

An Object Model for Geologic Map Information

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Abstract

National geologic map databases are presently being constructed in the U.S. and Canada, as well as in several other countries. Here, we describe an object-based model for geologic map information, specifically designed to represent digital geologic maps and related geoscientific information. Although oriented to geoscience, several fundamental issues in representing geospatial information are explored in this design, including the philosophic and cognitive basis of mapping in general, and the overall framework in which map-related information can be represented. Thus, we take an ontologic approach to geospatial representation, supplemented by an epistemic view of the scientific process, which culminates in a very general model—a meta-model—for map information. Practical as well as theoretical considerations motivate this approach. Primarily, however, we describe the theoretical foundations of our meta-model, specifically semiotics, category theory, and ontology in geospatial information. Finally, we report briefly on a specific prototype data model derived from the meta-model and implemented in a commercial object-oriented GIS.

Keywords: geologic map information, data models, ontology, classification.

1 Introduction

The public agencies that provide geologic maps and related information in the U.S. and Canada are just now beginning to actively develop on-line systems for their work. These systems simultaneously address two basic needs: improving the efficiency of routine information handling within an agency, and promoting the non-traditional usage of geologic information within and outside the agency. Though conflicts in information policy do exist among agencies, the need to cater to on-line science is cautiously overriding such concerns as several multi-agency systems are emerging. In North America, for example, three major systems

exemplify this approach: (1) the Canadian Geoscience Knowledge Network (CGKN; <http://cgkn.net/>), a co-operative initiative to link the public geoscience data providers in Canada; (2) the U.S. National Geologic Map Database project (NGMDB; <http://ncgmp.usgs.gov/ngmdbproject/>), a Congressionally-mandated repository for map information from many state agencies as well as the USGS; and (3) GeoInformatics, a proposed network of U.S. academic geoscience databases (GEON; <http://www.geoinformaticsnetwork.org/>).

In this paper we discuss a project undertaken for NGMDB in particular¹: an object-based geologic map information meta-model derived from the North American Digital Geologic Map Data Model standards effort (NADM; Johnson *et al.*, 1999; <http://geology.usgs.gov/dm/>). The design of our meta-model rests on two ambitious objectives regarding the underlying geospatial² map information:

1. To supplement *feature-based* geospatial information with *ontologic* context, explicitly represented; and further
2. To supplement the ontologic aspects of geospatial information with *epistemic* considerations, drawn from geoscience directly.

The first objective expresses our view that scientific meta-modelling, i.e. abstracting the many types of models within geoscience, is critical for the effective representation of geoscientific information (Bennet, 1997; Gahegan & Brodaric, 2002; Raper & Livingstone, 1995; Langley, 2000). Specifically, in our design we designate and encode four fundamental types of models, symbolic, conceptual, occurrence, and descriptive, that underpin the structure of geoscientific information and its visual presentation.

The second objective reinforces the point that our meta-modelling emphasis proceeds from epistemology, the fundamental knowledge acquisition and evaluation task (Clancey, 1993). In particular, geologists' evolution of environmental concepts from their interpretation of observed occurrences is often incremental, complex, uncertain and dynamic, and frequently results in multiple valid models for a geographic region (Brodaric & Gahegan, 2001). This behaviour contrasts with many non-scientific domains in which concept development is a minor component, and where indeed, concepts are often known *a priori* rather than dynamically obtained and revised, and where feature occurrences are distinct.

In general, ontologically-driven geospatial information frameworks are well suited to relatively fixed domains, for example in land cadastre, and urban utility networks. In these contexts, they serve to partition geospatial concepts into perspectives and to instantiate relatively certain and unambiguously described occurrences within them (e.g. Benslimane, 2000; Fonseca *et al.*, 2000). However, geospatial information frameworks for dynamic and exploratory work, in science particularly, also need to be epistemologically-driven to account for the creation

¹ Variants of this architecture are also being implemented within CGKN

² We use "geospatial" to subsume the terms "geographic", "geologic", and "geoscientific" uniformly

and evolution of concepts and occurrences, and to engage the uncertainties and ambiguities consequently introduced.

In this paper, we begin tackling the central representational issues inherent in geoscience by exploring the complex of relationships between concepts and occurrences, and by modelling them. This requires a general structure for modelling concepts and their relation to phenomena, which is a level of abstraction higher than traditional knowledge engineering approaches that directly model domain concepts rather than the structure organising them (Clancey, 1993). Thus, we arrive at a general object-based structure, a meta-model for geoscientific information that embeds very broad ontological and epistemological factors and can be refined into domain-specific data models. This design complements related work on geological maps that considers relational data model design (Baines & Giles, 1997; Johnson *et al.*, 1999), web-based and multi-media applications (Brodaric *et al.*, 1999; Heyn, *et al.*, 2000), geometric representations (Balovnev, *et al.*, 1997), reasoning (Voisard, 1998; 1999), and cognition (Brodaric & Gahegan, 2001). It is novel in terms of (1) integrating aspects of cartographic presentation with concept development and information ontology into (2) an object-based meta-model for geologic map information.

The paper is organised as follows: Section 2 describes the meta-model developed; Section 3 describes a prototype implementation; Section 4 sketches future work; and Section 5 concludes with a short summary.

2 Theory and Design

Geologic maps depict geologic occurrences within a specific geographic region and spanning particular periods of geologic time. Typical maps are 2D, representing the intersection of 3D occurrences with a surface, usually the Earth's. These maps often represent a causal-process history that explains the evolution in time of the occurrences and their interactions. The history is typically located in accompanying texts and diagrams, and is supported by the occurrences themselves. Not all occurrences, or their parts, can be directly observed or measured, as some are historical and others inaccessible mainly due to sampling constraints, causing them to be inferred. Even observables can be variously described and identified according to the specific expertise of different investigators. Reasoning is thus affected by the amount and type of evidence, by the known theory, by the physical situation, and by the mapper's cognitive orientation. Geologic map representations are thus *meta*-models of geologic space-time-process models, including observed and inferred occurrences, their causal history, contexts and other factors impacting reasoning (Voisard, 1998; 1999).

In this section we describe our meta-model and indicate how individual geologic map reference models can be derived from it. To attain generality we ground the meta-model in semiotics, category theory, and geospatial information ontology.

2.1 Semiotics

Semiotics, the study of signs (Noth, 1990), provides a useful initial framework for representing a scientific view of a geologic map. In cartographic semiotics the meaning of a map symbol derives from the relationship held between the symbol, the concept being symbolised per some interpreting agent, and the occurrence being referred to (MacEachren, 1995). We implement these semiotic primitives as foundational objects in our meta-model (Fig. 1):

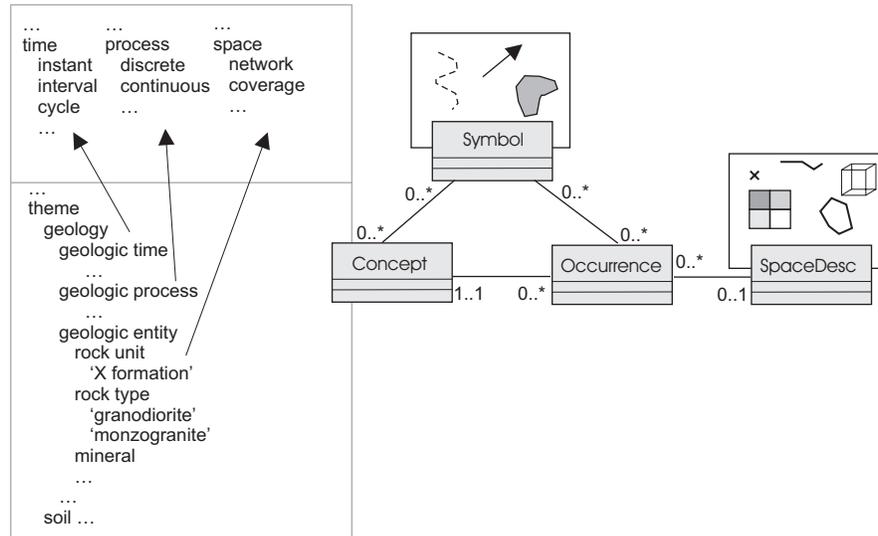


Fig. 1. The semiotic triangle is shown using UML notation (Rumbaugh *et al.*, 1999); some relations for concept, symbol and occurrence primitives are not depicted. Insets show example instances of spatial descriptions (geometry; right), symbols (top) and concepts (left); indents and arrows denote concept specialisation.

1. **Concept:** refers to the *abstract* objects that constitute geoscientific vocabulary; these can instantiate specific occurrences (below) and relations, and serve as values for attribute domains: e.g. “X formation”, “granodiorite”, “fault”, “intrudes”, etc. Concepts may tier from very general and perhaps universal, such as Aristotle’s “substance” (Sowa, 2000, 57), through generic, such as “space”, “time”, “process”, among other aspects, to particular (Guarino, 1998), such as those for a specific discipline, theory or even a geographic region.
2. **Occurrence:** refers to the *tangible* object observable in the field and/or on maps (geospatial features), and their relations in space, time, and otherwise. Note that an occurrence is an instance of exactly one concept and optionally possesses one spatial description, its geometry. Thus, a geospatial feature possessing constant identity might be represented by several distinct occurrences distinguished by conceptual, spatial, temporal or other variation. Though this

notion of geospatial feature is implicit and not explicitly modelled, the meta-model does allow multiple concepts to be applied to the same spatial object.

3. Symbol: refers to the (*carto*)*graphic* objects in the visual display, presented as areas, line and point markers, charts, tables, and so on. Independent treatment of symbols enables cartographic behaviour related to scale dependencies, symbol overlap, etc., to be associated with both concepts and occurrences. This permits the establishment of cartographic norms via concept symbolisation, and allows for cartographic exceptions in specific occurrences; e.g. though the default designation for all occurrences of the 'X formation' concept is blue, a particular pluton occurrence might be showcased in red.

2.2 Category Theory

The human interpretative process involves categorisation where concepts and occurrences (Fig. 1) are obtained in parallel and mutually affective. The meaning of concepts is thought to become increasingly contextual in lower conceptual tiers, affected by epistemological factors such as methodologies, actions, physical situations, and other factors related to how humans categorise, construct/recognise concepts (Smith & Mark, 2001; Frank, 2001). This insight would seem to hold for geologic mapping, suggesting more complex relations between concepts and occurrences than typically modelled in databases (Baker, 1999; Brodaric & Gahegan, 2001; Dehn *et al.*, 2001).

Specifically, in the mapping process, occurrences interact with concepts in two ways: as *instances* of established concepts, such as various map polygons labelled according to a geoscientific concept, e.g. 'X formation'; and also as *evidence* leading to the development of these concepts, such as the field observations employed in determining 'X formation' (Fig. 2). In information science these interactions are typically referred to as instantiation and classification, respectively. Instances are unique identifications, whereas classifications are prototypical statements based on evidence of varying typicality in which concept meaning is closely related to either (1) an average summary of evidence, or (2) an ideal description (Lynch *et al.*, 2000), viz. a 'type locality' in geologic parlance.

Thus, occurrences are distinguished by their role as instance or evidence in relation to concepts. Identifying and modelling these roles (Fig. 2) then permits them to be described so that, for example, human or machine classification methods can attribute evidence, increasing the context explicitly modelled in the database.

A consequence of varying typicality of evidence is that evidence descriptions, consisting both of structure, such as attributes and behaviour signatures, and of content, such as attribute values and behaviour functions, will be variously similar to concept descriptions. In particular, concept descriptions will vary dramatically with descriptions for outlying evidence, but concepts will share descriptions with ideal evidence. Descriptions may also be shared between occurrences, as understandings converge within and between individual mappers in a specific mapped area (Brodaric & Gahegan, 2001). The meta-model therefore possesses a

free-standing data store for descriptions (Fig. 2), enabling them to be shared among and between concepts and occurrences. For example, in Fig. 2 the concept 'X formation' shares a 'granodiorite' rock type description with ideal evidence at a site; however, a single polygonal instance of the 'X formation' concept is described by 'monzogranite' instead.

Thus, descriptions are the central information repository in the meta-model, containing the bulk of traditional data and information. Descriptions may be subclassed and also inter-related among themselves, as needed (not depicted in Fig. 2). The remainder of the meta-model can be seen as a knowledge superstructure adding conceptual, cartographic and occurrence-driven context to the descriptions. Loading specific concepts and description types into the meta-model can generate reference models.

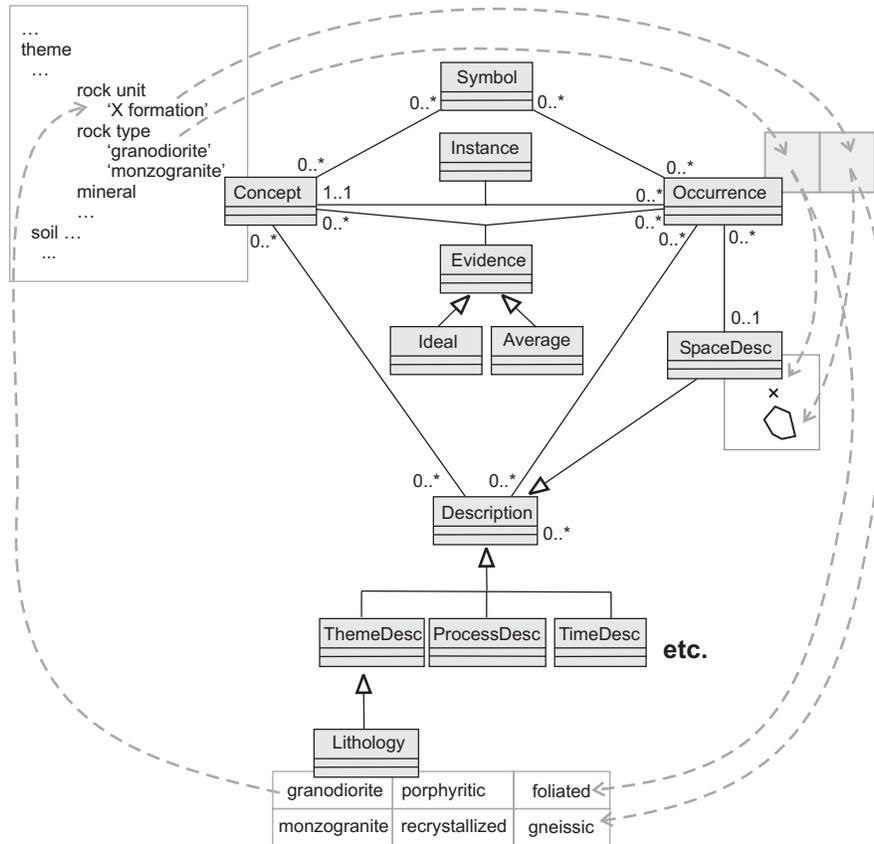


Fig. 2. Insets show example instances of concepts (left) and occurrences (right), with spatial (right) and thematic (bottom) descriptions. The dashed lines illustrate concepts evolving from evidence. See text for details.

2.3 Information Ontology

The knowledge structure described above emphasises the relationships among and between symbols, concepts, occurrences, and descriptions. Specific knowledge representations can be achieved by grouping these primitives into arrangements, called models. We designate four types of models, conceptual, occurrence, cartographic and descriptive, and denote legends and maps as combinations of these basic types.

In information science, conceptual models are formally known as *ontologies* (Guarino, 1998). In the practice of geoscience these are commonly expressed as vocabularies, taxonomies, or classification schemes, such as those for geologic time (e.g. “Precambrian”), rock units (e.g. “X formation ”), rock types (e.g. “granodiorite”), or as more complex models such as those for petrography, stratigraphy, genesis, among others. (Heyn, *et al.*, 2000). By extension, we consider occurrence models as part of *epistemologies*, formalising how we know/evaluate geologic realities (Raper, 1999). Epistemologies and ontologies are fundamentally linked: an ontology provides a set of concepts and logic for how occurrences might be arranged in space and time, such as typically described in a map legend and in accompanying notes. Epistemology, however, provides a specific arrangement of geologic occurrences and their causal explanations emplaced in space and time, thus demonstrating on the map the validity of the concepts and related logic. A map in which the conceptual and occurrence models are inter-consistent is deemed to ‘work’, expressing this connection.

Ontologies (conceptual models) are represented in the meta-model as logically consistent collections of concepts, their relations, descriptions, and evidence (Fig. 3). Similarly, epistemologies (occurrence models) bind together logically consistent occurrences, their relations, descriptions and instances.

Conceptual models enable concepts to be bound in different arrangements, thereby providing various conceptual perspectives on, say, a single occurrence model (Fonseca, *et al.*, 2000). Likewise, multiple occurrence models can derive from a single conceptual model, recognising that, for example, a common taxonomy may lead to different maps for the same area.

The meta-model also accommodates *cartographic* models for symbols and *descriptive* models for descriptions. For example, a palette is a model of symbols from a specific symbol library or agency-approved cartographic standard. A geospatial model formalises the spatial descriptions and relations (geometry and topology) that denotes a dataset/layer in a GIS.

A map legend may then be thought of as a symbolised conceptual model devoid of occurrences. Applying a legend to a valid set of occurrences enables their instantiation, classification and visualisation; furthermore, applying an alternate legend to the same set of occurrences effectively generates a re-conceptualised (derivative) visualisation for the area.

In conclusion, we define a geologic map view as a complex model consisting of a legend (symbolised perspective) manifesting a conceptual model (ontology) that in turn exemplifies an occurrence model (epistemology) for the region of interest.

This map view draws objects from one or more geospatial models (GIS layers), and/or utilises descriptions from some aspatial models (attribute databases).

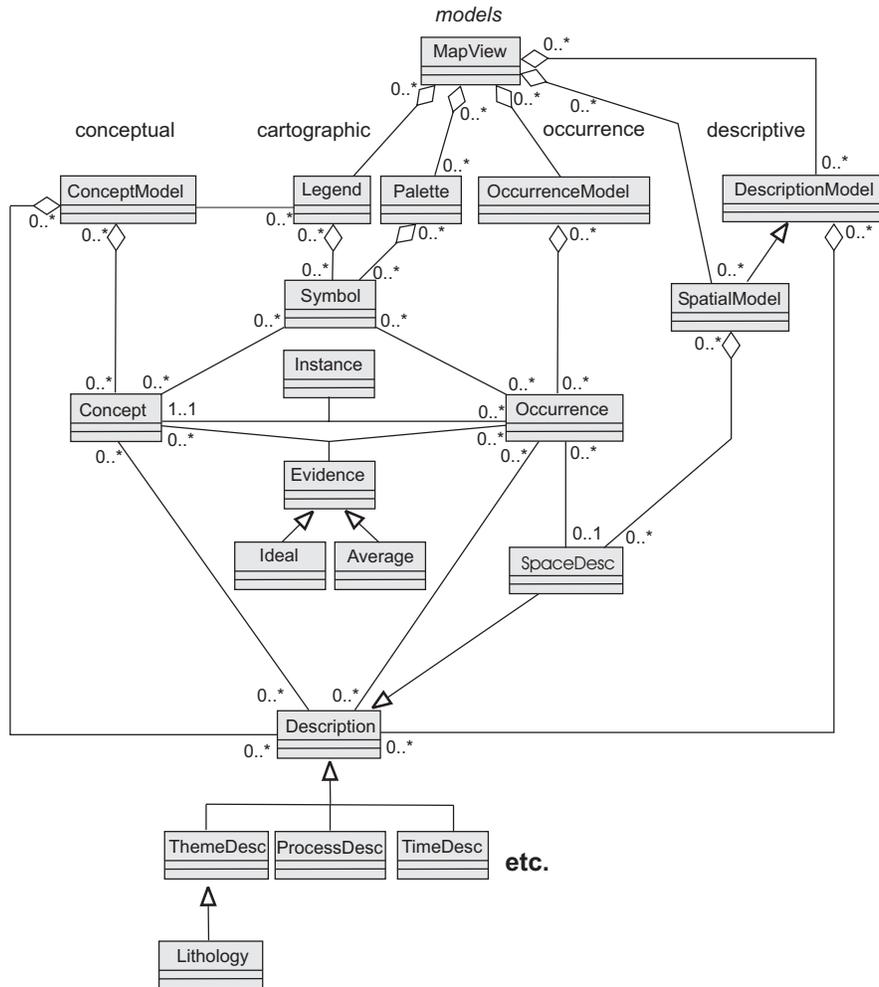


Fig. 3. The definition of a map in the meta-model. See text for details. Note, for reasons of clarity and space some details are omitted

3 Implementation

Testing of the meta-model is proceeding on several fronts: within NGMDB (Hastings & Brodaric, 2001), in a web-based geologic map database project (Davenport *et al.*, 2001) and in a prototype digital library for sustainable development (Journey, *et al.*, 2000). Testing within NGMDB has thus far concentrated on evaluating (1) the suitability of the meta-model to geological data

and (2) the ease of execution of some common operations, putting aside for the moment issues of efficiency and scalability.

The NGMDB test data consisted of four 1:24K geologic maps provided by the Kentucky Geological Survey (KGS), who collaborated with the USGS and GE Smallworld™ (GESW) for the evaluation. As a preparatory step, the meta-model was configured to suit the maps: concepts and description types were specified for the geologic formations, faulted structures, and coal beds, found in the region. Once configured, the meta-model was implemented virtually ‘as is’ inside GESW’s case tool, requiring only minor custom programming to implement specialisation relations such as those between the description object and its subclasses (Fig. 3). Custom methods were also added to some meta-model objects to achieve the desired mapping functionality (see below). Testing involved loading data and performing some typical visualisation and analysis operations.

3.1 Loading Data

The Kentucky data were supplied in ESRI “shapefile” and MS Excel spreadsheet formats. Populating the data-model with map information involved disaggregating this “legacy” feature-based structure—thematically distinct layers of geospatial features each with spatial, symbol, and descriptive attributes, as well as external database links—and re-organising it into conceptual, occurrence, symbol and descriptive models. It also involved unifying related information scattered amongst disparate data sources, such as externally held stratigraphic lexicons. Concepts embedded in feature attribute values, theme labels and external sources were collected and organised into conceptual models for rock units (Table 1), rock types, and minerals. The symbol attributes of features were collected and organised into a single cartographic palette. The spatial attributes of features from all maps became distinct GESW native spatial objects that comprised a single spatial model. The descriptive attributes became descriptions in a single descriptive model; and the external database links, which inherited GESW’s external data access methods, became descriptions in a description model for each external source. This transformation resulted in a dataset that was on the one hand more normalised, as concept, symbol, and attribute descriptions were not replicated for features, and on the other hand more integrated, as some scattered data were unified and previously external data links were directly embedded.

Table 1. Developing conceptual models. Some rock unit concepts and relations intended for input to the database are listed in this table

...
Stearns coal zone	Contains	Beaver Creek coal horizon
Stearns coal zone	Contains	Stearns No. 2 coal horizon
Breathitt Group	Contains	Princess Formation
Breathitt Group	Contains	Grundy Formation
Breathitt Group	Contains	Alvy Creek Formation
Grundy Formation	Contains	Corbin Sandstone Member
Alvy Creek Form.	Contains	Livingston Conglomerate
...

3.2 Visualization

The map view as defined by the meta-model above provides sufficient structure for performing map-based visualisation from a geospatial database. We tested this structure under three visualisation scenarios: (1) direct display of a stored map; (2) re-display based on reclassification of existing spatial objects; and (3) dynamic symbolisation of concepts and occurrences at multiple scales.

Display: a **mapview→display** method was added for displaying a map's occurrence model from the database (Fig. 4, left). This method also activates various model information, so that, for example, querying a spatial object returns only those concepts, descriptions, and symbols belonging to the map view.

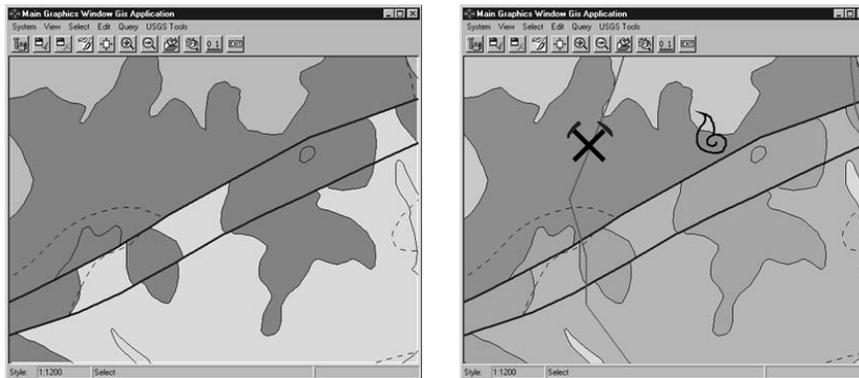


Fig. 4. Displaying and generating maps using the meta-model and test data; rock unit occurrences (left) are dynamically reclassified into their dominant rock types (right)

Reclassification: a **mapview→reclass** method was added for re-conceptualising a map, i.e. deriving a new map view from the active one. In this method, concepts and spatial objects from the active map view are retained, whereas additional occurrences and symbols are created or activated; models for all these are then built for the new map view. Fig. 4 shows rock unit occurrences

(left) and a derived map view displaying their dominant rock types (right) dynamically derived from associated rock unit concept descriptions.

Symbolization: an **occurrence**→**display** method was added for dynamically displaying an occurrence. Display happens when a scale-appropriate symbol is found, first for the occurrence, or second for its associated concept. This allows for default and unique occurrence appearance, and it enables both appearance and presence to vary dynamically by scale, such as when zooming.

3.3 Analysis

A simple network analysis was performed in which dominant rock type occurrences derived from the input geologic maps (see above) were evaluated in terms of their downstream proximity to pollutant discharge and their resultant material susceptibility to contamination. Stream and digital elevation model information, organised as simple features with attributes, was used in conjunction with the model-based information held in the meta-model. The resulting map high-lighted several potential contamination sources.

Beyond its scientific application, this analysis exercise has practical importance. It demonstrates the meta-model can interact with common data sources in typical GIS environments where objects are associated primarily in terms of spatial relations, with little regard for the knowledge and highly semantic relations inherent in geoscience and maintained by the meta-model.

4 Future Work

Results from the Kentucky prototype and other implementations indicate the meta-model provides a normalised and integrative environment for organising and manipulating geoscientific map information. Several aspects require further testing and development; these remain to be explored in future work:

- (1) scalability and efficiency of the design with respect to increased data volume;
- (2) multi-map, multi-resolution, multi-ontology environments;
- (3) modelling geoscientific explanations (Voisard, 1998; 1999);
- (4) modelling and implementing process and simulation models;
- (5) using the meta-model as a mediator for interoperability;
- (6) mapping to existing geospatial standards;
- (7) guidelines for incorporating geological phenomena; and
- (8) developing an ontology for geologic mapping.

5 Conclusions

Developing broadly applicable standards for geologic map information is critical to improving the overall usability of such information within the geosciences and beyond. We believe that attaining such agreement depends on: (1) embracing a very general meta-model; and (2) deriving specific, but adaptable, data models from this meta-model. Here we have described one such meta-model design and briefly demonstrated a model implementation from it.

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