Planetary Geologic Mapping: Initial Thoughts on an Ontology Framework

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Abstract. This work is intended to provide initial considerations on building a domain ontology in the field of planetary geologic mapping and cartographic representation. It introduces formal aspects of a higher-level planetary geologic map data ontology using an OWL-based taxonomic description of objects and object properties. It is intended as a first step towards providing a common knowledge framework covering vocabularies, semantic classifications, interdependences in order to (a) build a common understanding of what planetary mappers perceive when mapping different planets and to (b) build and infer objects, properties and constraints. By establishing a focused formalism through a domain ontology, a targeted knowledge representation is created which provides means to extract and distribute information from the planetary mapping domain and allows to consistently merge map-data information retrieved from dispersed sources. Such an ontology therefore represents all knowledge aspects when dealing with planetary geologic mapping and helps to define (a) the nature and (b) the special purpose of planetary mapping in the context of geological mapping sensu lato.

Keywords: Ontology, Mapping Data Model, Planetary Mapping and Cartography, Geologic Mapping

1. Introduction

1.1. Background and Aims

Data models, hereafter termed software data models, used in geographic information systems (GIS) are usually designed to streamline processes, to
define data relationships, to formulate constraints for maintaining data integrity and consistency, and, in particular, for allowing an efficient work process. Software data models therefore represent the upper-most layer of a stack of abstraction layers of a common scientific worldview (see Raper 2005). The technically-oriented software data model builds upon a representation of relations, relationships and integrity constraints from the data viewpoint. Only during normalization, relational attributes are grouped and thematically related in order to establish a consistent data view. The software data model, however, does not allow to model and infer relationships on the semantical level and provides little means to maintain, extract and organize actual knowledge or to make to inferences based on initially defined classes and properties. To accomplish this, ontological models have been revived in recent years and as response to developments in the Web 2.0 era. The ontological framework forms one of the first worldview layers in which objects have been structured, organized and related to other objects in such a way that higher level inferences allow extraction of new information about a domain of interest and its objects.

Van Gasselt & Nass (2011a) in a special volume on planetary mapping described a mapping data model which followed a number of aims, covering (a) overarching workflows between various actors in the field of planetary mapping (so-called use-case scenarios), (b) organization of entities and map-data objects and their relationships and integrity rules, and (c) aspects of model and data exchange between organizations in order to facilitate and streamline integration of different map products and sharing data. This data-only model has been conceptually designed in response to a considerable increase of cartographic products created by different researchers who use state-of-the-art GIS technology to map and design maps but without having in-depth insights into cartography and communication through maps (for a discussion, see Kraak 2010). The model has also been created to find a solution for integrating planetary maps from a variety of sources within an overarching data model. This also includes finding a possibility to cope with non-standard demands that have historically been cultivated in the field of planetary geological mapping (cf. section 1.1).

In order to define planetary geologic mapping objects and their relationships within their specific (mapping) domain, we here focus on the formal description of planetary geologic mapping. Inherent information on geologic units, materials and geologic timing can be semantically related to each other by defining a common ontological vocabulary, taxonomy and relationships. While a formal attempt for establishing a joint vocabulary in geological sciences and geological data description has been started within the GeoSciML initiative its focus is not primarily put on map unit descriptions (Sen & Duffy 2005). Its formal hierarchical description, however, is built
Figure 1. Example of a lunar geologic map, part of the Geologic Map of the Moon, I-705 (LAC-26) Eudoxus Quadrangle, 1:1 M by David H. Scott (1972), USGS. Color-coded map units are associated with a legend describing materials and timing of events.

on a larger domain ontology and provides formal descriptions and vocabularies. The level of granularity is much higher due to the complexity and huge amount of different data and methods applied in the field of (terrestrial) geologic sciences, including mapping. However, planetary mapping is not a simple subset of terrestrial geologic mapping due to the fact that (a) partly different methods are applied (see sect. 1.2) and (b) a variety of different objects are mapped. In the case of planetary geologic mapping, it seems appropriate to first build a common higher-level ontological framework which is then critically compared to existing approaches designed by terrestrial initiatives.

1.2. Geologic Maps vs. Planetary Geologic Maps

Classical geologic mapping and geologic-map cartography have a long history dating back to somewhere in the middle of the 17th century when N. Steno formulated his main axioms about the relationship of geologic layers and their relative timing (Steno, 1916). Over a hundred years later, in 1815, the first national geologic map covering major parts of Great Britain was
crafted and published by W. Smith. Since then, national programs have led to systematic geologic mapping and the production of hundreds of thousands of geologic maps at various scales. In the 1960s space born exploration of the solar system heralded the start of planetary mapping programs coordinated by US and USSR authorities. Apart from photomosaics and topographic maps, geologic maps were among the first scientific products based on image interpretation that were put into a cartographic framework. Geologic maps are special-purpose maps that condense four-dimensional information on a two-dimensional sheet of paper. The third dimension is usually re-constructed using height information from topography data by means of isohypses and the superimposed information of the extent of geologic materials. This property is an essential asset of a geologic-map but it has received only little attention in modern planetary geologic mapping. Along with Steno’s axiom on the principles of superposition and its derivatives, a relative timing can be reconstructed from simple geometric methods. In order to communicate time more directly and also to provide information about absolute geologic time, the fourth dimension is symbolized using an accompanying legend that relates color codes of geologic units to an overarching time frame (see Figure 1).

In summary, (1) map units with signatures and color codes relate geologic materials to (2) time and the combination of contour lines and material units provide information about (3) the unit’s position in space. These three components are the main ingredients of conventional geologic maps. However, planetary geologic maps deviate from that scheme. First, contour lines are not always systematically employed in geologic maps, thus information on position in space and relative position in time is limited to non-existent. Much geologic information is lost in planetary geologic maps when compared to classic geologic maps due to the suppression of 3D information. Secondly, for historical reasons, units are not always described as (geologic) material units but as so-called geomorphic units which contain a description of a unit’s appearance (e.g., knobby, pitted, fretted) rather than its composition. The term geomorphic, however, is highly misleading as discussed later (see section 2.2).

Geologic timing is usually established through age determinations based on remote-sensing data. A method, which again, deviates from terrestrial geologic age dating techniques. As a consequence, the underlying ontological model of geologic mapping is different from the conventional view on geologic maps and does not only form a subset of a terrestrial ontological framework.

Despite the generally positive development of “democratization of mapping” (Mattmiller 2006, Smith 2010) a number of issues dealing with the
maintenance of cartographic quality have been raised and approaches in dealing with issues of Neocartography are being discussed (Kraak 2011). As for terrestrial cartography, the same problems apply for planetary mapping and cartography. Planetary cartography looks back on 50 years of modern “tradition” when the USGS Astrogeology branch was set up to define, organize and maintain planetary cartography in the context of the lunar exploration program. Today hundreds of high-quality maps of planetary bodies have been published by the USGS and new mapping programs have been set up to map (and remap) the Earth’s moon, Mars and Jovian Satellites. The general acceptance of geographic information systems as tools for spatial data analysis and cartography in the planetary domain in the early 2000s have lowered the entry threshold to integrating planetary data and mapping other objects in the solar system. Most products, however, have not been cartographically checked, standardized or corrected and remain unpublished. Despite a large planetary mapping community, little motivation is given for non-US researchers to craft planetary geologic maps due to a lack of organizational coordination. Outside the US, little effort has been spent on formalizing and defining GIS-based cartographic products and as a logical consequence, researchers and mappers make use of GIS-integrated tools on an intuitive basis to build maps that are neither controlled in terms of technical cartographic quality nor in terms of their inherent message and the way in which information is communicated.

While organizational coordination of such an international mapping program cannot be established spontaneously, work towards a common understanding and framework for planetary mapping could be a first step towards homogenization of mapping attempts collected from different institutes in Europe.

2. Planetary Map Unit Ontology

2.1. Methodology

To ensure that a geologic map of Saturn’s satellites is comparable to a map covering Mercury and to ensure that it is understood in Southern Europe in the same way it is read in Eastern Europe or elsewhere, the employed (higher-level) vocabulary and taxonomy must be the same for all map products. Once established, objects can be related to each other using pre-defined properties and it is possible to make new inferences.

The map-unit ontology is built as a low-level domain ontology. There is currently no formal approach in designing a domain ontology but it has been emphasized that the process is highly iterative (e.g., Smith, 2010). A num-
ber of methods have been established for creating ontologies and they usually consist of (a) a formal specification, (b) acquisition of knowledge, (c) conceptualization, (d) integration of pre-existing ontologies and vocabularies, (e) implementation, (f) evaluation, and (g) documentation. For a detailed treatment see Smith (2010) and references cited therein. For space reasons, we here focus on aspects of specification, in particular on the level of formality and some first-order competency questions. We here chose to build a formal domain ontology by addressing the following tasks:

- Definition of domain boundaries in order to limit the knowledge extent.
- Definition of a higher-level taxonomy within this domain.
- Definition of object properties.

First, we here describe the general taxonomy of classes (entities) and inheritances, followed by object properties. If the ontology is well-designed, it should provide answers to certain questions known as competency questions which are the actual motivation and validation scenario for the ontology. We here do not cover reasoning and inferences due to the ontology’s initial state. Some of the fundamental questions to be addressed by the ontology cover:

1. Which different characteristics of a map unit are necessary to define a planetary geologic map unit?
2. Which characteristics are sufficient to represent a planetary geologic map unit?
3. What is needed to transfer a FeatureUnit to a GeologicalUnit?
4. How do units of a given time-span on planet A correlate with units on moon B and C?
Figure 2. Simple taxonomic class display with basic properties. Classes are displayed as diamonds, properties are represented by lines with arrows.

2.2. Taxonomy and Object Properties

The GeoMapUnit forms the central class (see figure 2) of this approach and constitutes of three subclasses: a GeologicUnit which describes the well-defined geological unit in a conventional sense, a FeatureUnit which forms a unit described by non-genetic and non-material features, and a MorphologicUnit which is defined by its morphological expression and which is genetically related to the GeoUnit. These subclasses provide objects that have either geological properties (material, relative age, absolute age, associated stratigraphy, positional values, ...) or which only describe a feature or shape and appearance (coll. geomorphologic unit). The historically accepted term of a geomorphologic unit (in contrast to a geologic unit) is not well-chosen as it is intended to be used as a descriptive term. A geomorphologic unit, however, is more than just a description of shape and features as these already imply a set of potential forms of development, the unit has undergone. If a planetary map unit is described as, e.g., pitted terrain, nothing is usually said about its geologic composition nor its geomorphologic evolution. It is correctly suggested, that a unit consists of a geolog-
ic material deposited at a discrete time in which pits (as morphological expression) have been formed (at the same time or later during a non-distinct process). For this ontology, it is therefore suggested to differentiate between classical geological units (with associated materials and ages), superimposed morphologic units (with genetic implications) and miscellaneous (non-material) feature units carrying no genetic implications. Since feature units (F) can be transferred to geological units (G) and there exists an inverse property which allows to transfer G to F (G canBeTransferredToF), and since morphological units (M) are superimposed on geological units (M IsSuperimposedOn G), it must be inferred that morphological units are not only superimposed on G, but also on feature units (M IsSuperimposedOn F).

G carries most of the map unit contents along with a number of properties relating temporal and stratigraphical classes to G. G shows several special object properties: it is reflexive as G always isSuperimposedBy another G. Its inverse property is IsUnderlainBy which again must be reflexive. It is also inferred that each G which isUnderlainBy another G does so because this property is by definition transitive (see Figure 2).

Unfortunately, many planetary geologic maps (also official ones) do not differentiate between geologic material units and non-material units so that a homogenization of different maps using different sets of descriptive terms becomes complicated. This problem has not been addressed thus far and no attempt has been started yet to “translate” feature units to geologic units.

Object properties concerned with the stratigraphic system (formation, series, systems) and absolute chronologies (epochs, periods) are independent of each other initially. A unit has a well-defined age and it therefore belongs to a geologic time. Along with knowledge about the unit’s location and geologic material, a stratigraphic position is extracted. This must, axiomatically, be reflected in the unit’s chronological position in time. Therefore, chronological and stratigraphical classes support each other but they are not equivalent (see IsUnitOf property in Figure 2).

Despite different planetary chronological and stratigraphical schemes, properties between these classes remain the same for each planetary object that is mapped geologically. Consequently, such an ontology can easily be utilized within a different geological context. The stratigraphic record of each planetary object is characteristic of that object (hasRecord property).
3. Conclusions and Outlook

The presented ontology models forms a first outline of basic taxonomic levels describing planetary map units as part of cartographic products. Much work needs to be accomplished in order to distill a vocabulary allowing to investigate data and relationships and to integrate the map units’-based taxonomy into an overarching ontology framework. Such works will help to provide a semantic platform in which a variety of different geologic map products are to be integrated (e.g. Nass et al. 2013).

In geological sciences, formal geological ontologies have been established in recent years. These attempts build on models that were initiated at various organizations and institutes, mainly in the US (e.g. Johnson et al. 2008, GMDM 1999, NADM 2001, Bedford et al. 2003, Soller et al. 2002, Richard et al. 2003, Richard & Soller 2008). GeoSciML forms a hierarchical approach to establish a structured geologic vocabulary on which science applications can be built (Sen & Duffy 2005). Planetary geologic classes are not being dealt with in that approach but it seems feasible to identify a common nomenclature to either expand GeoSciML taking into account planetary aspects or to adopt the GeoSciML vocabulary for building a formal ontological description for planetary geology and planetary geologic cartography.

Time is the fundamental building block of geologic sciences which establishes a link between material units as depicted in a map sheet and the timing of their formation as depicted in chronostratigraphic relationships. Time and its various relative and absolute expressions are not fully covered in neither relational nor hierarchical data models. A considerable amount of additional work needs to be invested to allow answering a richer set of competency questions in an appropriate OWL-based ontology (see van Gasselt & Nass 2013 and references cited therein: Peuquet 2000, Raper 2005, Le & Usery 2009).

Formal map ontologies as initially designed by, e.g. Richard (2010) have not been created so far for planetary thematic cartography. Addressing this topic would solve issues related to cartographic design and quality control in a growing mapping environment where map products are usually created by non-cartographers. Furthermore, due to the highly diverse nature of planetary mapping in which not only map scales, projections and symbols but also individual reference body characteristics (geometry and inventory) play an important role, a formal map ontology would significantly improve establishing cross relationships between target bodies and their map entities.
References


