National Topographic Modeling, Ontology-Driven Geographic Queries in the Context of the U.S. Geological Survey's *The National Map*

Abstract

Ontology for *The National Map* aims to integrate a wide range of landscape features and events within the diverse United States and to make information about those features available to the public using natural language-based queries. The conceptual model is composed of three parts; the ontology, its interface with the Geographic Names Information System, and the geospatial database.[1] Methods for the measurement of semantic similarity, classification context, and spatial relations are discussed.

Introduction

This research examines the extension of national topographic mapping cartographic categorization to categorizations for topographic narrative, a type of geographic modeling. Topographic narrative, the language-based representation of local scale landscapes, is a basic and commonly-used form of geographic modeling, essential to other specialized forms of geographic analysis. By examining the semantics and defining an ontology of topographic narrative, a syntax can be formed for the retrieval and modeling of geographic information of varying granularity. This paper describes topographic narratives and their role in topographical mapping, the potential of ontology

[1] Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

to the mediate the tensions of topographic narrative as geographic modeling, and the approach the U.S. Geological Survey is implementing toward this objective.

Topographic Narrative

The history of topography is a long and complicated one, but historical concepts of topography, chorography, and geography can be generalized to be defined as measurable space relative to the surface of the earth; chorography is the characterization of regions on earth; and topography is the experience of discrete features on the ground, one to another (Lukermann 1961; Curry 2002). Topography is a spatial experience ordered along processes of cognition, narrative, and temporality. One example of a topographic narrative is that of the Konza Prairie of the Flint Hills of Kansas, organized by USGS topographic quadrangles, in what the author, William Least Heat-Moon, called a “Deep Map” (1991).

> The river and large streams here—Rock, Buck, Spring—and the roads that follow them strike similar southwest-northeast courses; only Den Creek runs counter. Sharp’s Creek also comes in contrary, but just the mouth of it nips into the quad; with no other village near, inhabitants along the farther reaches of the stream belong to Bazaar.

Topographic narrative also can take the form of the story that the map reader reflects about in relation to maps and life experiences, including personal identity and community (Harley, 1987). Based on the viewpoint that places are defined by activities that are recorded in the landscape and symbolized in texts, those activities, narratives, and symbolization of those narratives store the memories that make an American identity, with place as the background of society and culture.

National Topographic Mapping

The meaning and purpose of topographic maps vary.[2] Topographic mapping historically has been the mapping of natural and man-made landscape features, especially elevation, at local scales, often that serve as navigation devices. As base maps, topographic maps are a foundation for added informational value and are a development tool. When maintained with time, topographic mapping indicates a process-oriented representation of places that documents the consumption of local resources for development and urbanism. Cumulatively, sequential editions of quadrangle maps document the history of American landscape developments. A national topographic mapping program is a symbol of national identity; when nationally organized, topographic mapping creates a powerful symbol of a united geographic entity, though one polarized between the scale of the nation and locality.

The nation's investment in topographic mapping may be justified by pragmatic benefits, but also presents the challenge of including and representing multiple viewpoints. National topographic mapping requires a diversity of features for a wide range of applications. Traditional topographic mapping in the 20th century was based on the cartographic idea of a base map as a foundation for added informational value,

[2] The term "topographic mapping" through out this paper refers to the national topographic mapping program products.

depending on specific applications. The general nature of the intended applications requires topographic mapping to adopt flexible design objectives, though they remain largely inflexible. Reasons for this inflexibility include the 'flat' technological nature of graphic maps and thematic map layers in geographic information systems (GIS) and fixed thematic categorizations.

The challenge of diversity and equity has been the subject and message of critical GIS theory that posits ontology as an avenue toward achieving critical GIS objectives by enabling diversified viewpoints and their interrelations (Schuurman, 2006; Schuurman and Leszczysnki, 2006; Kitchen and Dodge, 2007). It remains to be seen if national topographic mapping would be supported by geospatial ontology and ontogenetics to enable the multiple perspectives of the American landscape at different locations, scales, and time. Ontologies of topographic mapping include relations between features that are necessary for narratives and the mathematical, geographical framework of placing them in regional and global systems. Twentieth-century technologies supported locality primarily through field surveys and surveying notes, but trends in the digital transition towards central, standardized databases, obscured those contributions toward local narratives that is the basis of every query a user brings to *The National Map*. The loss of the distinction between human topographic places and national geographic spaces in national topographic mapping creates tension between locality and centralization. The landscape features can be shared, but the narratives are personalized.

The purpose of this paper is to examine cartographic and GIS data model flexibility in the USGS *The National Map* and whether or not these tensions can be balanced by an effective ontology, especially its textual, narrative nature. Objectives of ontology in support of *The National Map* are to manage data among a range of scale, data models, sources, technological platforms, and time, and to use ontology to respond to common-language queries of geospatial features and their parts and process/relations among them for knowledge extraction (National Research Council, 2007). This paper addresses the second objective mentioned above of a framework for natural language queries for *The National Map.* In addition to both these operational objectives, ontology research must incorporate socially-diverse cartographic perspectives required by the American public, if *The National Map* is to frame a national topographic program for mapping and geospatial information for a wide range of users.

Topographic Ontology and Semantics

A geospatial ontology is a conceptual and implementation framework for organizing a set of geographical features by their defining characteristics, including location, time, resolution or scale, and characterization (attribution). Ontology captures the invariant definition of feature types that organizes the basis for all comparable data. Digital technology enables the extension of the idea of a base map to an interoperable ontology of features that can be defined, selected, and assembled in sets by users for unique applications. Features are defined as intellectual concepts of entities and objects in the world combined in flexible relations.

Ontologies function by creating a complex context of the physical world, human cognition, social-collective agreements of symbol meaning and assemblages of signs formatted for systems applications. An important start to ontology implementation is to define the individual features and objects and their attributes and relations to each other. Features are the elements of complex messages between data users and representations of the world within syntactic arrangements forming statements of encoded and interpretive meaning. The final framework must present a cohesive digital "narrative" capable of understanding natural language queries and making knowledge statement replies.

Processes to build ontologies often begin with a statement of scope or of purpose and audience. Other national mapping agencies are exploring ontologies for specific purposes. A natural language interface has been attempted by the British Ordnance Survey (Hart and others, 2007). Ontology for dataset integration has been researched in The Netherlands (Uitermark, 2001). Ontologies automatically derived from cartographic databases have been used for knowledge discoveries by mapping (Gómez-Pérez and others, 2008). Statements of scope are difficult for national topographic mapping programs to define because of the broad and flexible nature of topographic maps as base maps for multiple and diverse users and purposes. In contrast to complex abstractions regarding users and purposes, topographic themes and information are presented as concrete and relatively fixed features on the cartographic landscape. This contrast of abstraction and accuracy is possible because landscape and natural resource features are seen as independent entities separate from society. Environmental and natural resource concepts and scenarios are historical outcomes of technology, sociological practices, and their effects and reflect society as a critical part of how the world is conceived to be (Braun, 2006). The scope of ontology for *The National Map* is broadly defined as the social relation to science as reflected by the work of the USGS.

The National Map

The USGS is responsible for the primary national topographic mapping system for the United States. The national topographic mapping program was the primary data developer in the 20th century, but now accepts and integrates data from the best possible sources according to standards. Because data production and contribution to *The National Map* is uneven, areas lacking standardized data are filled with data developed by the USGS, which provides data integration and data sharing challenges in this task (Goodchild and others, 2007).

The scope of the data of *The National Map* originates in the criteria of inclusion in databases. The data are integrated into a framework of layers classified by thematic domains: hydrography, transportation, structures, government units, land use/land cover, elevation, names, and digital ortho-photo imagery. Of these, digital ortho-photo imagery is categorized to visualization, not the ontology. The base scale of data is 1:24,000. *The National Map* will incorporate best available data, but 21st-century standards are not in place. Although much of the mapping process reflects a process of landscape interpretation, the photogrammetric collection of features for topographic maps that dominated the 20th century implied the direct observation of landmarks and networks, depicting the environmental characteristics as independent and self-evident to the analyst, when in fact, cartographic themes were classified by color separation process of photo-reproduction technology. The arbitrary technical classifications of feature categories were reproduced by the early Digital Line Graph (DLG) data that were digitized or produced from scans of the color separates. This legacy is part of the need for a new ontological system.

USGS science is oriented by its relation to society. The mission statements of the disciplines are to provide scientific knowledge and technologies applied toward specific topics to customers to support decisions and actions.[3] USGS science is a product resulting from the physical, mental, and technological modes of its work as a Federal agency and its social relations with the public and partners. The National Hydrography Dataset (NHD), a thematic layer of *The National Map*, is an example of USGS science and society. The NHD is a set of digital spatial data with a data model that organizes features into layers: line, point, area, flow line, and water body. The dataset combines information about surface-water features, such as lakes, ponds, streams, rivers, springs and wells, with "reaches," a concept defined as a uniform surface of water crossing feature boundaries. Within the NHD, reaches provide the framework for linking water-related data to the NHD surface water drainage network. These linkages enable the analysis and display of these water-related data in upstream and downstream order. The design of the NHD enables U.S. Environmental Protection Agency pollution modeling.

The Best Practices data model for vector data is the current (2008) template for *The National Map*. In analogue topographic mapping, feature collection standards for security, hazards, or emergency response applications were sometimes established, but not graphically represented on the map or in the map legend. In the Best Practices data model, thematic layers for homeland security appear at a certain level of unclassified information. The Best Practices Data model was developed in partnership with Environmental Systems Research Institute (ESRI) in response to the content definition

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[3] Mission statements of the five USGS science areas are available at www.usgs.gov .

specifications from the Department of Homeland Security. The requirements were implemented into vector data themes of *The National Map* as Foundation and Operation data groups. Foundation data are base, reference data; operational data are organized by disaster management and are event-based. Although the data model was intended to encompass hazardous events, the Best Practices data model is not time-based, thus limiting the ontology roles and events that feature instances can assume. Features and events are recorded as feature type layers within themes, where selected feature instances are stored collectively as a single group.

Partnerships are a key component of *The National Map* and USGS science. The Federal Geographic Data Committee (FGDC) Framework standards were developed in partnership with multiple agencies for data publication on the National Spatial Data Infrastructure. FGDC partners address traditional topographic mapping domains, such as transportation, hydrography, government boundaries, geodetic control, and elevation. The role of the USGS to support national programs involves integration of Federal databases, such as the Homeland Security Infrastructure Program (HSIP), the U.S. Census Bureau, and the Hazards U.S. Multi-Hazard (HAZUS-MH) program of the Federal Emergency Management Agency (FEMA). The role of the USGS as the national repository of geospatial data, including state and local data, involves integrating those data, acquired through grants with local producers. The final feature catalogues for data integration with Federal and local partners are not completed; it is expected that feature lists will be fluid, reflecting regional and national interests because of the contributions of local data producers.

Approach

Topographic mapping accommodates users of a wide range of semantic domains. Among these are topographic landforms and land cover, historical geography and geographic temporal change, economic and infrastructure development and resource use, and cultural, social, and symbolic landscapes. The conceptual model of the ontology (fig. 1) shows the main parts of the system—the ontology interface, the gazetteer, and the database—and their interrelations structured as feature types, properties, and

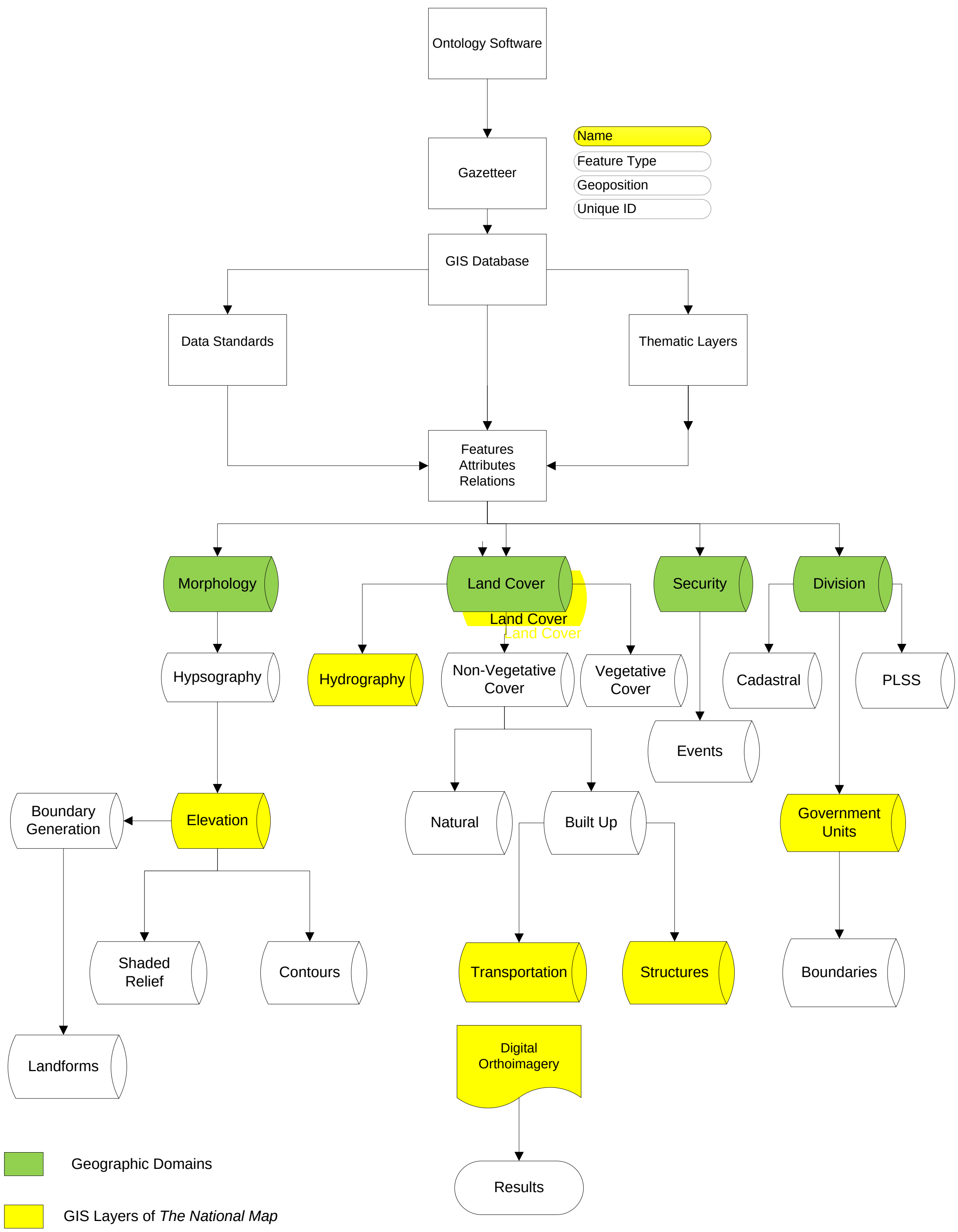

Figure 1. Conceptual model of ontology for *The National Map*

relations. These parts of the ontology, and elements such as geographic terms and statement syntax, will be described in the next sections.

Conceptual Model of Ontology for The National Map

The conceptual model of ontology in support of *The National Map* is composed primarily of three levels; ontology related software, a gazetteer, and the feature database. The USGS Geographic Names Information System (GNIS) gazetteer mediates between a name query and its associated feature type and geographic coordinates. A hierarchy of domains, classes, and subclasses of features fall within the database. The user domains of the *The National Map* focus on earth processes and land cover, political and land management divisions, and hazard and security events. Varying levels of subclasses fall within these domains. The ontology interface structures the relations between feature classes, properties, and relations. From these, statements are composed of subjects, predicates, and objects. The model is arranged in the order that a query would be processed, from top to bottom, from ontology to visualization of results.

The transition of national topographic mapping from paper maps to digital databases created a dialectics of cartographic vs. geographic data. Geographical ontology classes in figure 1 are colored to distinguish their equivalency compared to those named in *The National Map,* which occur in a roughly vertical order. Though roughly distributed across subject domains, the GIS layers for cartographic representation and geographic modeling categorizations are mismatched at finer granularities of categorizations. This may be explained by visual logic of cartographic hierarchy rather than logic of physical science. Similar distinctions between the cartographic and geographic representations of earth processes appear in discussions of such concepts as cartographic vs. operational scale (Lam and others, 2005) and Digital Landscape Models vs. Digital Cartographic Models (Brassel and Weibel, 1988). The cartographic abstraction process has been defined as a transformation from real-world features to cartographic features from observation and experience. To model landscape processes, cartographic abstraction is expanded with physical and ecological knowledge to simulate non-visual spatial transformations. This process is enabled with ontology, which structures features (data) and science (information) (Buckley and others, 2005). The role of ontology is to relate features as expressions of processes.

Terms

A central concept of geospatial ontology is the articulation of features and relations between them. These feature and relation structures are based on complex assemblages of linguistic and cognitive signs arranged in semantic, syntactic, and lexical meanings. The large number of American dialects, borrowings from foreign languages, and ways that technology mediates our conceptualizations about the world create significant levels of semantic ambiguities, both linguistically and with regard to feature classification. An ontology explicitly defines a range of hierarchical and topological relations by identifying and linking definitions, synonyms, and other properties of meaning.

The formation of topographic narrative structures in ontology-driven GIS database involves multiple levels. The basic geographical concepts of the ontology framework are feature terms taken from the extensive history of domestic cartographic map production, the “once-over” (once over the nation) and combined field and air-based mapping from the late 19th through the late 20th centuries. A type of topographical feature ontology, in changing form with time, was developed cognitively through the process of cartographic abstraction during these 100 years of experience (Usery, 1993). Although they were not designed for accomplishing ontology-driven GIS (ODGIS), the existing feature catalogues and data models are compatible to an undefined and unarticulated cognitive ontology that is a crucial stage before implementation (Fonseca and others, 2002). Although *The National Map* involves more than the legacy data from 20th-century topographic mapping, this project is limited in scope to this set to minimize additional ambiguity.

To interpret national topographic mapping within our approach to ontology, five USGS supported feature data catalogues for national applications were reviewed and compared to help establish the desired ontological criteria for *The National Map*. Five USGS-related projects addressed feature lists; the Committee Investigating Cartographic Entities, Definitions, and Standards (CICAEDAS) of the enhanced Digital Line Graph data (DLG-E), completed in 1988 (Guptil and others, 1990); the feature-based Digital Line Graph data (DLG-F), (USGS, 1996, 2003); Spatial Data Transfer Standard (SDTS) (ANSI/NIST, 1997), Federal Geographic Data Committee (FGDC) Framework Standards (ANSI INCITS, 2006), and Best Practices Data Model of *The National Map* (USGS, 2008).

A trend toward institutional centralization and digital application of domestic national topographic mapping of the United States in the late 20th and early 21st centuries has resulted in greater ambiguity of semantic meanings of landscape feature terms. When maps formerly were produced regionally, the feature types and names were generic, common-use words. Some terms refer to entities in more than one domain, such as "bridge," which refers to a geomorphological landform and to a man-made structure. Though some features are recognized to have more than one meaning or application, evidenced by their appearance in more than one thematic group, feature lists of the past were largely prescriptive, allowing little or no negotiations based on varying local knowledge claims or user meaning. Ambiguity was eliminated by providing singular, narrow definitions and no presentation of alternative contexts or process modeling.

When integrated into a central national database, feature types often assumed terms as parts of the geographic data model. For example, what was a "road" on topographical maps can be called a "road segment" in later, topographical mapping standards and data models such as the FGDC Framework. These are treated as objects to be written into Unified Modeling Language (UML). The specific road was identifiable indirectly through attributes, but this trend served to make ambiguous the meaning of the geographic feature. For example, a feature called "hazardous waste dump" is semantically more specific than a data model layer called "hazard point." The consequences of reproducing data model relations, rather than geographic features, are that they obscure and dominate environmental relations, and reproduced relations will be limited to spatial relations.

Statement Syntax in the Gazeteer and Ontology

Key concepts and features of a subject domain and the relations between them form the core knowledge statement. For example, 'fence' and 'parcels' are key objects in a core concept that "A fence divides adjacent parcels." The range of available features, domains, and statement structures in the ontology will define the range of query possibilities. Formal syntax structuring enables natural language queries and user interaction. Relations between objects create types and rules of structures for coded applications.

Concept conditions and knowledge statements form the basis for user queries on the data. Since most queries involve geographic names, the Geographic Names Report, which formed the basis for the U.S. Geographic Names Information System, provides basic statements regarding named features. The Geographic Names Report that the U.S. Geological Survey used during 20th-century mapping followed a common format. For example,

> … where appropriate, give shape, length, width, direction of flow or trend, direction and distance of extremities from points with established names, and section, township, range, meridian where useful, also elevation if known.

A passage from the Geographical Names Report for New York Mills quadrangle in Minnesota collected data in this format as follows:

> Bluff Creek is a stream about 10 miles long heading in [sec./twp./range] flowing generally southeast to the Leaf River in [sec./twp./range] about 5 miles southeast of Bluffington (R.R. Barrett, USGS, written commun. 1969).

The passage reduces to

[name] [predicate] [subject] [modifier_length] [start_location] [event] [direction] [junction] [end_location] [proximity]

In this example, the description of Bluff Creek has a structure of name, subject, modifier, location, event, direction, and proximity. To query the data, we convert the syntax of the description to

What is Bluff Creek? What is [name] Bluff Creek is a stream.

Where is Bluff Creek? [start-location] [event-direction] [end-location][proximity]

Headed in [sec./twp./range] Bluff Creek flows generally SE to the Leaf River in [sec./twp./range] about 5 miles southeast of Bluffington.

To broaden the range of narrative structures supported by *The National Map*, analysis of feature types and syntactic structures is sought in various narrative forms. Sources of narrative forms relating to topography include:

- Feature definitions, domain expertise, and content analysis of scientific texts;

- Cartographic map production: surveys, instructions, memos, and compilation;
- Volunteer information;
- Map reading events; and
- Surveys of user needs.

Historically, statement details were added via a narrative vehicle called 'memos' exchanged between field and national offices. Variations in mapping technique were negotiated and modified via memos issued from regional field mapping centers and testing of techniques was negotiated via memos. For example,

> To clarify any misunderstanding, the 1.5 meter contour to be added on all metric Great Lakes shoreline quads is the first regular contour [above the shoreline], not a contour 1.5 meters above the lake elevation (William Mengel, USGS, written commun., 1981).

Since our aim is to establish language-based topographic features relations in geospatial ontology to provide ideas of topography as sequential process and narrative that can restore individualized experience to the centralized nature of national digital databases, the ontology requires object-oriented data models, object-type attributes, and categories that lend themselves to multiple extents of geographical scale and granularity of information. National mapping database legacies have an implicit ontology that was implemented at the time of the database definition and design, but for an ODGIS, the results of this study indicate that feature lists and data models will need to capture more diverse and more complete multiple perspectives and more flexible assemblages in cognitive and logical frameworks. The working hypotheses are that

- we share a common-term vocabulary, but statements and queries are personalized,
- the tendency to move feature types to data model implementation may be narrowing our discourse about topography,
- regionalization is still implemented through partners.
- syntactic variance of query statements reflects the narrative of topographical experience,

Relations, modifiers, events, objects, and material composition can all be refined from concept statements. Attributes of the features include the unique identifier, the feature type, values and units of measurement for quantified data, name, alternate names, synonyms and antonyms, relations, objects, and complex functions. A list of relations is given in table 1. Cartographic and geographic categorization will depend on these feature qualities and relations.

Table 1. Set of relations for Ontology for *The National Map* (2008)

Connects to	Forms	Is mixed with
Connects with	Has	Is filled with
Consists of	Has a part	Is on
Contains	Has members	Near
Confined within	Has no	Over
Ends with	Is a	Starts at
Ends at	Is part of	Starts with
For [use]	Is a member of	Under
For [object]	Is in	Yields

Analysis

The conceptual flow path of implementation centers on the design of a data exchange knowledge base that mediates between the ontology software and USGS geodatabases to generate a pool of possibilities in response to a semantic query. The translation of that query extracts results from the geodatabase, and the results appear in a map engine (Wei and others, 2008). A user-based interface enables the entry of the query to *The National Map* system. In ontology-driven system design for "Ontology for *The National Map*", there are three critical components. One is the legacy data in database management systems. In our case, it includes the data from the Geographic Names Information System (GNIS) gazetteer, and other spatial and nonspatial data in the Best Practices data model. The GNIS, which is composed of a name, a feature type, and geographical coordinates, is linked to the database by the unique identifier of a feature. The second component is the ontology knowledge base, including the ontologies, mapping among them, and their connection with the legacy data. The last layer is the application layer, which tells the users how to use the other two components. For example, when a query is made using a name and feature type, the set of features with those attributes is returned with the support of the gazetteer.

The GNIS is an Oracle database; every feature has a name, a coordinate location, and a unique identifier. Feature class terms consist of nine or fewer letters originally defined for mainframe computer search and retrieval; all kinds of cultural and natural features are not defined. The terms generally are consistent with dictionary definitions, but represent more generalized categories. Commonly-used generic alternatives are listed in parentheses to assist in understanding the range of cultural and natural entities represented by the term. Every feature in the database is assigned to one feature class. GNIS enables queries of 'where is <name>?' and 'what is <name>?' and responds with segments of feature types and locations as relations such as 'is' or 'is_a.' Granularity of information increases with returns from the classes and subclasses of the ontology. The system searches the ontology for terms. Key prepositions in the triples indicate subclasses and slots.

Several areas of semantic research remain to be investigated for query analysis. Each query a user brings to the distributed character of the Internet-based national topographic map will involve data integration of features that exist in attribute tables under varying attribute heading names. "Cross walks" are the manual method of integrating semantically related features at this time. Semi-automated methods such as those present in extract, transform, and load (ELT) software such as Safe Software Feature Manipulation Engine (FME) assists this process. Our research aims toward the development of methods for testing measurement principles for semantic similarity of feature models of attribute headings and feature type terms as to the degree that topographic mapping categories differ from locally-based data categories (Schwering, 2008). Multiple semantic meanings could lead to the same feature instance, confirmed by returning the correct location on a graphical map. Each of the four subject domains and data layers that fall within the scope of *The National Map* has a corresponding complex data model that would require other methods aimed toward geometric, network, alignment, or transformation models.

The semantics of spatial relations are a particular problem in geo-spatial ontology research. The behavior of coordinate and topological relations are predictable in GIS, but relative locations such as “near” or temporally-sensitive relations of environmental processes such as “forms” or “yields” are much more difficult to model (Dolbear and others, 2007).

Feature categorizations depend on perspectives of space. Though they differ, categories and perspectives overlap. A specifically defined broader context of spatial perspectives and categories can identify the common elements of semantically differing data (Kokla and Kavouras, 2001). Measures of semantic contexts of *The National Map* terminology can provide enhanced query functionality by relating the perspective of the users and their likely categorizations. Research is planned for 2009 to apply this principle at the USGS for ontology (K. Clarke, written commun., 2008). Features with indeterminate boundaries carry semantic ambiguity in definition, name, and recognition. By relating landform features to elevation, a geographical or environmental context, the identification, extent, and naming of these features is defined despite linguistic or spatial perspective ambiguity.

The design of this application again favors topographic (cartographic) information. To interface the topographic ontology and the database of cartographic origin, additional layers are required for two purposes: model the user cognition of the real world, and map user cognition models to *The National Map* models.

Summary

The 'grammar' of the topographical mapping ontology is rooted in topographical narrative, meaning the ordering and sequence of geographical entities are as if encountered one after the other, as they would be by navigation over the land with time (Curry, 2006). Such narratives are common in literary sources, in way-finding, and in other forms of geographical description. To restore the narrative component of topographic mapping that Lukermann (1961) and Curry (2006) write about, definitions were composed and concept conditions were identified. For example, a statement such as "A stream is a body of water, with a current, confined within a bed and stream-banks" carries relations, objects, and conditions such as "… is a …body of water" or "… has a…current source, and mouth" and "… is… confined within a bed and stream-banks." Relations identified from the glossary of feature definitions become object-type attributes and together with classification hierarchy, form the basis for topographic narrative syntax. A broad range of vocabulary, syntax, and semantics is required to reflect the diversity of man-land relations between the U.S. public.

The system being designed for the ontology consists of the interface, the gazetteer, and the databases. Only legacy databases are analyzed at this time to contain uncertainty until better uncertainty techniques are implemented. Several areas of research remain for investigation, particularly how properties of the ontology semantics, categories, and spatial relations can enhance query analysis.

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