point E, i.e., the length of the curved segment.

After calculating the offset coordinates between two points (i.e. Δx , Δy and Δz), the coordinates of point E can be obtained based on point B. Equations (6)–(8) provide the X, Y and Z at any point along curved segments of a well trajectory.

$$x_e = x_b + \Delta x \quad (6)$$

$$y_e = y_b + \Delta y \quad (7)$$

$$z_e = z_b - \Delta z \quad (8)$$

If the wellhead coordinates have been measured, the coordinates of any point along the well trajectory can be obtained based on the equations above. By connecting the control points of each trajectory segment in sequence, the 3D well trajectory model can be accurately created. Similarly,

the core samples, the geophysical logs and the geological interfaces of wells can also be precisely located according to their directional parameters, such as relative depth, the inclination angle and the azimuth angle obtained indirectly along the trajectory.

Geological data multi-scale representation

The multi-scale representation of geological data is based on its accurate position in 3D space. The geometric and property representation of a geological object is conducted comprehensively according to three perspectives: (1) the view of objects themselves, it mainly consists of drilling samples and geological entities; (2) from the standpoint of representing contents, it contains mostly geometric features and attribute information; and (3) the perspective of describing details, it primarily includes conventional representation and high-resolution expression.

Well trajectory and samples

The representation of well trajectories, core samples and log sampling points in 3D space are usually achieved by using MultiPatch components. The spatial positioning algorithms are first used to determine the control points of a well, and then the wellhead, trajectory, core samples and log sampling points can be created by using ArcGIS's MultiPatch features. The well feature includes vertical wells, inclined wells, and complex directional wells and horizontal wells. The trajectories of wells are usually represented by cylinders designed by MultiPatch features, and core samples are generally represented by cylinders or cubes, as shown in

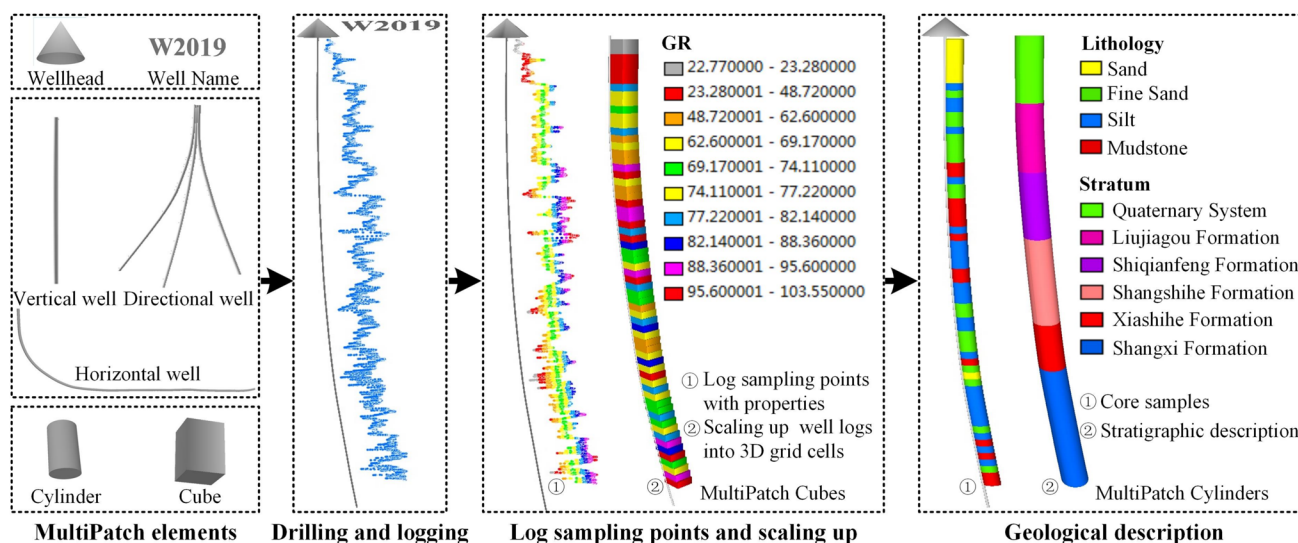


Fig. 6 Multi-scale representation of well trajectory and samples

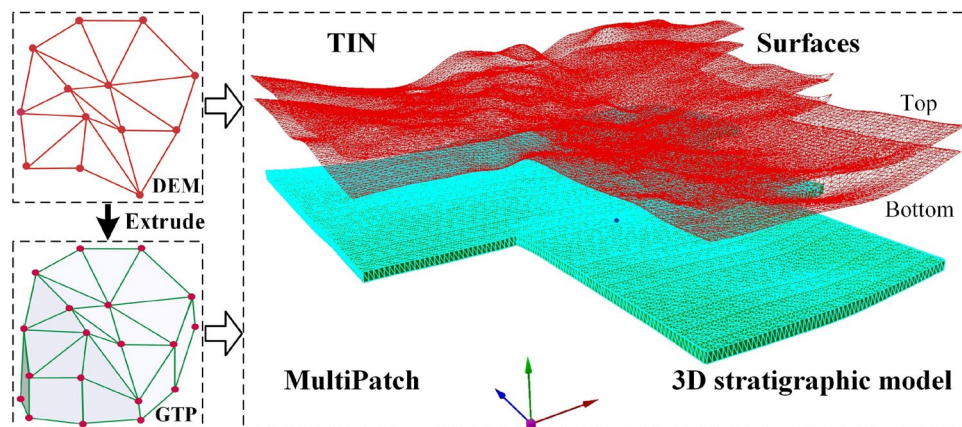
Fig. 6. Besides, well paths and sample points can also be expressed using conventional polyline or point features of ArcGIS.

3D geological geometry data

The 3D geological geometry models created by GIS are usually expressed in two basic modes: surface or model. ArcGIS software mainly uses two DEM methods to represent surfaces: triangulated irregular network (TIN) and regular grid (Grid) (Werbrouck et al. 2011). And a MultiPatch-based feature is defined to describe the model. The new MultiPatch-based feature is composed of triangles of TIN data. A series of triangle strips is formed by extruding TIN data, and the essence of which is a collection of general tri-prism (GTP) units. As the single-layer DEM, the TIN consists of the discrete points obtained by sampling points, and it can simulate the geological interface accurately by connecting these distinct points into continuous triangular networks. In practice, when the original borehole control

points are too sparse to capture detailed geological features, additional control points can be densified using spatial interpolation methods (e.g., minimum curvature) before triangulation, thereby ensuring a more refined representation of geological interfaces. Therefore, in addition to representing the geometry of geological interfaces, the multi-layer DEM describes vertical characteristics and spatial relationships of geological interfaces in ArcGIS. However, compared with the conventional representation methods, the MultiPatch-based GTP data structure can provide a better way to simulate 3D geological entities. The GTP features create 3D geological entities according to the spatial relationship between the upper and lower layers of TIN. Firstly, the non-parallel triangles of the upper and lower TIN data were used to represent different geological interfaces (red surfaces in Fig. 7), and then the triangle strips was used to describe the side of the GTP and the spatial relationships between the layers. Finally, the GTP polygonal cylinder combined by MultiPatch features was used to express complex geological geometry entities, as shown in Fig. 7.

Fig. 7 Data structures for representation of 3D geological geometry models



3D geological property data

As geological bodies have gone through various geological processes during their formation and evolution, their properties have typical continuity, heterogeneity and anisotropy in three-dimensional space. Since internal features of geological bodies are complex, the usual method is to abstract and simplify their internal structure by filling a certain number of homogeneous voxels with multiple attribute fields, such as cuboids, cubes, tetrahedrons, etc. (Prinds et al. 2020). The internal heterogeneity characteristics of geological bodies are described by using these discretized voxels as the carrier of their various geological properties.

According to the MultiPatch features of an ArcGIS Engine and voxel types of 3D geological models, the MultiPatch-based voxels for 3D geological property data expression are designed as cubes or cuboids, which are convenient for multi-scale representation of geological attributes, as shown in Fig. 8. By using multi-scale voxels, modeled 3D geological geometries can be filled with single or multi-level voxels to create 3D property models with multiple property fields; thus, the 3D spatial distribution of geological properties can be represented in various forms, such as multi-scale, multi-resolution and multi-attributes.

Results

To demonstrate the applicability of the proposed methodological framework, a case study was conducted in the southern Qinshui Basin, one of the most important coalbed methane (CBM)-producing regions in China. The stratigraphy in this area is relatively simple and flat-lying. The primary CBM target is the No. 3 coal seam, which has an

average thickness of 6.25 m and is hosted within the Permian Shanxi Formation (average thickness 66.05 m, ranging from 30 to 85 m). From bottom to top, the stratigraphic sequence consists of the Taiyuan Formation, Shanxi Formation, Xiashihezi Formation, Shangshihezi Formation, and Quaternary System (Chen et al. 2023). A total of 189 wells from the study area were used as input data.

Based on the research methods and algorithms described above, a 3D geosciences modeling software prototype was developed using ArcGIS Engine components and Visual Studio C#. This software prototype enables the automatic construction of not only traditional 3D surface models but also 3D geological models, including complex well trajectories, core samples, log sampling points, geological descriptions, geological surfaces, geological structure and property models.

3D Well modeling

The well data accurately provides the position of the 3D geological bodies and captures the high-resolution geological property characteristics along the well trajectory. This software prototype can automatically establish high-precision and complex 3D drilling models with detailed characteristics such as drilling tracks, samples, stratums and lithologies, as shown in Fig. 9, which are important data sources for 3D high-resolution geological modeling.

3D geological surfaces modeling

3D visualization of geological surfaces is an essential means to express the spatial geometry and relationships between underground geological bodies. The construction method of geological surface models is the same as that of the surface

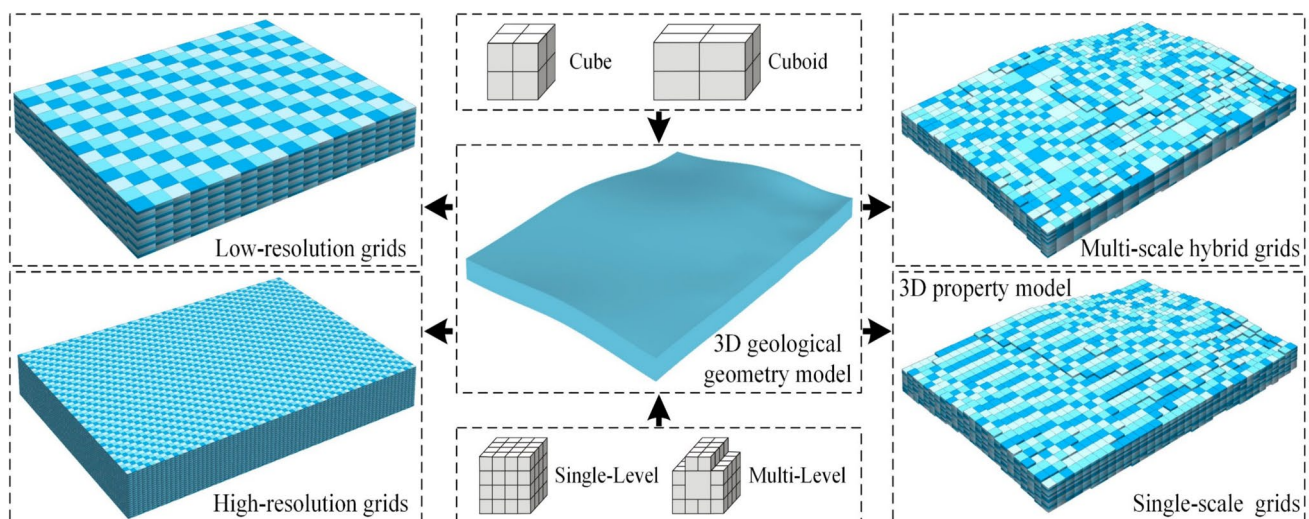


Fig. 8 Data structures for representation of 3D geological property models

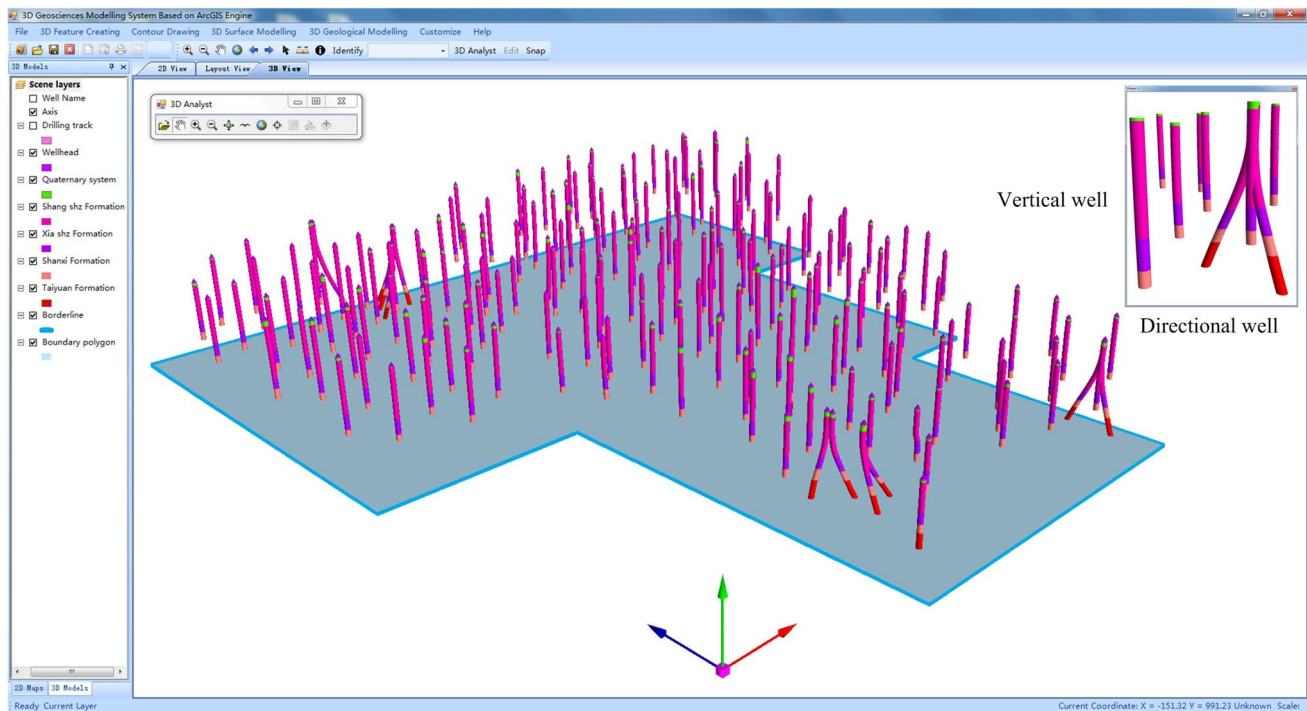


Fig. 9 Automated construction of 3D high-resolution drilling models based on ArcGIS Engine

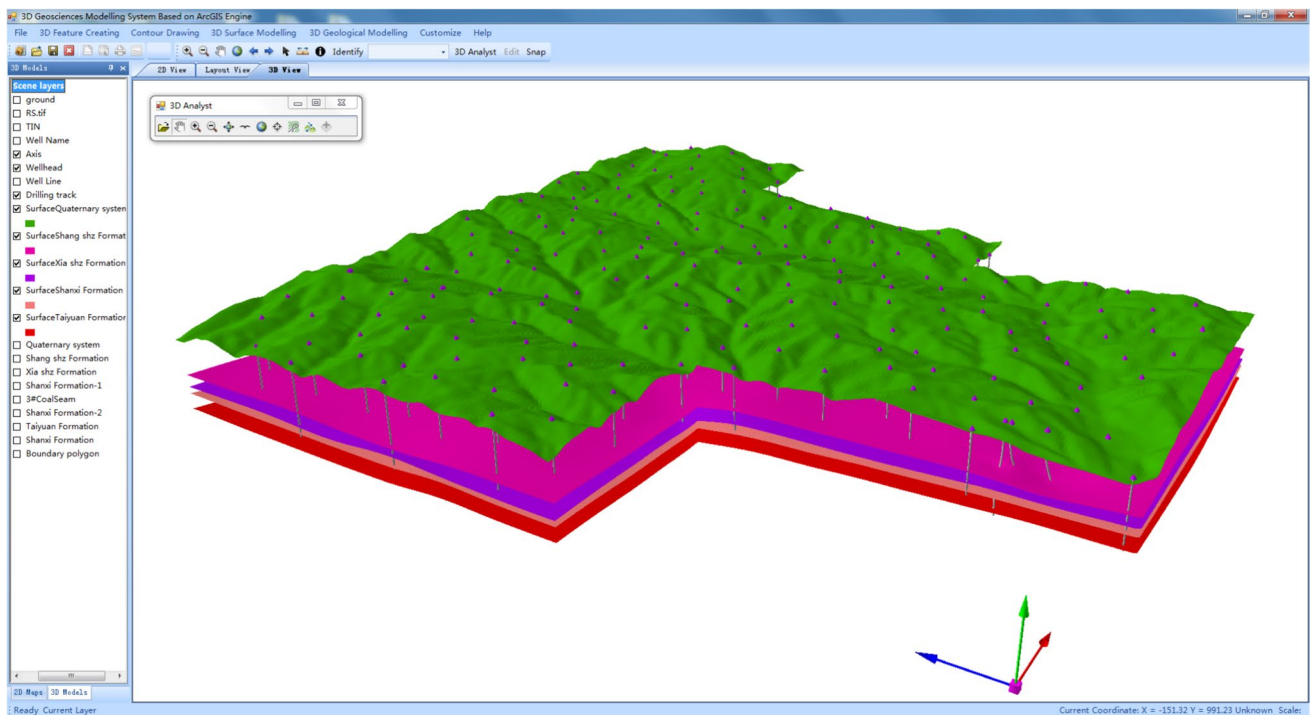


Fig. 10 Construction of 3D geological surfaces based on ArcGIS Engine

terrain models. With the help of the software functions, geological bodies' interfaces are determined according to the data sampled by the borehole and the geological interpretation results of lithology and its place in the stratigraphic column.

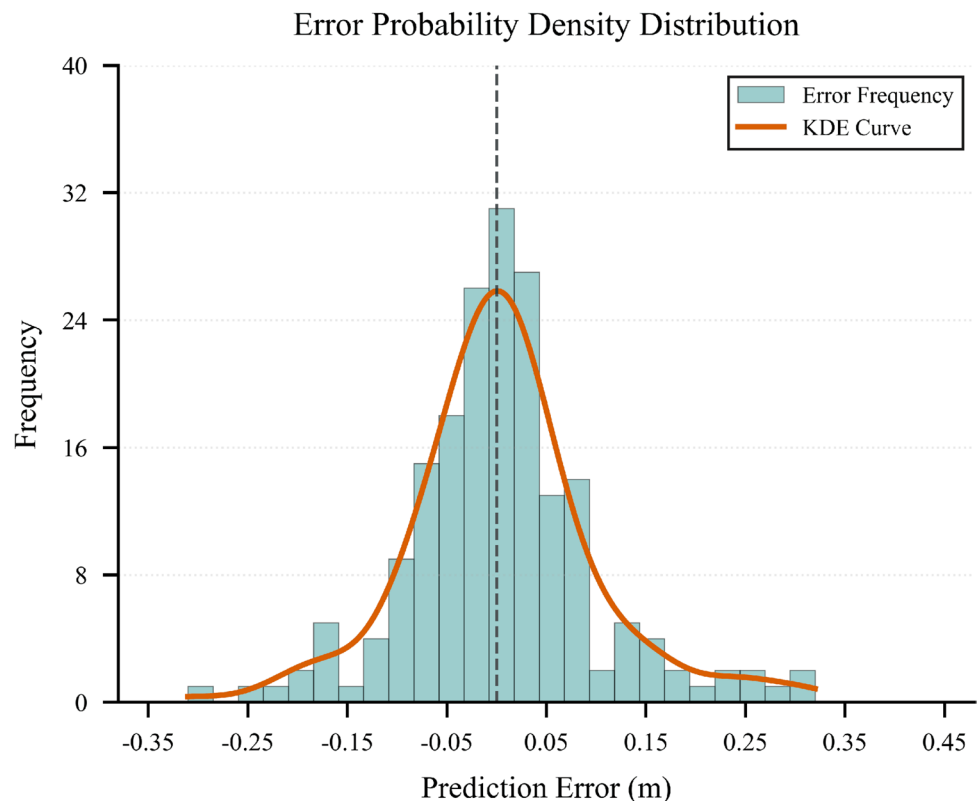
A set of geological surfaces constructed with TIN sets can be used to control the morphology of geological bodies, as shown in Fig. 10. This work is the basis for the automated construction of the 3D geological structure and properties models.

To quantitatively evaluate the geometric accuracy of the modeled stratigraphic surfaces, we compared the interpolated TIN surface depths with the original borehole measurements at 189 locations. The root mean square error (RMSE) is 0.0936 m, and the mean absolute error (MAE) is 0.0654 m, demonstrating that the TIN surfaces honor the input control points with high precision. Figure 11 presents a histogram of the errors between the modeled TIN surface depths of the No. 3 coal seam roof (generated from $50\text{ m} \times 50\text{ m}$ densified control points) and the original borehole measurements ($N=189$). The error distribution is centered near zero, indicating no systematic bias.

3D geological structure and property modeling

The 3D structural model can describe the geological body's spatial morphology, while the 3D property model can represent its heterogeneity. The perfect combination of 3D structure and 3D property models makes the constructed 3D geological models more consistent with the actual geological conditions. After completing the 3D geological surface models based on the software's relevant functions, the 3D geological structure models were built under constraints, such as the stratigraphy, the rock layer models, the reservoir models and so on. Then, the 3D geological structure models are segmented into voxels, and the sampling or assay data is interpolated into the 3D space to obtain the 3D high-resolution property models. The integrated results are

Fig. 11 Histogram of the errors between the modeled surface of the coal seam and the original borehole measurements



presented in Fig. 12. Figure 12a displays the stratigraphic framework with integrated structural and property models. Figure 12b and c provide detailed views of the coal seam: (b) its structural geometry, and (c) its gas content distribution as a standalone property model (color gradient). All models were built using the ArcGIS Engine.

Discussion

The 3D geological modeling algorithms and software prototype developed in this research can play an essential role in expanding the application area and ability of GIS software. Based on ArcGIS Engine components, high-resolution 3D surface entities and subsurface geological bodies containing geometric structure and attribute information can be constructed and integrated, and geo-spatial analysis functions such as virtual drilling analysis and arbitrary sections of geological bodies can be taken to explore geometrical relationships. This methodology can effectively reduce the complexity of 3D geological modeling using GIS software, reduce the workload and improve work efficiency for geologists.

3D geosciences data integration

Geospatial objects consist of aboveground, ground surface, and underground entities. The core of 3D geoscience data

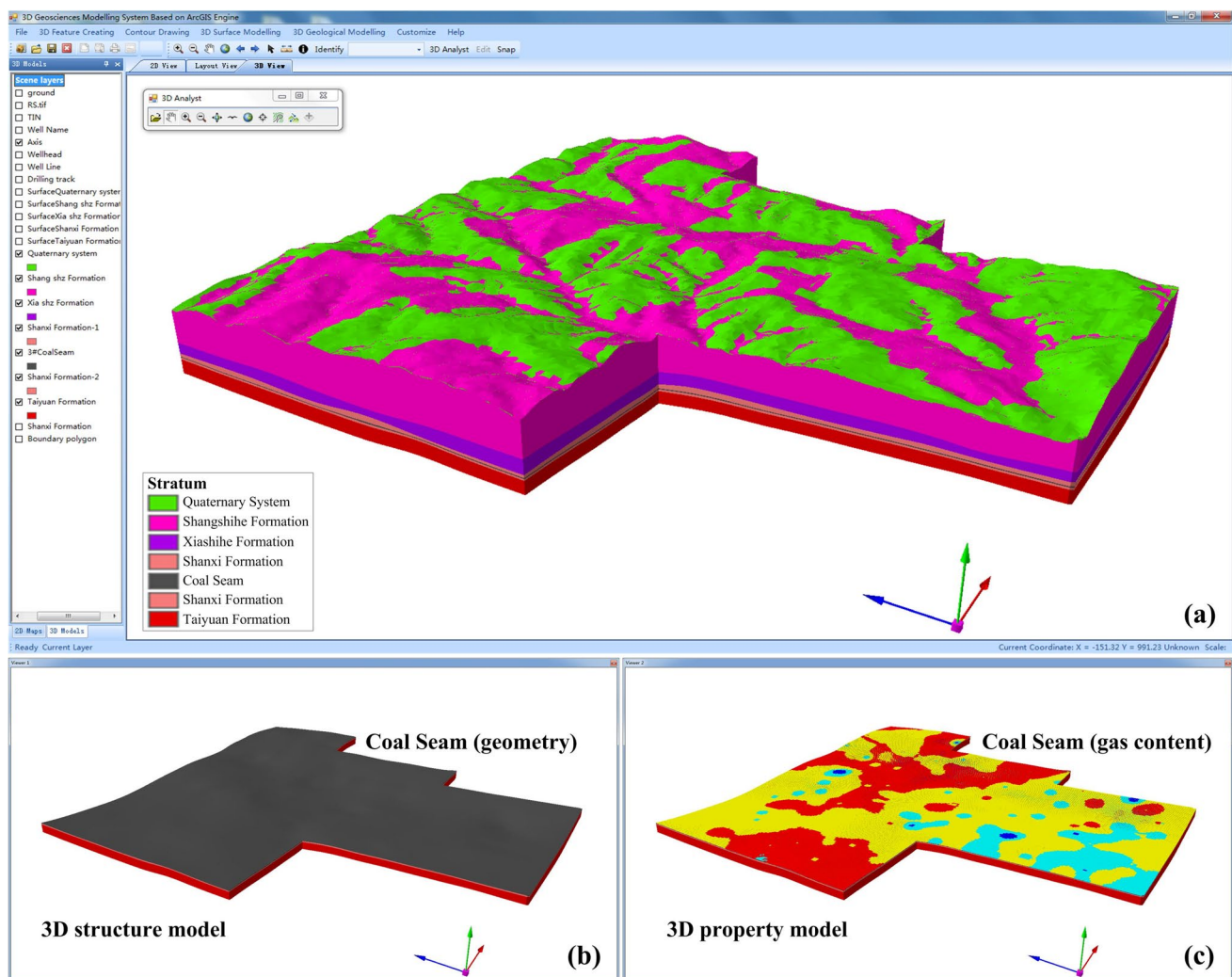


Fig. 12 Integrated 3D geological modeling: **a** Stratigraphic framework with structural and property models; **b** Coal seam geometry; **c** Coal seam gas content distribution

integration is to combine 3D surface models, such as terrain, buildings, trees, etc., with 3D underground models, such as wells, cores, formations, coal seams, etc. In this experiment, a DTM was built based on ground vector maps and prospecting projects, which is a bare ground surface without any objects and connects the surface and subsurface entities. Remote sensing images were integrated above the ground surface, covering the 3D surface entities with Esri CityEngine, such as houses, trees, and vegetation. And 3D geological models such as wells, stratigraphy, and reservoirs, were integrated under the ground surface. The integrated 3D geosciences model is shown in Fig. 13.

3D geological property data multi-scale modeling

Geological data usually contain two types of information: spatial features and attribute values. Based on these data, a 3D geological structure model is first constructed. Then,

according to the modeling purpose, this structure model is discretized into multi-scale grid voxels. To populate these voxels with attribute values, it is necessary to interactively set parameters and select interpolation algorithms for spatial interpolation. As a result, the initially empty grids are filled with interpolated values, forming a high-resolution 3D geological property model. This property model is thus integrated into a discrete, multi-scale, multi-dimensional big grid dataset that contains rich attribute information.

We illustrate this process using an example of 3D gas content modeling. Using the software prototype platform developed with ArcGIS Engine components, the coal seam geological model was divided into a multi-scale, high-resolution 3D grid. Subsequently, a high-resolution 3D property field with multi-dimensional attributes was obtained through spatial interpolation and GIS attribute tables. In this study, the inverse distance weighting (IDW) method with a power parameter of 2 was employed, as shown in Fig. 14.

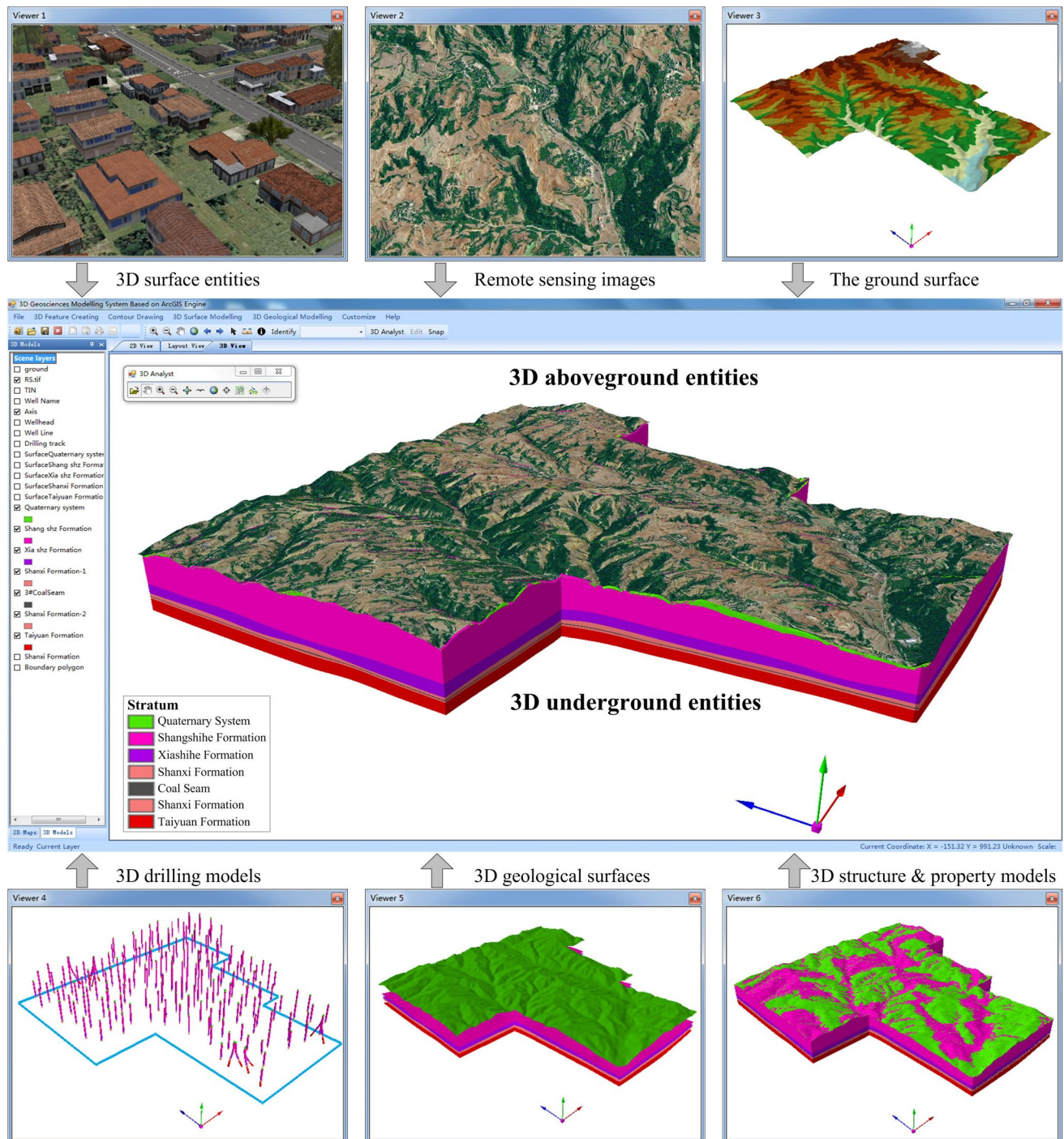


Fig. 13 Integration results of 3D surface models and 3D underground models based on ArcGIS Engine

These processes and results are difficult to obtain using traditional GIS software platforms.

3D geological spatial analysis

Similar to traditional GIS surface spatial analysis, 3D geological spatial analysis can support geologists in

understanding geological bodies and phenomena better, and thus, improve the accuracy and efficiency of geological information utilization. The software prototype with ArcGIS Engine component developed in this study can also provide various feature analyses and statistical calculations for geologists, such as spatial geometry and attribute information for wells and geological bodies, 3D mine

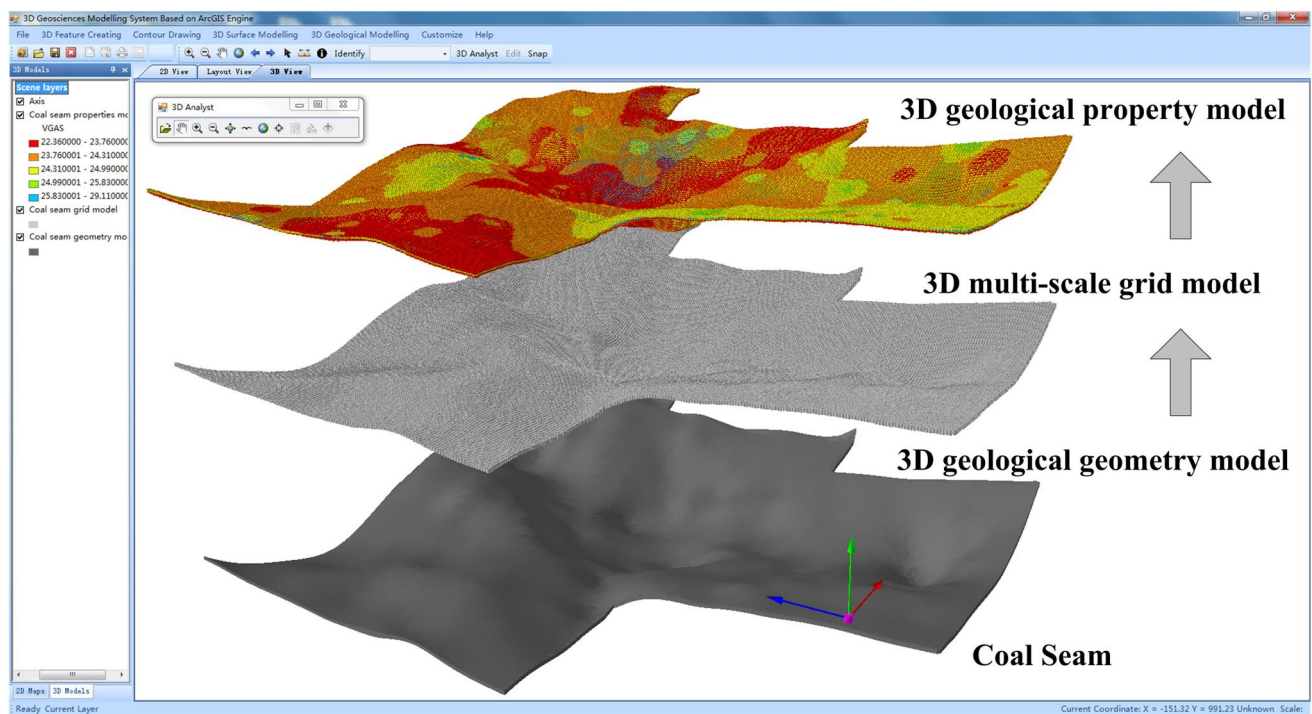


Fig. 14 3D geological property data multi-scale and multi-dimensional visualisation based on ArcGIS Engine

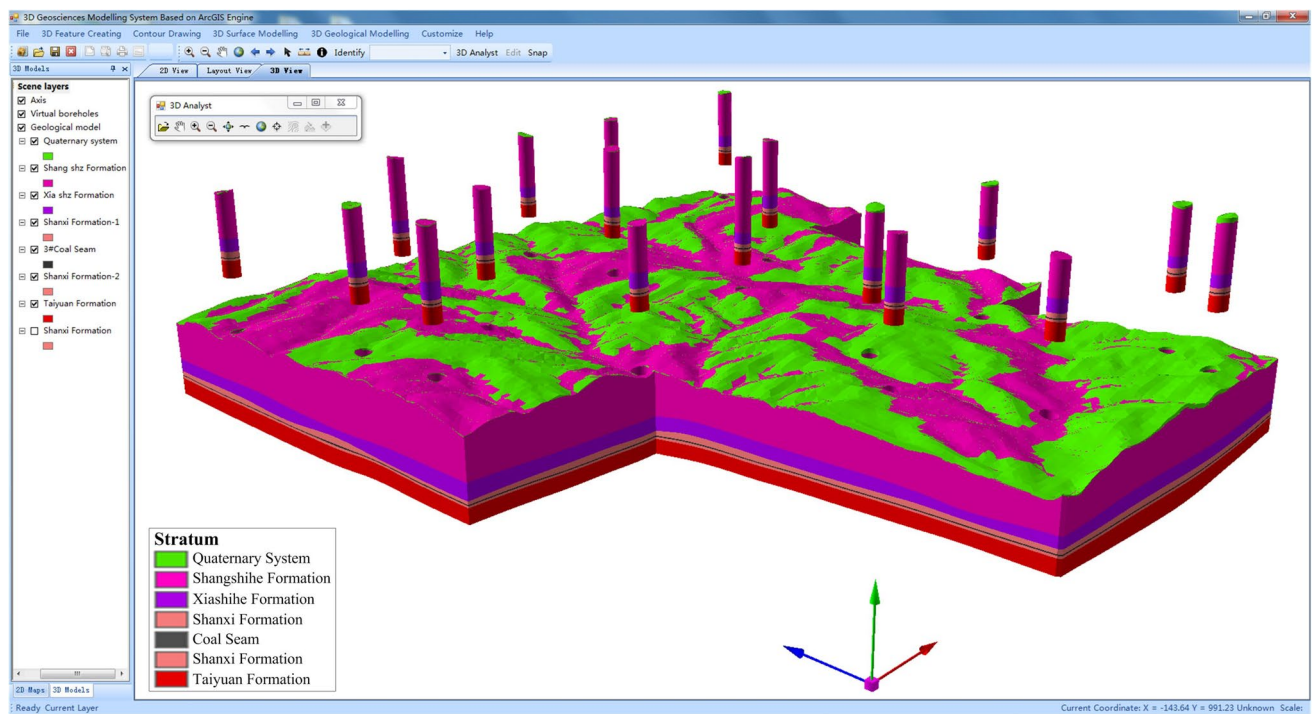


Fig. 15 3D virtual drilling analysis based on the 3D geological models

tunnel simulation and scene roaming, virtual drilling analysis (Fig. 15), the capability to create arbitrary sections for the analyses of geological bodies (Fig. 16), etc. All these

features and workflows enable geologists to gain a more realistic understanding of the internal structure of geological bodies of interest.

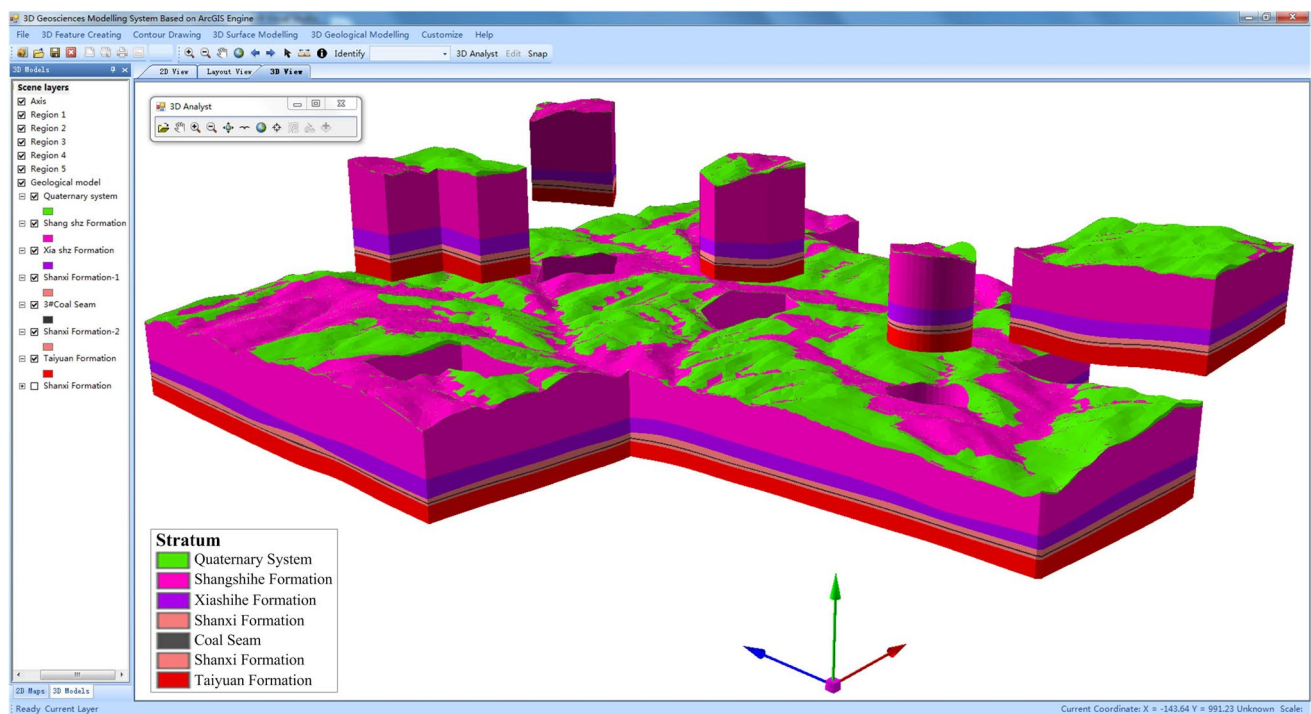


Fig. 16 3D arbitrary sections to analyse geological bodies

Limitations and comparison with existing tools

Limitations

Although the proposed method for extending ArcGIS to subsurface geological modeling has demonstrated feasibility, several limitations remain. First, automated modeling of faults and other complex geological structures (e.g., discontinuous strata, complex lithological lenses) is not yet supported. Their data structures, algorithmic design, and functional implementation remain open for future development. Second, although the MultiPatch datatype is native to ArcGIS, its inherently simple and regular geometry limits its ability to represent complex, irregular geological structures. Third, the current workflow is based on the designed geological structures and uses several representative algorithms to validate the feasibility of the development framework and data structures, resulting in a 3D geological modeling prototype system. However, substantial improvements are still needed in algorithmic diversity, seamless data integration between functional modules, and system intelligence.

Comparison with existing tools

To clarify the positioning of this work, Table 3 qualitatively compares our technical methods and functionalities with those of specialized geological modeling software (e.g.,

Petrel, GOCAD, GeoModeller) and open-source Python libraries (e.g., GemPy, LoopStructural, ArchPy).

As shown in Table 3, this work demonstrates how to extend ArcGIS's subsurface modeling capabilities rather than developing a standalone commercial product. ArcGIS natively excels at aboveground modeling (e.g., terrain, buildings, vegetation) but lacks robust tools for subsurface geological modeling. Our method extends ArcGIS to fill this gap, enabling seamless aboveground–subsurface integration within a single environment. This capability is not offered by specialized standalone software or open-source libraries, both of which require data export/import across platforms and face data structure compatibility challenges.

The contribution of our framework lies in three aspects: (i) an integrated workflow that forms a complete chain: borehole data, control point extraction, TIN surface interpolation, automatic contact relationship determination, 3D geological structure construction, voxel discretization, 3D property interpolation; (ii) MultiPatch-based geological data structures that leverage and extend ArcGIS's native 3D datatype to represent subsurface geological objects; (iii) an automated/semi-automated strategy that balances batch processing efficiency with user-defined parameters (e.g., stratigraphic column, interpolation algorithms, voxel resolution).

Our work is not intended to compete with specialized software (Petrel, GOCAD, GeoModeller) or open-source libraries (GemPy, LoopStructural, ArchPy). Instead, it fills a specific gap in the ArcGIS ecosystem, offering a

Table 3 Qualitative comparison with existing geological modeling software and libraries

Comparison dimension	Our method	Specialized software (Petrel, GOCAD, etc.)	Open-source libraries (GemPy, ArchPy, etc.)
Core nature	ArcGIS extension (secondary development)	Standalone software	Library
Target audience	ArcGIS users (surface → subsurface) ArcGIS Engine developers	End users (geological modelers)	Python programmers
Delivery form	Methodological framework Soft prototype	Commercial product	Open-source code
What is new?	Integrated workflow MultiPatch-based geological data structures Automated/Semi-automated strategy	Not applicable	Algorithms
3D Aboveground modeling (terrain, buildings, vegetation)	Native ArcGIS (directly usable)	Not supported	Not supported
3D Subsurface modeling (wells, strata, voxel)	Extended (fills ArcGIS gap)	Advanced (faults, folds, etc.)	Algorithm-based
Surface–subsurface integration	Seamless (same environment, no data conversion)	Requires export/import	Requires export/import
Faults & complex structures	Not yet (limitation, requires future extension)	Supported	Supported
Primary contribution	Enables seamless aboveground–subsurface modeling natively in ArcGIS	Complex geology modeling	Flexible, free, scriptable

methodological framework for ArcGIS users and Engine developers to rapidly represent subsurface geological objects and achieve integrated aboveground–subsurface modeling natively within ArcGIS. Notably, although this study is implemented with ArcGIS Engine, the proposed methodological framework is equally applicable to the ArcGIS Pro SDK, as the core design relies on standard MultiPatch geometries and .NET-based development patterns that are consistently supported across both platforms.

Conclusions

This paper presents an automated methodological framework that extends ArcGIS to integrate surface and subsurface 3D geological models, a capability not natively available in standard GIS platforms. Quantitative validation against 189 borehole control points demonstrates the geometric reliability of the modeled surfaces, with an RMSE of 0.0936 m and an MAE of 0.0654 m. The 3D geological modeling workflow was decomposed and reorganized using an object-oriented method, and an automated approach based on ArcGIS Engine components was developed. Finally, using ArcGIS Engine components and Visual Studio C#, the 3D geosciences modeling software prototype was developed and realized. The software prototype can support traditional 3D surface models constructed by ArcGIS Desktop, Esri CityEngine or ArcGIS Engine and automatically build

3D geological models with ArcGIS Engine components, such as complex 3D well trajectories and samples models, geological surfaces, structure and property models, etc. In addition, the software prototype has a series of 3D geological feature analysis functions, such as space information query for wells and geological bodies, virtual drilling analysis, and the capability of obtaining arbitrary sections of geological bodies to facilitate their analyses. This software prototype expands the 3D geological modeling capability of GIS software, reduces the difficulty of geological modeling, and provides a new way for the integration of surface and underground data. The software prototype created is effective for integrating surface and subsurface data, enabling automated building of geological models including engineering features such as wells and tunnels. However, at this stage, automated modeling of faults and complex sedimentary rock lenses (i.e. not continuous strata) has not yet been realized and will be the subject of future research.

The coalbed methane case study demonstrates the value of integrated surface–subsurface modeling for energy resource engineering. The 3D geosciences model that integrates surface and subsurface is of great significance for the location selection and drilling design of coalbed methane wells, with the potential to reduce production cost and increase gas production. Many other applications can be envisioned in the areas of mining, oil and gas production, groundwater management, subsurface storage of gases (hydrocarbons, CO₂, hydrogen) and heat.

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Data availability The data are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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