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# Implementation of cartographic symbols for planetary mapping in geographic information systems

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ABSTRACT

The steadily growing international interest in the exploration of planets in our Solar System and many advances in the development of space-sensor technology have led to the launch of a multitude of planetary missions to Mercury, Venus, the Earth's moon, Mars and various Outer-Solar System objects, such as the Jovian and Saturnian satellites. Camera instruments carried along on these missions image surfaces in different wavelength ranges and under different viewing angles, permitting additional data to be derived, such as spectral data or digital terrain models. Such data enable researchers to explore and investigate the development of planetary surfaces by analyzing and interpreting the inventory of surface units and structures. Results of such work are commonly abstracted and represented in thematic, mostly geological and geomorphological, maps. In order to facilitate efficient collaboration among different planetary research disciplines, mapping results need to be prepared, described, managed, archived, and visualized in a uniform way. These tasks have been increasingly carried out by means of computer-based geographic information systems (GIS or GI systems) which have come to be widely employed in the field of planetary research since the last two decades. In this paper we focus on the simplification of mapping processes, putting specific emphasis on a cartographically correct visualization of planetary mapping data using GIS-based environments. We present and discuss the implementation of a set of standardized cartographic symbols for planetary mapping based on the *Digital Cartographic Standard for Geologic Map Symbolization* as prepared by the United States Geological Survey (USGS) for the Federal Geographic Data Committee (FGDC). Furthermore, we discuss various options to integrate this symbol catalog into generic GI systems, and more specifically into the Environmental Systems Research Institute's (ESRI) ArcGIS environment, and focus on requirements for symbol definitions in the field of planetary mapping. A symbology of this type can be embedded into any modular GIS environment capable in dealing with external stand-alone as well as database-driven management of symbol sets. Using such a uniform GIS-based symbol catalog will give the research community access to map results already cartographically elaborated, enabling them to create digital maps as a secondary data source in subsequent studies.



## 1. Introduction and background

In the context of and in parallel to society's increased demand for up-to-date, promptly available data, the abstraction of information and the production of maps are undergoing continuous technological progress. Consequently, since the beginnings of the 1980s, hand crafted maps and analog cartography have been widely replaced by computerized and digital mapping (e.g., Olbrich et al., 2002; Cartwright et al., 1999). This change in the map-making process characterizes cartographic products in a variety of application fields.

This paper deals with the implementation of a standardized map symbology in the field of planetary mapping and discusses issues concerning the usability, management and portability of uniform symbols. To begin with, we give an overview of the cartographic visualization process, describe important aspects of cartographical concepts, and focus on developments in the fields of planetary research to highlight the resulting new requirements for planetary mapping. Secondly, we discuss the aims and motivation of this work illustrated by a workflow example of the geomorphological/geological mapping of a Martian region, highlighting important aspects of the underlying concept. The following sections outline the possibilities of generating symbolizations within the Environmental Systems Research Institute's

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(ESRI) ArcGIS environment, and discuss capabilities and requirements, that are especially relevant in the field of planetary mapping. The subsequent section deals with the technical realization of symbol sets and their implementation into an underlying geodatabase model (GDB). Finally, we conclude and evaluate the results and give a short outlook on subsequent work.

### 1.1. Developments in cartographic visualization

Spatial information is, as a rule, visualized using photographic and thematic maps (e.g., Batson, 1990; Gehrke et al., 2006). While photographic maps claim to be an accurate reproduction of the original settings, thematic maps portray their content in an abstract form while the topology of spatial units is maintained (e.g., Olbrich et al., 2002). A photographic base map serves as reference for general orientation and for the placement of topical information (Hake et al., 2002), while a thematic map focuses on the type or style of visualization and representation for each of the thematic layers. Thematic maps often use discrete measurement points and other details related to terrain characteristics as reference (Imhof, 1972). Thematic maps in geoscience (a) display geophysical and geological or geomorphological settings using static and dynamic object information, (b) are usually related to qualitative and quantitative data, and (c) are commonly prepared on a small to medium map scale (Hake et al., 2002).

With respect to the potential of cartographic visualization and the communication of complex information via the map designing, Bertin (1982) emphasized, it is obvious that a map should not have to be *read*, but one should be able to *see* it, i.e., the map should be understood simply by looking at it. To facilitate this, cartographers use a specific form of map symbolization as their key design elements. These symbols, each with a variety of options regarding denotation and application, represent in their entirety the relevant spatial information of a map. In particular, they consist of and depict geocoded information on any object itself and its known interrelationships with other objects (e.g., Hake et al., 2002; Kraak and Ormeling, 2003; Longley et al., 2005).

Display options range from abstract object pictograms and icons to conventional signs and are used to replace any underlying text. In contrast to map fonts and typographic elements, symbols occupy less space on the map, and act more directly on the imagination (Bertin, 1982). This explains the importance of employing signatures because since there is no general connection between a sign (syntax) and its conceptual meaning (semantics), the use of a system of symbol interpretation, i.e., a map legend, becomes indispensable.

In addition to requiring a map legend, symbol presentation is subject to predefined sets of rules and guidelines. These rules have been defined to ensure that the map content is correctly communicated between mapper/cartographer and map-reader. A classic example of such rules are the displacement guidelines for cartographic generalization. In order to (a) implement such rules and guidelines in a user-friendly way, (b) for a (technically) correct visualization, and (c) to ensure comparability between various map products (analog and digital domains), the most commonly used spatial objects are predefined by individual symbols. Summarized and described in various symbol models, they are made available to user groups in the form of recommendation documents, also known as standards (e.g., the *Digital Cartographic Standard for Geological Map Symbolization*, FGDC, 2006). Furthermore, in addition to general guidelines, complete mapping systems have been developed, outlining symbology recommendations for specific scientific topics (e.g., Barsch and Stäblein, 1978; Gustavsson et al., 2006). These documents describe and discuss which symbols should be used for a given spatial object within a specific domain and for a given map scale.

Once a mapping process has been finalized and its digital end product evaluated, the information may either be converted into analog products or stored for later use as a cartographic model. The choice of how to present individual pieces of information, however, depends on the intended purpose and the depth of any additional statistical data to be given, putting constraints on the software environment used for map preparation. Analog and digital map sheets, such as Internet presentations, are often created with the help of vector- and raster-based graphic software tools. They come with a variety of design options facilitating the processing, rendering, and communication of different map elements but they usually lack the ability to work with spatial reference systems and geocoded data. For increased efficiency when working within a common spatial domain and context, mappers/cartographers nowadays commonly use geographic information systems (GIS or GI systems). These software environments are based upon a spatial database management system and are used for capturing, managing, processing, analyzing, and presenting spatial data (e.g., Hake et al., 2002; Bonham-Carter, 2006; Davis, 2001; Longley et al., 2005).

### 1.2. Application in planetary mapping

The last decades have been marked by a steadily growing international interest in the exploration of the planets in our Solar System. Among other stimuli, it is in particular the rapid development in sensor technology that has led to numerous planetary mission endeavors. Instruments carried along on these missions image a planet's surface at different wavelength ranges by means of multispectral and hyperspectral sensors, allowing the derivation of new data. Results of geoscientific investigations are represented in thematic, mostly geoscientific maps and have helped to improve our understanding of surface processes and surface evolution on a local, regional and global scale (Tanaka et al., 2009; Batson, 1990; Wilhelms, 1990). These developments and processes are expected to initiate a significant increase in the production and use of highly specialized maps in the future (Shingareva et al., 1999). Geological and/or geomorphological maps of planetary surfaces, in particular those of the Moon, Mars and Venus, are systematically prepared in the framework of survey-coordinated and agency-funded scientific mapping projects. In the context of such programs, analog and digital map sheets, map series and catalogs have been published since the early 1960s (e.g., Lunar and Planetary Institute, 2009, 2006; Astrogeology Science Center, 2010). Other examples of work carried out without financial support from US agencies include photographic and topographic planetary maps, such as the *Topographic Image Map Mars 1:200,000 series* (Lehmann, 1996; Albertz et al., 2004), or the series of *Maps of the Icy Saturnian Satellites* (Roatsch et al., 2006). In the context of the *Series of Multilingual Maps for Terrestrial Planets and Their Moons* (e.g., Shingareva et al., 2005), a number of elaborate analog maps have been published since 1996 with the support of the Planetary Cartography Commission of the International Cartographic Association (ICA) (e.g., Buchroithner, 1999; Shingareva and Krasnopevtseva, 2001; Shingareva et al., 2002, 2003), which comprise both traditional and digital mapping techniques (Shingareva et al., 1999).

While the overall prerequisites regarding data integration, analysis and visualization from other planets are comparable to those of terrestrial geoscience, there are a number of data and analysis requirements for planetary mapping that are not completely met by standard GIS environments. Such shortcomings

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initiated various projects, dealing for example with a web-based GIS interface to provide users with a database link and tools for data acquisition and processing (e.g., Hare and Tanaka, 1999; Hare and Plesea, 2008; Hare et al., 2009; Gaddis et al., 2004). Other projects focus on the development of GIS-based software for specific planetary research tasks, such as GIS-integrated impact-crater diameter-size frequency analyses to determine the absolute age of planetary surfaces (Kneissl et al., this issue; Hare et al., 2006). In the field of planetary mapping and in the context of the High Resolution Stereo Camera (HRSC) experiment, the project *PIMap* has evolved, which is about automated cartographic data processing for generating planetary topographic and thematic maps (Gehrke et al., 2006).

## 2. Planetary mapping—motivation and concepts

Due to the complexity of planetary surfaces and their great variation between different planets, geomorphological and geological mapping is challenging work and – due to the accessibility by remote-sensing techniques only – highly interpretative work. In order to illustrate the required preparatory and evaluation procedures for producing a map, we will, as a starting example, run through a geologic mapping workflow. Afterwards, we will describe the aims, requirements and concepts of GIS-based mapping but leave out any issues related to the process of geological/geomorphological interpretation and mapping work as this subject is covered elsewhere in great detail (e.g., Wilhelms, 1990; Barnes and Lisle, 2005).

As a first step before any actual mapping takes place, appropriate data needs to be found, processed and incorporated, serving as a mapping basis (Fig. 1, A). Owing to the lack of ground-truth information in planetary sciences, remote-sensing data are the only available data type yet for most parts of a planetary surface. Planetary researchers have access to online data platforms such as the Orbiteral Data Explorer (Planetary Data Service, 2010), Lunar and Planetary Institute websites (Lunar and Planetary Institute, 2006, 2009), United States Geological Survey (USGS) catalogs and GIS front-ends (Astrogeology Science Center, 2010), the Mars Global Data interface (Arizona State University, 2010) and other, less well-known catalogs such as the one provided by ELTE University (ELTE University Budapest, 2010). These web portals provide primary sensor data, derived products and a number of other datasets comprising catalogs and thematic map sheets at different scales and in different formats. In order to select the appropriate image data for a given mapping project the mapper has to define and query by attributes (Fig. 1, B). These depend on the mapping topic as well as on the data platform used. As a result of such a data query, raster data and auxiliary meta-information such as imaging time, boundary coordinates, or geometric resolution, is provided (Fig. 1, C). For data ingestion into the mapping project, researchers and mappers have to check the quality and usability of each image dataset in a separate data viewer. For a conventional mapping example (mapping of the Libya Montes region on Mars, Jaumann et al., 2009) we used data from the HRSC experiment (Neukum et al., 2004; Jaumann et al., 2007), the Mars Orbiter Camera (MOC) instrument (Malin and Edgett, 2001) and the Thermal Emission Imaging System (THEMIS) (Christensen et al., 2004). As thematic context maps we incorporated analog geological maps published by Meyer and Grolier (1977), Greeley and Guest (1987), and Schaber (1977). In order to ingest sensor data products, a data processing sequence needs to be performed comprising decompression, radiometric, geometric, and (optionally) photometric calibration and corrections (Fig. 1, D). Most of this work was carried out using the Integrated Software for Imagers and Spectrometers (ISIS) (cf., USGS, 2010). Following raster format conversion, image data were ready to be loaded into the GIS environment for multi-dimensional interpretative mapping (Fig. 1, E). For GIS integration and mapping, the commercial software package ArcGIS developed by ESRI is frequently used in the community.

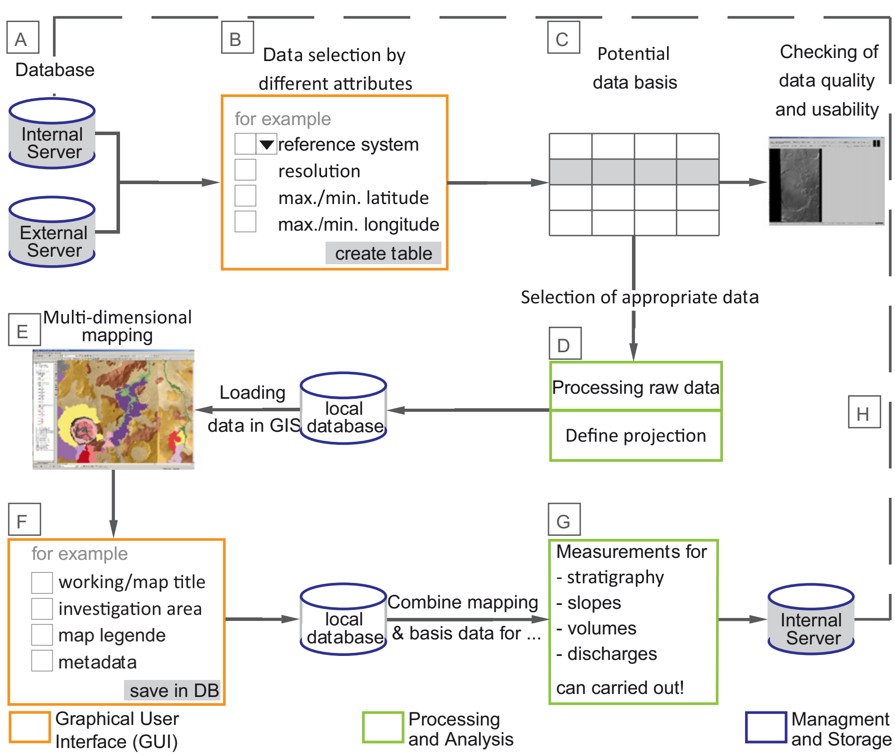


**Fig. 1.** Workflow diagram describing comprehensive geomorphologic mapping in Planetary Science. The upper case letters A–H indicate the particular workflow steps explained in the text.

Before the actual mapping process is initiated, mappers need to decide how they intent to structure their project and how to organize their map layers; this decision mainly depends on the complexity of the map contents and the type of publication envisaged. In GIS-based mapping, and as also known from terrestrial work (Gustavsson et al., 2006, 2007), the mapper has two structure options, one being a structure based on layers while the other one is based on an object model. The layer structure separates all the vector datasets for mapping (shapefiles) into feature layers of a certain geometry type. The object structure groups data into classes and hierarchies (subtypes and domains, ESRI, 2009), a structure which "accurately reflects the real world" (Gustavsson et al., 2006). Once the structure has been determined, the interpretative work, i.e., the mapping process based on the comparative view of different datasets (Batson, 1990), can be carried out. After digitization and the following definition of attributes and appropriate attribute values it needs to be decided what type of feature representation is to be used in order to allow comparability of different map products (Fig. 1, F). Subsequently, supporting the comprehension of the map results, the mapper has to describe the data basis and interpretation results which formed the cornerstone for the visual layout of the map. This description must be formulated at the individual map level as well as at the dataset level. With a thematic map produced in this way, and with a set of meta-information and auxiliary data, e.g., morphometric measurements of spatial objects or stratigraphic information, results can be represented in a new derivative map (Fig. 1, G).

In this or in a similar way, planetary researchers and mappers conduct work on various topics, at various map scales, and on various regions. To allow for efficient collaboration among researchers and groups within the community, all mapping results have to be prepared, described, managed and archived uniformly. This will give the research community access to previous elaborated results, ready for use as secondary data basis for further studies (Fig. 1, H).

In order to simplify this mapping process, conceptual GIS-based approaches are currently underway, addressing issues such as data integration, management, processing aspects and analysis within a geodatabase context, including the use of secondary relations and topologic constraints (van Gasselt and Nass, this issue). One important aspect, beyond the scope of the data model itself, is that of a GIS-based implementation of cartographic symbols. This last aspect is the main topic of this paper. Details concerning specification and implementation will be discussed in subsequent chapters, bearing in mind, however, that the use of symbols is principally independent of the exact GIS environment and the database management system. For creating these symbols we used the *Digital Cartographic Standard for Geologic Map Symbolization* (FGDC, 2006) prepared by the USGS for the Federal Geographic Data Committee (FGDC) for point, line, and areal objects. By using such a standard, data for geological and geomorphological maps are visualized by lines and point symbols, hachures, and patterns, either as stand-alone signatures or as a combination of features. Furthermore, as this standard is primarily based upon Earth Science symbols, it helps to easily understand planetary maps because the map reader is usually familiar with the symbol set and is able to adapt this knowledge to planetary maps (Hargitai, 2006).

While lines represent features such as boundary contacts, or structural elements such as faults, point symbols denote features such as craters or small structures on small-scale maps. Hachures are used only in combination with lines and represent objects such as truncated beds, or they are employed to point towards the inclination of a scarp. Patterns are used for polygon features and represent areal units, such as ejecta blankets, terrace deposits, or wide-spread materials.

Concerning the graphic variables (cf. Imhof, 1972), used in the traditional map-design, these are distinguished in *color, orientation, shape* and *size*. Particular attention is paid to *colors*, as these are the most powerful graphic variables in cartography. Different colors are mainly used to portray stratigraphy and lithology, i.e., surface material, but they are also employed for line features such as regional fractures or wrinkle ridges. *Shape* and *size* can be varied the point and line symbols to represent, for instance, crater in small-scale maps or fault lines, having additional attribute values describing the quality, i.e., accurate, approximate, inferred or concealed. Manipulation of *orientation* angles helps to characterize areas of channelized erosion, aeolian transport as well as symbols for strikes and dips, i.e., attitude data (FGDC, 2006). In addition to this standard document, however, further symbol development is needed as the definitions in standard symbologies are primarily based upon terrestrial features, whereas a number of widespread landforms which appear on other planets are not covered by this symbol set thus far (Hargitai, 2006).

From this the basic requirements follows that a GIS-based implementation of symbol sets for planetary mapping purposes is, in essence,

1. easy to implement and apply,
2. portable and usable on different systems,
3. easy to be managed and maintained,
4. controllable/customizable regarding specific behavior via rules and guidelines.

## 3. Symbols in ArcGIS—capabilities and requirements

For planetary mapping conducted in the research community, ESRI's software package ArcGIS was utilized for digitizing, data managing, map production as well as defining symbols. For the creation, modification and management of individual symbols and symbol sets for cartographic display purposes, three different approaches are available.

The first method is the fastest way to assign graphic properties to a spatial object and to determine how the object is to be displayed on the map. For this, the mapper uses the *symbol selector* to access predefined symbols and symbol groups listed in symbol categories, thus narrowing the search for a required symbol. Here only objects having the same geometry type as the selected feature can be accessed. The mapper has the possibility to modify symbol properties, i.e. color, size, alignment options and symbol-specific attributes. A modified, redefined or completely new symbol can then be used to mark the spatial object, and saved in an already existing symbol category for a later use. Individual symbols can be exported into a specific binary *layer* file in which all properties are stored and organized. By using such a *layer* file, additional symbol properties become accessible, including specific symbol information, classifications, label shape and placement properties and scale dependences, but the mappers need to assign signatures to each object manually. Though this method is comparably straightforward, flexible and can be further refined at user level to permit local feature representation and a local project-based map design, it lacks the possibility of transporting and distributing such definitions among different users, as *layer* files are not designed for cross-platform integration and their use is limited to the ArcGIS environment.

The second possibility to define how data are visualized on a map in ArcGIS is to use *styles* organized in the *style manager*, which means that every time the content of a *style* is used, a particular map element or symbol is chosen and applied (ESRI, 2009). Technically, predefined colors, symbols and their specific properties as well as individual map elements are collected and stored in a binary file, one for each required symbol category. As part of *style* definition, the mapper can modify existing symbols and broaden the *style's* content by creating and adding new symbols. As an additional option it is possible to generate a personal *style* file and populate it with symbols for individual use. Each time a new symbol or symbol element is created, it must be classified by symbol type and filed in the appropriate category folder. Mappers can choose only those symbol properties that are associated with the symbol's specific geometry type to ensure an organized symbology structure (ESRI, 2009). A *style* definition can optionally be exported into a *layer* file as discussed earlier. Furthermore, a *style* is stored as a Microsoft DataBase file (*.mdb-format) in which each relation stands for a different presentations of map elements (line symbols, fill symbols, area patches). Each symbol element is referenced by an identification number (id) which is the relation's primary key field (see Table 1). A symbol's name and its associated category are stored in other fields as text strings. The way it is to be represented graphically requires more complex information and is therefore stored as Binary Large Object (BLOB) data type. This data type also allows to store and manage large binary multimedia data (e.g. raster graphics) dynamically. The main advantage of this method is that it allows the mapper to meet symbolization standards, helps to promote consistency in the organization of maps and allows to easily share symbol catalogs between different users. The current drawback is that there is no direct link to an underlying database model so far. However, a geodatabase structure could easily be expanded by adding the style's relational data organization by means of, e.g., associated relations.

The third method for accessing ArcGIS-based symbolizations is through *representation* classes which allow the mapper to visualize data using a rule-based symbol structure that is stored inside a geodatabase along with the data, and is organized at the feature-class level. This method consists of adding two fields to the attribute table of each feature class to store information on the symbology and on feature-specific overrides of placement and display rules. The benefit of this approach is that a single feature class can thus store multiple representations simultaneously, allowing to derive different map products from a single database (ESRI, 2009). Symbols are stored with and related to the data and can thus easily be shared by the community. A drawback, however, is that handling and modifying symbols using *representations* is quite complex, and there are currently no options for portability to other GI systems.

In order to select an efficient method of GIS-based symbol management, requirements need to be defined and appropriately applied to the specific needs that occur in the context of planetary geological mapping.

### 3.1. Combinations of symbols

In order to account for the geologic and geomorphologic complexity of planetary surfaces that have undergone a variety of formation processes, spatial objects need to be able to represent the resulting characteristics. While a geologic map mainly displays the material within a relative or absolute stratigraphic context, a geomorphologic map usually consist of a two-dimensional representation of several surface units, which may be similar regarding material properties, i.e., composition, but different in terms of surface expression, i.e. morphology, shape and textural properties (e.g., Lehmann et al., 2006). This means that for one single spatial object, symbols need to be defined that represent both geological *and* geomorphological features in parallel. For example, a tectonic graben has a geomorphological expression but it is also part of a geological unit that is usually displayed in a different way. These relationships require a smart combination, arrangement, or amalgamation of symbol properties. However, this function must be handle by the administrative data structure that controls and supports a particular mapping project, rather than being part of the implementation of each single symbol (van Gasselt and Nass, this issue).

### 3.2. Color scheme

For the visualization of surface ages and stratigraphic relationships between different surface areas, time-stratigraphic color recommendations (e.g. *International Stratigraphic Chart*, Salvador, 1994, for terrestrial mapping) have been developed. In these charts various chronological and chronostratigraphic subdivisions are defined based on a color scheme. In the context of planetary chronostratigraphies and associated geological mapping, this subject matter has been addressed by Tanaka (1986), Tanaka and Skinner (2003) who mention the *International Stratigraphic Guide* (Salvador, 1994) as a reference basis for lithologic units. Furthermore, a range of map-unit colors for volcanic and plutonic rocks as well as for the stratigraphy of sedimentary and metamorphic rocks have been suggested in section 33 of the FGDC (2006) standard. In order to make use of and benefit from these recommendations, color schemes for surface units need to be defined and implemented in a flexible way, so that the mapper can, e.g. choose a variable number of units within a variable time-span and assign appropriate color ranges.

**Table 1**
This table shows an extract of a *style* in database format.

| ID | Ref_No | Name | Category | Object |
|---|---|---|---|---|
| 1 | 25.1 | Contact, pl.-Loc. acc. | Planetary Geology | Long-binary data |
| 2 | 25.2 | Contact, pl.-Loc. approx. | Planetary Geology | Long-binary data |
| 3 | 25.3 | Contact, pl.-Loc. inferred | Planetary Geology | Long-binary data |
| 4 | 25.4 | Contact, pl.-Loc. concealed | Planetary Geology | Long-binary data |
| 5 | 25.5 | Fault, pl., sense of offset unspecified—Loc. accurate | Planetary Geology | Long-binary data |
| 6 | 25.6 | Fault, pl., sense of offset unspecified—Loc. approximate | Planetary Geology | Long-binary data |
| 7 | 25.7 | Fault, pl., sense of offset unspecified—Loc. inferred | Planetary Geology | Long-binary data |
| 8 | 25.8 | Fault, pl., sense of offset unspecified—Location concealed | Planetary Geology | Long-binary data |
| 9 | 25.9 | Normal fault, pl.-Loc. accurate Ball and bar on downthrown block | Planetary Geology | Long-binary data |
| 10 | 25.10 | Normal fault, pl.-Loc. approximate Ball and bar on downthrown block | Planetary Geology | Long-binary data |
| 11 | 25.11 | Normal fault, pl.-Loc. inferred. Ball and bar on downthrown block | Planetary Geology | Long-binary data |
| 12 | 25.12 | Normal fault, pl.-Loc. concealed. Ball and bar on downthrown block | Planetary Geology | Long-binary data |
| 13 | 25.13 | Strike-slip fault, pl., right lateral offset—Loc. accurate | Planetary Geology | Long-binary data |
| 14 | 25.14 | Strike-slip fault, pl., right lateral offset—Loc. approximate | Planetary Geology | Long-binary data |

Exemplified by line symbols 25.1–15.14 of the FGDC chapter 25-Planetary Geology Features.

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### 3.3. Orientation of symbols

Planetary surfaces undergo dynamical processes, and traces of such surface dynamics are observed in the geologic materials record. In order to be able to provide information on the dynamics, i.e. directions and orientations, a set of special symbols are commonly used which deal with this topic in two different ways: (1) a direction is displayed by line symbols in combination with an arrow pointing to the direction of movement (e.g., orientation of flow, or wind direction); (2) a direction is given by point symbols (mainly arrows) showing, e.g., flow directions in small-scaled maps, based upon a generalization from line to point symbols. While linear features are usually implemented by plotting each vector separately, point feature map representations require additional information for the exact placement and orientation in order to minimize the need for manual intervention. Other special symbols cover representations and symbolizations of three-dimensional information (FGDC, 2006), such as the dip and dip direction or strike of geological planes or axes plunge of linear geological features. These are usually represented by orientation options in combination with text labeling to account for the third dimension.

### 3.4. Cartographic generalization of spatial objects

In contrast to fixed map scales as used in analog maps, the scale of digital maps constantly changes. This fact challenges the symbology as spatial objects undergo constant changes in their geometry as a result of the different cartographic generalization processes, e.g., simplification, displacement, enlargement (e.g., Hake et al., 2002). This could mean that an impact crater with a diameter of 250 m is drawn as a polygon at a map scale of 1:25,000, but the same structure must be transformed into a point signature at a scale of 1:150,000 to maintain readability. This issue has to be resolved to ensure efficient and accurate GIS-based processing.

### 3.5. Symbols for new and thematic objects

In the field of planetary mapping, surface units (i.e. spatial objects) appear frequently that are not well constrained regarding their exact compositional characteristics or related processes and that cannot be put into a proper stratigraphic context. Consequently, such objects cannot be connected to any standardized symbology at the time of mapping. Mappers therefore must have the option to modify and extend a given symbol catalog by creating or defining new symbols. To facilitate adding statistical information on a later stage, irrespective of qualitative or quantitative, symbol catalogs should also provide a number of predefined geometric symbols which can be used as variables and as thematically required differenced in color, size, or shape.

## 4. Work in ArcGIS—technical implementation

The technical implementation of symbols in GI systems and in the underlying GDB is performed stepwise and, to begin with, requires the selection of appropriate symbols suitable for and planetary geological and geomorphological mapping.

### 4.1. Selecting and building symbols

Regarding the selection of symbols required for planetary mapping, maps must be designed so as to ensure that any surface formation process is properly displayed and understood. We therefore need a unique symbol for each spatial feature, and these selection of appropriate symbols based upon the *Digital Cartographic Standard for Geologic Map Symbolization* (FGDC, 2006). The signatures described in that document are scale-independent, which means that symbols are appropriate for use at any scale. This allows the user to produce small-scaled outline maps (e.g. map scales of 1:500,000) as well as large-scaled detailed maps (e.g. map scales of 1:20,000). However, in order to guarantee a correct cartographic display over a wide range of map scales, symbols are grouped into features *mapped to scale* and features *not mapped to scale*; in one case different symbols are used to indicate the exact extent of a surface feature at different scales, and in the other case symbols remain unaffected by map-scale variations. Appendix A, chapter 25—*Planetary Geology Features* of the FGDC (2006) was implemented to provide initial guidance as it describes the most common geological and geomorphological structures and features observed on planetary surfaces. Responding to the requirements for further symbol sets communicated informally by the Helmholtz Association's research group on the *Geological Context of Life* (Helmholtz Alliance, 2010), the symbology catalog was extended to include symbols from chapters 12—*Fluvial and Alluvial Features*, 18—*Volcanic Features* as well as 33—*Suggested Ranges of Map-Unit Colors* (FGDC, 2006).

Based on the *Standards for Geologic Map Symbolization* of the (FGDC, 2006), a wide range of symbol requirements are now being addressed for general planetary mapping. However, as also mentioned in the document guidelines, this standard is not intended as a static repository, i.e., it is recommended to use it as a modifiable and expandable basis. It is especially in the field of interpreting planetary surfaces that symbol creation needs to be kept flexible, because there are a variety of spatial objects that cannot be addressed and interpreted appropriately during the time of mapping. Consequently, four additional symbols for each geometry feature were defined to mark (1) *vacant objects* for individual modification by the mapper, and (2) *uncertain spatial objects*, which cannot be described and assigned properly at the time of mapping. For representing thematic statistical data we additionally defined symbol classes for (3) *qualitative data*, which can be varied in color or shape, and for (4) *quantitative data*, which can be varied in size or brightness/saturation.

Considering the variety of methods for symbol building outlined above, we decided against the *single-symbol* solution because this would restrict portability between different mappers. Although *representations* are highly customizable within their environment and have significant advantages over isolated symbols, they lack portability across different GIS environments. Furthermore, such a solution would not be easily accessible for occasional mappers and those researchers who are not familiar with all the technical GIS and data model ingredients. Consequently, the most efficient method at the present stage of implementing symbols into GIS and sharing these with other mappers is by storing them in *style* files. With this in mind, and also in the context of project and mapping requirements, we incorporated line, point, polygon symbols, colors and patterns. For creating individual symbols we used the *symbol property editor* within the ArcGIS environment in combination with vector-based graphic software (e.g., INSCAPE http://www.inkscape.org/ and Adobe Illustrator http://www.adobe.com/). Existing symbols were modified appropriately, while others were created from scratch, based upon recommendations set out in the FGDC (2006) standard (see Fig. 2). For symbol designation and id-assignment we adopted the reference numbers and symbol description of the standard document. Furthermore, every symbol was assigned to a new category termed *Planetary Geologic Features*, which can easily be accessed during any mapping process. Additionally, it was found that compared to the creation of line or polygon symbols,

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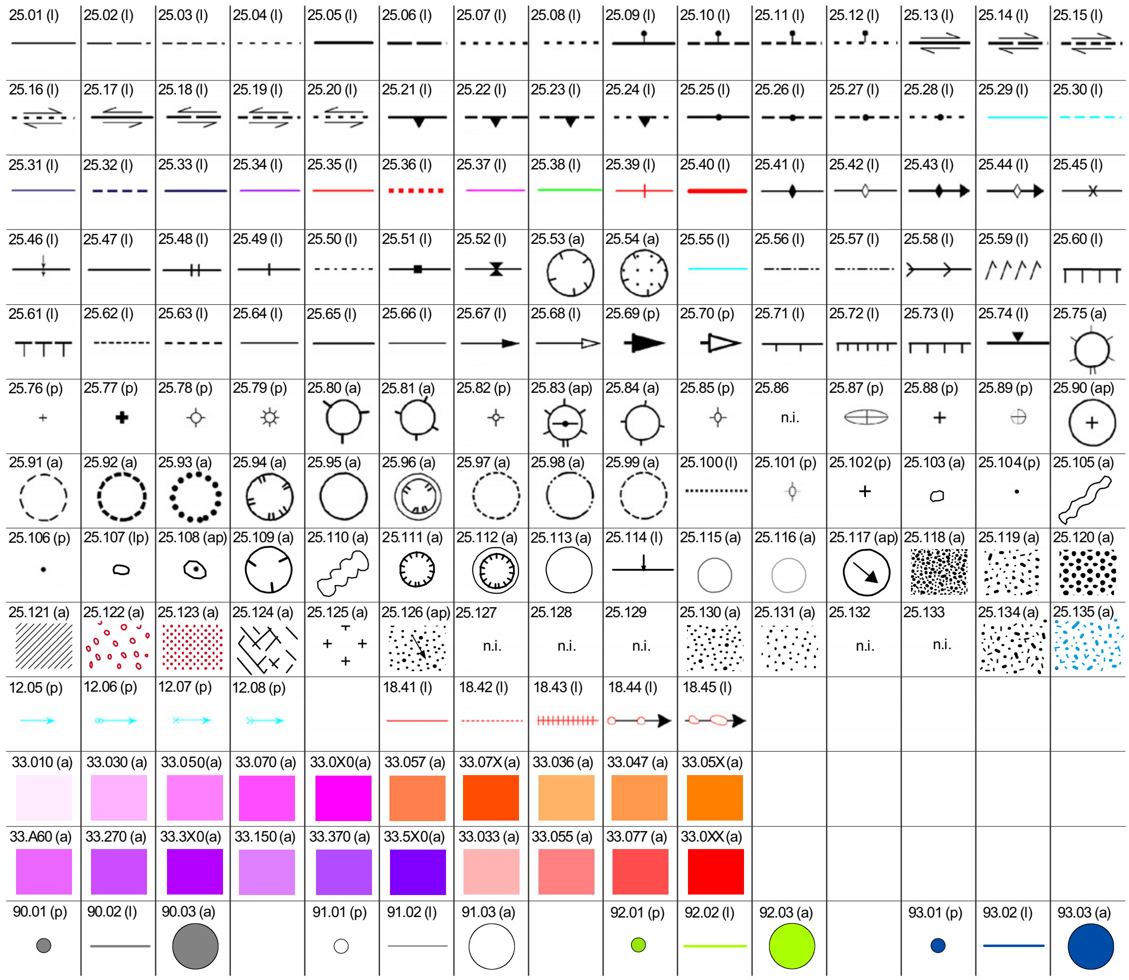


**Fig. 2.** Symbols implemented in ArcGIS. Numbers are the reference number used in the FGDC standard. (p) indicates a point symbol, (l) indicates a linear symbol, (a) indicates an area symbol.

point symbols were more challenging as some of them need to be assigned an orientation, i.e. directional properties. In order to handle this for each object individually, we extended the related attribute table (cf. Table 1) by a field in which the mapper can enter the required angle (geographic or arithmetic) for an individual object symbol. In a similar way, additional attribute fields can be easily defined in order to extend the capabilities of point-symbol placement.

Regarding the technical possibility of creating new symbols and modify existing ones, the symbol *style* option provides a relatively efficient and flexible basis for the adaptation and collection of standardized symbols for planetary mapping needs. Its usability is enhanced by a detailed description (label and unique id) and easy access to the symbology. The fact that the *style* file is stored in a *.mdb-format (cf. Table 1) even permits the user to dispense symbols from the ArcGIS environment and transfer them to other GI systems. In addition to the stand-alone use of symbols in individual ArcGIS projects, the symbology is easily connected to a database model as each symbol in ArcGIS is clearly assigned to a reference number of the FGDC standard which can directly be implemented in the DB model.

With respect to specific symbol requirements, a definition of symbol combinations (two symbols for one object) is generally possible within the data model. The assignment of stratigraphic or lithologic information can be implemented as color schemes, and the assignment of directions and orientations can be handled via additional attributes. However, requirements regarding a dynamic-zoom adaptation of symbols in the framework of cartographic generalization must be addressed separately.

### 4.2. Implementation in the DB-model

The exact way in which components handling symbology requirements are integrated into a GIS depends on the underlying data model and on whether it is designed to handle and manage the data types needed for storing and accessing symbol sets. In ArcGIS, symbols can efficiently be linked to the database by using *representations*. Furthermore, it is possible to convert symbols from predefined *styles* into a *layer* file, whereby a single object is directly assigned to the correct symbol by its unique id. Similar to the contextual symbol building and management mentioned above, our primary solution for symbology integration is also based on *style* files, as these are portable to other GI systems mentioned above. By implementing the *style* files into the DB model we generated three possible scenarios (see Fig. 3) that are all geared to mapping at feature-class level.

Scenario 1 is composed of two relations (i.e., tables) that are directly related to the feature class attribute *symbol*. The first relation, *symbols*, contains the GIS-managed object identifier *id*, the symbol reference number *ref_no* as an artificial primary key (PK) composed of the FGDC symbol reference number and the appendix chapter number, a description of the feature resp. symbol *label*, and the attribute *chapter_no* that contains the

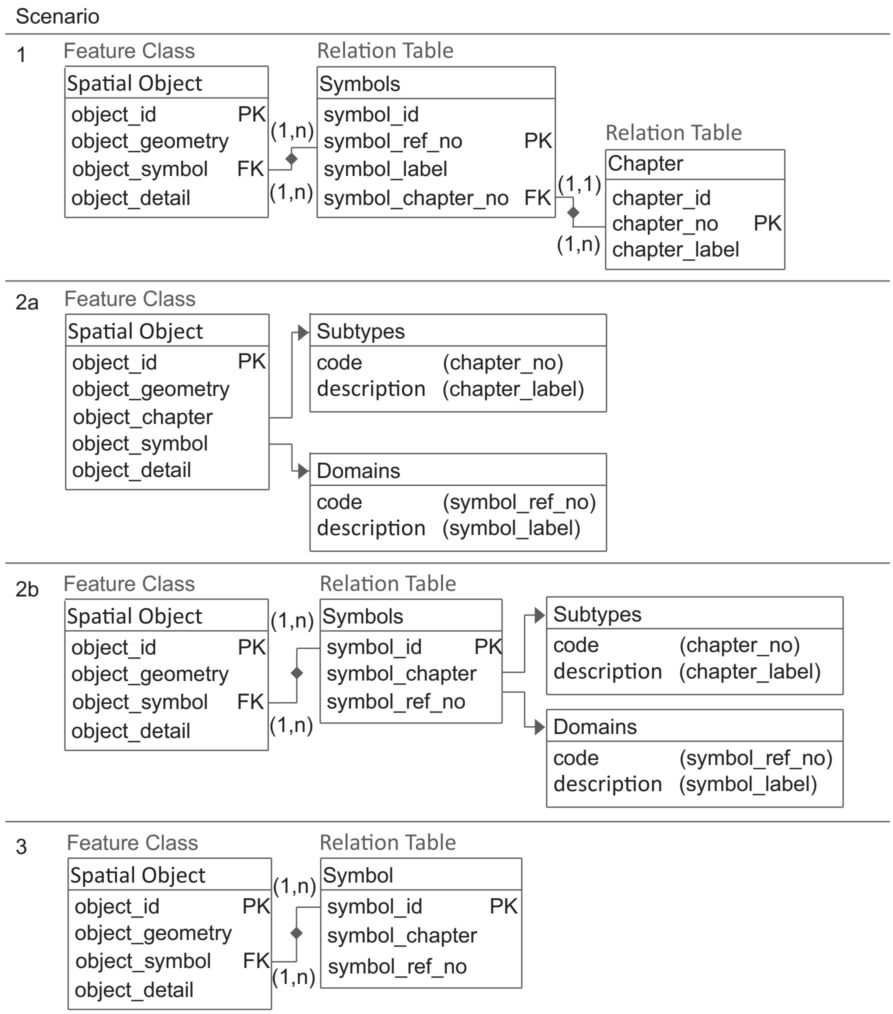


**Fig. 3.** Different scenarios for the implementation of the symbology into a GDB. (PK stands for primary key and FK stands for foreign key.)

appendix chapter as a foreign key (FK). The second relation *chapter* has the attribute *id*, the appendix chapter number *chapter_no* as primary key, and the *label* (cf. Fig. 3, scenario 1),

Scenario 2 uses subtypes and domains in order to describe objects on the object-relational level, permitting a convenient assignment of symbols on the basis of a specific subtype (cf. Fig. 3, scenario 2). These subtypes are feature class entities that share common attributes. For a direct assignment of symbols, the FGDC appendix chapter represents the subtype. The selection of the chapter number subtype subsequently limits the possible values for the domains defined by the reference number of each symbol. The difference between 2(a) and 2(b) is that an additional relation is added, which makes the assignment of attributes more convenient.

Scenario 3 consists a relation table *symbol* that is linked to the feature class *symbol*, which contains the attribute‘s *id* (PK), *chapter* and *ref_no* (cf. Fig. 3, scenario 3).

As we have previously introduced symbols for generic fields, i.e., *undefined, vacant, qualitative* and *quantitative* data, these can be similarly covered by all these three scenarios, which also permits integrating additional symbols.

For the relation that covers the assignment of orientation information to point feature-class objects, an additional attribute is created, which is pseudo-boolean and receives a value of 1 if the object can be rotated. If this is the case, another attribute termed *angle* is used for entering rotation values, i.e. angles. This can either be done during the mapping process manually, or by software extensions dealing with the derivation of directions, or by derived GIS-based spatial analyses that perform calculations on terrain-model data.

In all these, symbols are dealt with on the basis of simply structured relations that can easily be updated and modified as well as extended if required. It is not necessary in any of these scenarios to use a printout of the FGDC standard as a lookup reference for the assignment of symbols, contrary to what is recommended in the *Geologic Mapping Template* developed by ESRI (Cartography Team, ESRI, 2009). All symbol descriptions are included as attribute values, and the mapper can directly navigate to any desired symbol. When using two different relation tables, both the symbol and the corresponding FGDC chapter number can be chosen. Used in a combination, they constitute a unique allocation (cf. Fig. 3, scenario 1) of any symbol object. By employing subtypes, the mapper can pick appropriate symbols in a hierarchical way through subtype-control of attribute domains, which prevents the input of erroneous data and limits data inconsistencies (cf. Fig. 3, scenario 2a and 2b). When using a single relation as the simplest approach to making assignments, symbols are unequivocally identified by the native object’s *id* (cf. Fig. 3, scenario 3). As an alternative and in order to avoid any redundant storage of *chapter* entries, the *symbol_chapter* and the *symbol_ref_no* attributes can be combined to operate as an aggregate key linked to the feature class. Aggregate keys,

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however, are not supported by ArcGIS file-based geodatabases but can basically be handled by any database management system (DBMS). Relations containing symbol definitions can easily be used within other GI systems that are capable of accessing and utilizing BLOB entries to define symbols and cartographic signatures.

### 4.3. Rules for symbology

Rules and guidelines controlling the behavior of various symbols should address the correct representation of surface characteristics. Such rules, however, are significantly controlled by data model design parameters, i.e. relations, relationships and topologies for which basic questions and requirements are defined:

1. Topologic rule-sets and constraints at the object level need to be defined.
2. Representations of spatial objects should follow cartographic generalization guidelines (simplification, magnification and displacement, aggregation, selection, and classification (e.g., Hake et al., 2002). More specifically, a mapper has to decide, which data should be displayed, using the most important object characteristics as well as topic-oriented specifications based upon map theme, content and scale.
3. There should be an option to define spatial objects by multiple properties in parallel. The database system and the employed model should be able to manage these multiple properties.

## 5. Conclusions and outlook

This paper has discussed methods of a GIS-based implementation of digital standard symbology, a crucial component of advanced geological and geomorphological mapping. With respect to the general requirements for GIS-based symbology in the field of planetary mapping as formulated in Section 2 (Planetary Mapping—Motivation and Concepts), we offer the following concluding statements:

- With the FGDC standard (FGDC, 2006) as reference framework, a high degree of comparability and comprehensibility of mapping results are obtained, two much-needed qualities when it comes to integrating mapping results from different sources.
- Aiming for a standard symbology independent of a particular GIS environment, *style*-based implementation is the most efficient method of symbol creation and management thus far.
- Using the implemented symbology catalog and applying its symbols correctly ensures that maps will follow cartographic guidelines as closely as possible.
- The GIS-based mapping process has significantly improved researchers' working conditions because technical and cartographic issues are covered during implementation, freeing the mapper to focus on interpretation and analysis work.
- Due to the way in which symbology objects are organized and described in a GIS environment, mapping becomes more convenient while retaining a flexible basis for any adaptations required at a later stage.
- Based on the underlying database structure the symbol catalog is portable, sharable within the research community and theoretically convertible to other GI systems, capable of accessing attribute values for cartographic symbolizations.
- The implemented symbology can be used either in stand-alone GIS projects or it can also be integrated into a more sophisticated database model.

The limitations of such an approach are that it does not currently encompass an efficient and adequate set of rules concerning matters like signature arrangement and cartographic generalization. This can only be solved by applying separate topology rule-sets and constraints. Furthermore, at the present stage the symbology catalog has not yet been exported to other GI systems. Such issues are part of ongoing work, which also focuses on some additional elements:

- As we adapt symbols to specific requirements of planetary mapping, the available signature catalog is constantly evaluated, modified and extended. Those revisions can be directly obtained from the author.
- As the symbology can theoretically be used independently of specific software architecture, the description of vector-based graphics can be embedded in the underlying database model. We envisage conversion of symbols into the open and standardized format of *Scalable Vector Graphics* (SVG).
- Work on transferring the symbology catalog to open source GIS/free mapping software is presently in progress.

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