OBJECT-RELATIONAL DATAMODEL COMPONENTS FOR GEOLOGIC MAPPING CONDUCT

S. van Gasselt[1] and A. Nass[2,3]

[1]Institute of Geological Sciences, Free University of Berlin, Malteserstrasse 74-100, D-12249 Berlin, Germany.
[2]Institute of Planetary Research, German Aerospace Center, Rutherfordstrasse 2, D-12489 Berlin, Germany.
[3]Institute of Geography, University of Potsdam, Karl-Liebknecht-Strasse 24/25, D-14476 Potsdam, Germany.

KEY WORDS: geodatabases, geologic mapping, data models, geographic information system

ABSTRACT:

Processes of terrestrial geologic mapping and preparation of geologic maps are supported by Geographic Information Systems (GIS) and respective datamodels of which an assessable number are currently available. Such datamodels help mappers to define spatial geologic map units by integrating field and remote-sensing information and relate them to non-spatial information about unit details, in particular rock composition, age and age relationships, attitude data, and other characteristics. Apart from any interpretive tasks concerned with the delineation of various surface units in terms of geological and geomorphological boundaries and contents, basic mapping tasks involve an efficient management of attribute data needed for (1) applying an assignment of standardized cartographic symbols or color schemes, (2) performing spatial queries and data analyses, or for (3) combining and homogenizing mapping results generated by different groups. A unit usually carries multiple assignments to which an appropriate cartographic symbology representation is related. Such an assignment may describe the surface unit material, its stratigraphic name and relative position, or its chronostratigraphic and absolute position. The assignments of surface materials or the assignments of stratigraphic units within or without an absolute chronologic context and the subsequent selection of cartographic symbols can usually be handled using a standard geologic relationship model for which surface materials are the most important attributes. The complexity grows significantly if a data model needs to be employed which is capable of dealing with all such requirements at the same time and which is able to guide the mapper through entities and attribute values by employing object-relational concepts.
We here present a geologic mapping data model design that has been implemented within *Environmental Systems Research Institute's (ESRI)* ArcGIS environment for systematic mapping conduct of different planetary surfaces. The model copes with each planet's specific stratigraphic system, surface chronologies, specific naming conventions, and different body references. Additionally, standards developed by the *Federal Geographic Data Committee (FGDC)* for cartographic symbols in geologic mapping have been implemented on an abstract level and are incorporated via subtype-domain controls to achieve a high level of integrity of attribute data.

1 INTRODUCTION AND SCOPE

GIS–based datamodels are crafted for specific requirements and are commonly utilized for data management, collaborative analyses and mapping efforts; focused datamodels with varying complexity are set up and are published and shared by agencies and research or industrial institutes. For terrestrial geologic mapping a small number of datamodels have been developed since the late 1990s and some of the basic models have been considerably expanded to fit specific needs of mapping agencies (see discussion in section 2.3).

In the context of planetary exploration and systematic geologic mapping a growing number of planetary maps have been created through agency-funded programs or individual or collaborative research tasks. In order to manage and prepare that data for analyzing purposes, a geo datamodel is currently being developed which focuses on several modules dealing with integrating heterogeneous pieces of information derived from different sources, with map-unit and symbolization assignments, as well as with sensor- and map-data search and organization issues (van Gasselt and Nass, 2010a,b; Nass et al., 2010). These modules are developed, expanded and tested separately but they require integration into an overarching datamodel upon completion. The module dealing with the definition of map-units is the most complex component and partly focuses on the proper handling of planetary map units in terms of their stratigraphic framework.

One of the major aims of this work is to be able to transfer such database-model components to each planetary object that has been – or will be – in focus of planetary exploration and it should be able to easily cope with modifications that are introduced in the course of new findings and a better knowledge without having to reconstruct the overall datamodel. The mapper should then be able to focus on the mapping conduct rather than on having to deal with technical issues and implementations on the level of the GIS.

2 PLANETARY MAPPING BACKGROUND

2.1 Aspects of Planetary Mapping

Planetary geologic mapping has evolved significantly since first planetary missions provided detailed data of planetary surfaces in the 1960s. Geologic mapping was one of the first tools in planetary exploration and was conducted on the basis of various mission data returned back to Earth in the course of flybys, impactors and robotic landers or rover missions to the Moon and other terrestrial objects. An early culmination of planetary exploration was reached when manned missions in the context of the Apollo program and sample returns from the Soviet Luna missions brought back samples from another planetary's body surface. Apart from lunar and martian meteorites derived from an unknown location, lunar surface samples are thus far the only non-terrestrial rocks that have been age-measured by methods of radiogenic isotope decay (e.g., Dalrymple and Ryder, 1991; Albarede, 2009).

Few years after this initial phase mission programs dedicated to mapping terrestrial planets systematically evolved and returned a wealth of new data. The data basis has been growing considerably since the late 1990s with several new missions to the inner planets and, especially, to the outer icy satellites orbiting Saturn and Jupiter. In the context of such programs, mapping efforts, in particular geologic mapping projects, conducted by the *United States Geological Survey (USGS)* and associated researcher and under financial support by the *National Aeronautics and Space Administration (NASA)* have provided numerous thematic maps of the terrestrial planets. Most of these products were created in the 1970s and 1980s with several updates at the end of the millennium and a complete GIS-based re-mapping initiated as a response to high-resolution data that became available recently. These efforts are embedded into USGS-led programs funded by *NASA Planetary Geology and Geophysics Program* and carried out under the auspices of the *Planetary Cartography and Geologic Mapping Working Group (PCGMWG)* and the *NASA Geologic Mapping Subcommittee (GEMS)*.

Until today, a large number of local, regional and global-scale geologic maps have been published by agencies, surveys and individual researchers. Such work is mainly focused on the Inner Planets but also geologic mapping of the Outer Solar System objects – mainly the Galilean Satellites, is underway (e.g. Doggett et al., 2007; Williams et al., 2007, 2010). For the terrestrial planets, systematic endeavors by NASA and USGS have led to over 200 geological maps for Mars covering a scale range of 1:20,000,000 to 1:15,000,000 for global and hemispheric maps to local maps at scales of 1:500,000 and up to 1:200,000 (USGS, 2003a) and recent data acquisition provides the basis for ongoing efforts in terms of a dedicated mapping program for Mars and a completely remapping on a global scale (Gaddis et al., 2004; Skinner et al., 2006; Tanaka et al., 2007, 2008, 2009a). Due to the sparse data coverage, geologic maps of Venus and Mercury amount to 150 maps sheets in summary. Both planets have been mapped at scales of 1:5,000,000 back in the 1970s mainly (LPI, 2007; USGS, 2003b). Mercury's second hemisphere which remained unknown for over 30 years has now been revisited by the Messenger mission and the acquired new data will help to establish new mapping programs in the future. For the Moon, a new mapping project has been initiated in 2004 that focuses on surface mapping at a scale of 1:2,500,000 which corresponds to 30 map quadrangles (e.g. Gaddis et al., 2005; USGS, 2008). Earlier mapping efforts on the basis of Lunar Orbiter Data in the context of the Apollo program and later re-mapping using Clementine data led to 80 officially released maps starting at a scale of 1:5,000,000 for global and hemispheric views and ending at a scale of 1:250,000 for the Apollo landing sites; but also larger scale maps have been produced to cover local phenomena (LPI, 2010).

2.2 Concepts of Planetary Stratigraphy

The basis for any planetary geologic mapping conduct is the identification and delineation of homogeneous geologic surface units with respect to their lateral extent and their relation, i.e. boundary and position, to adjacent and underlying surface units. In theory, such surface units represent surface rock materials deposited or emplaced by a discrete process in a discrete timespan, and are termed *rock-stratigraphic* or *lithostratigraphic* units (Wilhelms, 1990; Tanaka and Skinner, 2003; Skinner and Tanaka, 2003; Stffler et al., 2006). Rock-stratigraphic units have traditionally been identified by primary characteristics, i.e. surface structures that are generated during deposition and emplacement (Wilhelms, 1990; Tanaka and Skinner, 2003; Skinner and Tanaka, 2003). The (relative) timing of emplacement has been established by using impact-craters densities of surfaces. This measure is valid if a planetary surface is considered to have accumulated impact craters by meteoritic bombardment homogeneously (Arvidson et al., 1979).

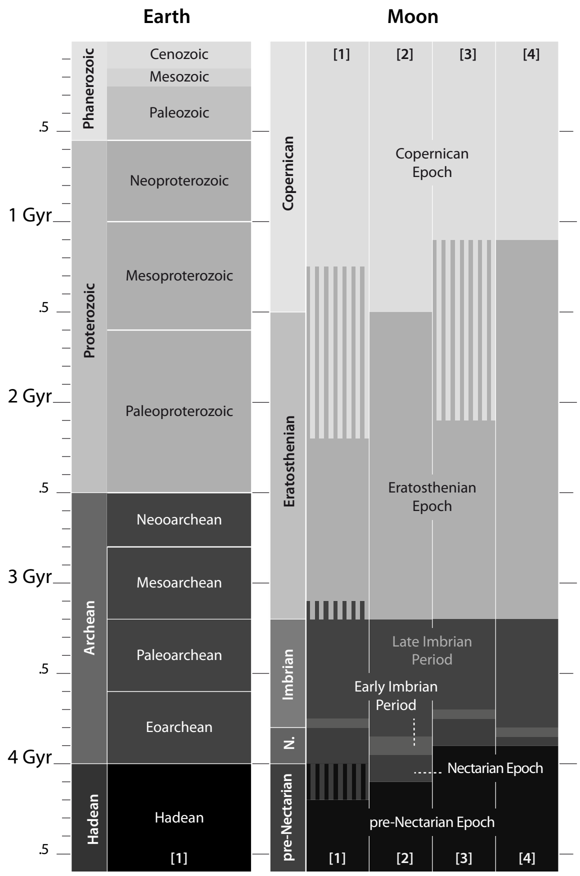

Figure 1: Extract of planetary chronologies as represented by epochs and periods for the Earth and the Earth's moon as compiled from different sources. Letters *L, M* and *E* refer to chronologically *late, middle* and *early* periods, respectively. Numbers in brackets refer to data sources: [1] Ogg et al. (2008), [2] Neukum and Ivanov (1994), [3] Stöffler and Ryder (2001), [4] Wilhelms et al. (1987). For space reason, other planetary objects have been excluded here; see also compilation in van Gasselt (2007); Tanaka and Hartmann (2008) for additional information.

The three-dimensional character of a surface unit that has originally been deposited horizontally allows to establish a relative stratigraphy in which older rocks are superimposed by younger units (as determined either by unit contacts or by the concept of impact crater frequencies). If absolute ages for an unit are known – either by radiometric measurements of returned lunar samples or by employing crater-size frequency modeling, rock-stratigraphic units can be transfered to *time-rock* or *chronostratigraphic* units using chronology models and impact-crater production functions (figure 1). For all major terrestrial planetary objects with a solid crust, the object's chronology is defined by the time between planet formation and today and is subdivided into Eras, Periods and Epochs mainly that span many hundreds to tens of millions of years, respectively. For planetary chronologies, Periods and Epochs are the main chronologic subdivisions. While the chronologic period and the chronostratigraphic system carry identical dedicated names, the next–finer level subdivides periods or systems into epochs and series, respectively (e.g. Tanaka and Hartmann, 2008; Tanaka et al., 2009b; Salvador, 1994).

The fundamental unit of lithostratigraphy are termed *formations* composed of characteristic lithologic units (so-called *members*). Formations can be grouped into so-called *groups* (Salvador, 1994). Each chronostratigraphic unit is defined by boundary ages of chronologic units and it has to be kept in mind for any data model that these boundary values differ significantly depending on the employed model and are prone to change. For the Earth, a large number of local stages, a subdivision of series, are employed, which may vary from national to even regional level depending on the geologic environment and rock characteristics of a certain area.

The convenient and efficient management of the different aspects of timing with respect to various types of geologic surface units and the uncertainties imposed by different planetary chronology models need to be depicted within a data model that copes with geologic mapping.

2.3 Geologic Data Models

A geologic data model forms the framework for integrating spatial geologic data, measurements as well as metadata (cf. Richard, 1998). The data model establishes a link between the spatial geologic unit and its boundaries and quantitative data as for example age measurements and chronologic units. As we here focus on this interrelationship and an integration of different planetary age models and classes, a core component of our data model is the efficient handling of chronologic and chronostratigraphic systematics on the relative and absolute-age scale in combination with radiometric ages where available as well as under consideration of different planetary objects. Within a slightly different focus, the handling of these components are paramount also for terrestrial geologic data models for which a review of existing data model solutions had been carried out in order to potentially adopt and modify established workflows that have already been communicated within and developed for a broad user community.

There are currently only few data models available that are concerned with GIS-based geologic mapping and management of meta information. These models were primarily designed and implemented for use with Environmental Science and Research Institute's (ESRI) commercial ArcGIS environment although some of them were intended to be created on a conceptual level in order to provide a technology-independent solution (e.g. NADM Steering Committee, 2004).

The conceptually most elaborated and accessible data model is the North American Geologic Map Data Model (NADM Conceptual Model 1.0 or NADM-C1) designed by the NADM Steering Committee Data Model Design Team (NADM Steering Committee, 2004). The model is a direct descendant of the North American Map Data Model (nadm 4.3) developed by the United States Geological Survey (USGS), the Association of American State Geologists (AASG) and the Geological Survey of Canada (GSC) working group (Johnson et al., 1999). It forms the basis for other contemporary developments such as the CORDlink variant of the GSC (Brodaric et al., 1999), the Digital Geologic Database Model of the Arizona Geological Survey (AZGS, Richard, 1998; Richard and Orr, 2001), or the Central Kentucky Prototype (Soller et al., 2002) and is an important component of the overarching USGS National Geologic Map Database (NGMDB, Richard et al., 2004).

Within the NADM geologic map units are modeled as objects of a so-called geologic-concepts subclass which contains all objects related to a geologic unit. Stratigraphy-related objects *sensu lato* are modeled as 1:$*$ relations and although rich in possible attributes providing the full range of terrestrial stratigraphic type assignments (e.g. litho-, chrono-, bio-, allostratigraphic) they are not related to each other in all aspects, i.e. on the object level. Geologic ages are related to stratigraphic eras via relationships classes so that erroneous data entries are avoided, however, assignments of, e.g. chronostratigraphic units or absolute ages do not necessarily involve feedback mechanisms that control the plausibility of entered values. In other words, when entering a specific age derived from radiometric dating or via other methods, the mapper is not limited by choosing stratigraphic attribute values or by selecting a certain chronologic basis. As this easily leads to inconsistencies on the contents level (not on the database level) a direct adaption of that particular data model component could not be made.

The ArcGeology Data Model (Gris and Brodaric, 2004) forms a simplified version of the NADM and operates with subclasses of concepts and occurrences that are related to stratigraphic ages (min and max values) via two relationship classes. According to the model documentation, however, pre-defined attribute values of stratigraphic, chronostratigraphic or chronologic systematics are not implemented.

The Geologic Mapping Template (GMT) developed by the ESRI Cartography Team (ESRI Cartography Team, 2009) focuses in particular on the implementation of the cartographic symbolization guidelines by the Federal Geographic Data Committee (FGDC, Federal Geographic Data Committee, 2008) and builds upon the concepts developed in the framework of the NCGMP. As stratigraphic systematics and ages are also incorporated through the FGDC guidelines, the model in copes with stratigraphic data model components in principle.

Within the GMT map units are modeled as feature-class objects of a feature datasets and contain attributes regarding ages that are controlled via domains. The coded-value domain consists of codes and descriptive fields that contain eras, periods and epochs on a non-hierarchical level. As an early (pre-NCGMP) and therefore deprecated alternative, ESRI incorporated an additional relation in which geologic ages are modeled via a relation consisting of attributes that are hierarchically organized and depict eons, eras, periods, epochs and fields for absolute ages as well as minimum and maximum values. Such an organization depicts reality more intuitively when compared to the recent model but it requires additional relationship classes that are not modeled in ESRI's most recent model version. The basic idea of having at least one additional relation for hierarchical attribute treatment seems to be an appropriate way to cope with different planetary objects.

Another approach is followed in the data model design by the Geological Survey of New South Wales (GSNSW) which has been created as personal geodatabase using ESRI's ArcGIS and MS Access (Xie, 2004). In the implementation version 1.3 stratigraphic names and geologic ages are simple attributes on the feature class level for a given rock unit. For a more precise depiction of surface types, additional subtypes are introduced which allow to differentiate between four subtypes of periods. Attribute values are controlled via domains and the geologic-age domain is a breakdown on the level of periods but a higher differentiation is not implemented. Also, a consistency check between ages, i.e. periods, and formation names is not established thus far.

A parallel branch of model developments was followed by the New Mexico Bureau of Geology and Mineral Resource (NMBGMR), mainly because of the complexity and modification requirements for adapting the NADM data model (Read et al., 2007, 2010). The NMBGMR works with a dedicated relation on geochronology data containing a variety of detailed information on chronologic boundaries. Additionally, there are a number of domains controlling object's attribute values down to the level of periods and epochs. The geochronology relation is designed to be used in connection with a feature class covering sample measurement points via a dedicated relationship class. In the data model, a relation on lithology is directly related to the geochronology relation. For all chronology entries, age ranges are directly hard-wired into descriptive attribute terms and thus it is not possible to use different age models for epochs and periods. For terrestrial purposes this is usually not necessary, for planetary geologic mapping, the proper assignment and identification of the employed chronology model is highly important.

In summary, some of the few geologic data models designed by terrestrial database designers, mappers and geologists are at a very mature level and require an in-depth understanding in order to be able to adapt model contents for specific settings. A high level of detail for the NADM led to the development of additional models that are either based upon NADM or that are completely re-designed. Both, the NMBGMR as well as the NADM show approaches that can be transferred to planetary geologic mapping and seem partially adaptable. Shortcomings from the viewpoint of planetary mapping require a re-implementation of aspects dealing with ages and chronology models which are discussed in the following chapter.

3 DATA MODEL DESIGN AND IMPLEMENTATION

3.1 Requirements and Aims

The terrestrial geologic data models discussed above do have a number of shortcomings that aggravate the direct transfer to planetary geologic mapping. Contrasting to this, terrestrial data models do often cope with a much higher degree of detail that is needed to depict field data efficiently and that is currently not available for planetary objects. We here outline the most important issues with respect to expectations and requirements for a planetary geologic data model that is intended to simplify a mapping process and emphasize the treatment of planetary chronostratigraphy across different planetary objects. The selection of requirements are taken from a detailed catalog which forms a development outline for the creation of an appropriate data model. These requirements affect the conceptual and internal data layer; the conceptual one depends highly on the actual implementation for which two methods are envisaged: a file-based structure to allow easy setup and transfer and a DBMS-driven structure for long-term persistent management.

Management requirements
M1: In order to allow different mappers to work with a common data model and provide feedback, the data model must be implemented as (exchangeable, see M2) file-based solution for which currently only ESRI's file geodatabase seems appropriate. DB migration and model redesign in order to benefit from a full-scale DBMS backend are an important aspect for the future.
M2: The model needs to be transportable, i.e. an exchange of data model via interchange formats (XMI) must be possible.
M3: The model needs to depict a high-level of interdependences without limiting later expansion and must applicable to all planetary objects.
M4: Each model component must be modular so that it can be seamlessly integrated into the existing base model. It must also provide junctions for linking additional model components defined in the course of the project.

Topical requirements:
T1: The model must grant facilities to check for erroneous data entries with respect to chronology data. These tests are most appropriately realized using a high level of detailed modeling on the level of subtypes and domain controls. Established terminology with respect to planetary chronostratigraphic units and chronologies should be covered in the data model either on the domain or subtype level in order to avoid erroneous data entries and to allow for convenient expansion (see M3 and M4).
T2: In order to maintain and update chronology data efficiently, chronology-related relations need to be defined and organized in a way that (a) access and maintenance is possible via any GIS connected to a DBMS and (b) the model is extensible and modifiable as soon as new chronology models and stratigraphic systematics as well as model ages are incorporated (see also M1 and M2).
T3: It must not be possible to enter attribute values independently that do in fact relate on each other (e.g. periods and epochs are directly related and must therefore be modeled directly). Historic assignments for formations and other lower-level systematics need to be handled efficiently and the data model must cope with future modifications (see T2).
T4: It must be possible to work with radiometric as well as crater-size frequency data in parallel. Both datasets must be fully modelled and related to spatial information.

3.2 Conceptual Design and Implementation Issues

Though the data model itself is relatively straightforward, the actual implementation using ESRI'S ArcGIS FGDB concept requires several modifications. These modifications are necessary in order to limit the use-interaction regarding data maintenance and attribute-data administration. The overall data-model concept was to simplify the process for geologic mapping and thus the model has to cope with this basic requirement. The data model has been tested initially in two scenarios. One is the lunar Apollo 15 landing site where a high level of detailed data is available either via digital sources or published Apollo 15 mission documents via the NASA History Office. The landing site area, although limited in terms of geologic complexity is related to a high level of available information on surface experiments and rock-sample locations. Along with these samples, radiometric age determinations are connected that form a perfect basis for testing the current datamodel concept. It allows to relate a high density of actual surface data with remotely-sensed geologic age data and forms a test bed for future missions to other planetary objects.

The other scenario is related to general geologic mapping of Mars for which a clear separation between geologic and geomorphologic map units must made. Additionally, different naming conventions brought up in the course of planetary exploration, different chronology models and systematics also lead to a high density of nested information. The implementation based on FGDB consequently differs from the baseline model (figure 2) in order to cope with FGDB limitations and to streamline and simplify the editing process.

The assignment of surface-unit attributes has been discussed in van Gasselt and Nass (2010a,b). Along with a detailed assignment of surface-unit characteristics it is possible to create surface-type attributes on a hierarchical level by selecting first genetic landform subtypes (volcanic, tectonic, sedimentary, ...) and select a more detailed description from a data-domain-driven list of attributes. This information is modeled via the FGDC cartographic standard (Geologic Data Subcommittee, 2006) with FGDC codes being hierarchically stored within the database (see also Nass et al., 2010). This way, units can be properly assigned and symbolization requirements can be directly integrated without having to

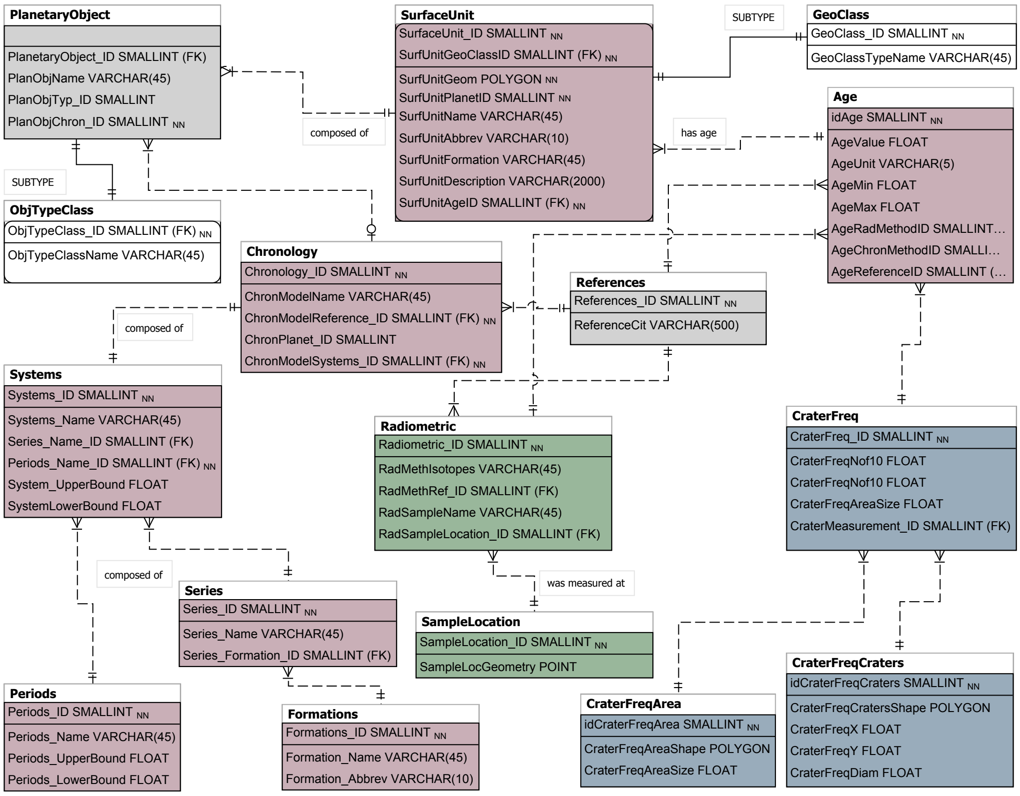

Figure 2: Enhanced Entity Relationship Model for managing planetary surface units and stratigraphic/chronologic assignments. Red colors refer to general entities related to mapping and chronostratigraphy in general, blue and green colors refer to crater-size frequency-based and radiometric data, respectively. This general conceptual layout had to be modified for use in a FGDB-based environment.

consult the printed standard document as suggested in other data-model descriptions (Richard et al., 2005; Geologic Data Subcommittee, 2006).

4 CONCLUSIONS

The presented data-model forms a sub-component of a larger-scale mapping model and has been tested individually using two planetary mapping objects with different level of detail regarding geologic and geomorphologic data. Both scenarios can be integrated within and depicted using the presented data model, however, adjustments had to be made for the FGDB solution to streamline the editing process. For DBMS-driven geologic mapping, more sophisticated query mechanisms (across relations and across spatial boundaries) are possible and additional tools could be easily implemented that allow more dedicated user-data interaction. This conceptual work will therefore be continued by (a) tuning it for FGDB use and (b) for expansion using DBMS-driven use. On the conceptual level, this component now needs to be integrated with the FGDC-based cartographic standards discussed earlier and forms finally the completed sub-component for planetary mapping.

One of the basic requirements was that entering already established data by the user should be minimized so that errors are reduced. This task requires work with respect to entering common background attribute data for geologic mapping and chronostratigraphic schemes for all major planetary objects. This rather cumbersome work is currently in progress and will probably be finished at the end of the year. For that time a component-based release is envisaged.

References

Albarede, F., 2009. Geochemistry: An Introduction. Cambridge University Press, Cambridge.

Arvidson, R. E., Boyce, J., Chapman, C., Cintala, M., Fulchignoni, M., Moore, H., Neukum, G., Schultz, P., Soderblom, L., Strom, R., Woronow, A. and Young, R., 1979. Standard techniques for presentation and analysis of crater size-frequency data. Icarus37, pp. 467–474.

Brodaric, B., Journeay, J. and Talwar, S., 1999. Using the proposed u.s. national digital geologic map data model as the basis for a web-based geoscience library prototype. In: Digital Mapping Techniques '99 – Workshop Proceedings, U.S. Geological Survey Open-File Report.

Dalrymple, G. B. and Ryder, G., 1991. Ar^{40}/ar^{39} ages of six apollo 15 impact melt rocks by laser step heating. Geophysical Research Letters 18, pp. 1163–1166.

Doggett, T., Figueredo, P., Greeley, R., Hare, T., Kolb, E., Mullins, K., Senske, D., Tanaka, K. and Weiser, S., 2007. Global Geologic Map of Europa. In: Lunar and Planetary Institute Science Conference Abstracts, Lunar and Planetary Institute Science Conference Abstracts, Vol. 38, pp. 2296–+.

ESRI Cartography Team, 2009. Geologic mapping template. Technical report, ESRI.

Federal Geographic Data Committee, 2008. Geographic information framework data content standard - part 0: Base document.

Gaddis, L. R., Skinner, Jr., J. A., Hare, T. M., Tanaka, K. L., Hawke, B. R., Spudis, P. D., Bussey, D. B. J., Pieters, C. M. and Lawrence, D. J., 2005. Lunar Geologic Mapping: Preliminary Mapping of Copernicus Quad. In: S. Mackwell & E. Stansbery (ed.), 36th Annual Lunar and Planetary Science Conference, Lunar and Planetary Institute Science Conference Abstracts, Vol. 36, pp. 2021–+.

Gaddis, L., Tanaka, K., Hare, T., Skinner, J., Hawke, B. R., Spudis, P., Bussey, B., Pieters, C. and Lawrence, D., 2004. A New Lunar Geologic Mapping Program. In: S. Mackwell & E. Stansbery (ed.), Lunar and Planetary Institute Science Conference Abstracts, Lunar and Planetary Institute Science Conference Abstracts, Vol. 35, pp. 1418–+.

Geologic Data Subcommittee, 2006. Fgdc digital cartographic standard for geologic map symbolization. Technical Report FGDC-STD-013-2006, Federal Geographic Data Committee (FGDC).

Gris, S. and Brodaric, B., 2004. ArcGIS Geology Data Model. Technical report, ESRI Redlands and Geological Survey of Canada.

Johnson, B. R., Brodaric, B., Raines, G. L., Hastings, J. T. and Wahl, R., 1999. Digital geologic map data model – version 4.3. Technical report, United States Geological Survey (USGS).

LPI, 2007. Lunar and Planetary Institute – Mercury Map Catalog. Internet URL http://www.lpi.usra.edu/resources/mercury_maps/.

LPI, 2010. Lunar and Planetary Institute – Geologic Atlas of the Moon. Internet URL http://www.lpi.usra.edu/resources/mapcatalog/usgs/.

NADM Steering Committee, 2004. North american geologic map data model (nadm) conceptual model 1.0 a conceptual model for geologic map information. Technical Report U.S. Geological Survey Open-File Report 2004-1334, U.S. Geological Survey.

Nass, A., van Gasselt, S., Jaumann, R. and Asche, H., 2010. Implementation of Cartographic Symbols for Planetary Mapping in Geographic Information Systems. Planetary and Space Science.

Neukum, G. and Ivanov, B. A., 1994. Crater Size Distributions and Impact Probabilities on Earth from Lunar, Terrestrial-planet, and Asteroid Cratering Data. In: T. Gehrels, M. S. Matthews and A. Schumann (eds), Hazards Due to Comets and Asteroids, University of Arizona Press, Tucson, p. 359.

Ogg, J. G., Ogg, G. and Gradstein, F. M. (eds), 2008. The Concise Geologic Time Scale. Cambridge University Press, New York.

Read, A. S., Rawling, G., Koning, D. J., Connell, S. D., Timmons, J. M., McCraw, D., Jones, G., Mansell, M. and Williams, S., 2010. Nmbgmr draft geologic data model - v. 1.0.1. Internet: http://geoinfo.nmt.edu/statemap/datamodel/.

Read, A. S., Rawling, G., Timmons, J. M., Connell, S., McCraw, D., Jones, G. and Smith, M., 2007. Nmbgmr draft geologic data model - v. 0.90. Internet: http://geoinfo.nmt.edu/publications/openfile/downloads/OFR500-599/500-525/507/507_CDROM/datamodel.

Richard, S., Craigue, J. and Soller, D., 2004. Implementing nadm c1 for the national geologic map database. In: Digital Mapping Techniques '04 – Workshop Proceedings, pp. 107–140.

Richard, S., Craigue, J. and Soller, D., 2005. National geologic map database (ngmdb) geologic map feature class model. In: Digital Mapping Techniques '05 – Workshop Proceedings, U.S. Geological Survey Open-File Report.

Richard, S. M., 1998. Digital geologic database model. Technical Report "Draft 1.0", Arizona Geological Survey.

Richard, S. M. and Orr, T. R., 2001. Data structure for the arizona geological survey geologic information system: Basic geologic map data. In: Digital Mapping Techniques '01 – Workshop Proceedings, U.S. Geological Survey Open-File Report.

Salvador, A. (ed.), 1994. International Stratigraphic Guide. 2nd edn, The Geological Society of America, Boulder, CO.

Skinner, Jr., J. A. and Tanaka, K. L., 2003. How Should Planetary Map Units be Defined? In: S. Mackwell & E. Stansbery (ed.), Lunar and Planetary Institute Science Conference Abstracts, Lunar and Planetary Institute Science Conference Abstracts, Vol. 34, pp. 2100–+.

Skinner, Jr., J. A., Hare, T. M. and Tanaka, K. L., 2006. Digital Renovation of the Atlas of Mars 1:15,000,000-Scale Global Geologic Series Maps. In: S. Mackwell & E. Stansbery (ed.), 37th Annual Lunar and Planetary Science Conference, Lunar and Planetary Institute Science Conference Abstracts, Vol. 37, pp. 2331–+.

Soller, D. R., Brodaric, B., Hastings, J. T., Wahl, R. and Weisenfluh, G. A., 2002. The central kentucky prototype: An object-oriented geologic map data model for the national geologic map database. U.S. Geological Survey Open-file Report 02-202, United States Geological Survey (USGS).

Stffler, D., Ryder, G., Ivanov, B. A., Artemieva, N. A., Cintala, M. J., and Greve, R. A., 2006. Cratering history and lunar chronology. In: B. L. Jolliff, M. A. Wieczorek, C. K. Shearer and C. R. Neal (eds), New Views of the Moon, Miner. Soc. Am. Geochem. Soc., Chantilly, pp. 519–588.

Stöffler, D. and Ryder, G., 2001. Stratigraphy and isotope ages of lunar geologic units: Chronological standard for the inner solar system. Space Science Reviews 96(1-4), pp. 9–54.

Tanaka, K. L. and Hartmann, W. K., 2008. Planetary time scale. In: The Concise Geologic Time Scale, Cambridge University Press, Cambrdige, pp. 13–22.

Tanaka, K. L. and Skinner, Jr., J. A., 2003. Mars: Updating Geologic Mapping Approaches and the Formal Stratigraphic Scheme. In: A. L. Albee & H. H. Kieffer (ed.), Sixth International Conference on Mars, pp. 3129–+.

Tanaka, K. L., Dohm, J. M., Hare, T. M., Irwin, R. P., Kolb, E. J. and Skinner, J. A., 2007. Mars Geologic Mapping: The Next Generation. LPI Contributions 1353, pp. 3143–+.

Tanaka, K. L., Dohm, J. M., Irwin, R., Kolb, E. J., Skinner, J. A. and Hare, T. M., 2009a. Progress in Global Geologic Mapping of Mars. In: Lunar and Planetary Institute Science Conference Abstracts, Lunar and Planetary Institute Science Conference Abstracts, Vol. 40, pp. 1975–+.

Tanaka, K. L., Dohm, J. M., Irwin, R. P., Kolb, E. J., Skinner, J. A., Miyamoto, H., Rodriguez, J. A. P. and Hare, T. M., 2008. Post-Viking Orbiter Global Geologic Mapping of Mars: Initial Steps. In: Lunar and Planetary Institute Science Conference Abstracts, Lunar and Planetary Institute Science Conference Abstracts, Vol. 39, pp. 2130–+.

Tanaka, K. L., Skinner, J. A. and Hare, T. M., 2009b. Planetary geologic mapping handbook – 2009. In: L. F. Bleamaster, K. L. Tanaka and M. S. Kelley (eds), Abstracts of the Annual Meeting of Planetary Geologic Mappers, NASA/USGS, NASA, pp. 58–78.

USGS, 2003a. NASA/USGS Planetary Geologic Mapping Program – Mars Geologic Maps in Progress. Internet URL http://astrogeology.usgs.gov/Projects/PlanetaryMapping/MapStatus/-MarsStatus/Mars_Status.html.

USGS, 2003b. NASA/USGS Planetary Geologic Mapping Program – Status of Venus Geologic Mapping. Internet URL http://astrogeology.usgs.gov/Projects/PlanetaryMapping/MapStatus/-VenusStatus/Venus_Status.html.

USGS, 2008. NASA/USGS Planetary Geologic Mapping Program – Lunar Geologic Mapping. Internet URL http://astrogeology.usgs.gov/Projects/PlanetaryMapping/Lunar/.

van Gasselt, S., 2007. Cold-Climate Landforms on Mars. Shaker, Aachen.

van Gasselt, S. and Nass, A., 2010a. Challenges in planetary mapping – application of data models and geo-information-systems for planetary mapping. In: A. Car, G. Griesebner and J. Strobl (eds), Geospatial Crossroads @ GI_Forum '10, Proceedings of the Geoinformatics Forum Salzburg, Wichmann, Berlin, pp. 79–86.

van Gasselt, S. and Nass, A., 2010b. Planetary mapping – the datamodel's perspective and gis framework. Planetary and Space Science (under review).

Wilhelms, D. E., 1990. Geologic mapping. In: R. Greeley and R. M. Batson (eds), Planetary Mapping, Cambridge University Press, Cambridge, pp. 208–260.

Wilhelms, D. E., McCauley, J. F. and Trask, N. J., 1987. The geologic history of the Moon. U.S. Geological Survey, Washington.

Williams, D. A., Keszthelyi, L. P., Crown, D. A., Geissler, P. E., Schenk, P. M., Yff, J. and Jaeger, W. L., 2010. Volcanism on Io: Results from Global Geologic Mapping. In: Lunar and Planetary Institute Science Conference Abstracts, Lunar and Planetary Institute Science Conference Abstracts, Vol. 41, pp. 1351–+.

Williams, D. A., Keszthelyi, L. P., Geissler, P. E., Jaeger, W. L., Becker, T. L., Crown, D. A., Schenk, P. M. and Rathbun, J. A., 2007. The Global Geologic Map of Io: Approach and Mapping Status. LPI Contributions 1357, pp. 147–148.

Xie, J., 2004. Nsw statewide geology geodatabase report. Technical report, Geological Survey of NSW (GSNSW).