Antonio Patera

Advanced techniques for the management of geological mapping

Thesis
Doctor of Philosophy

The Open University
Department of Information and Communication Technologies
Milton Keynes

September 2006

Abstract

The transfer of information from a 1:25.000 geological database to the printing of a 1:50,000 geological map sheet is a major problem in geological map production. It relates mainly to the greater detail of field information archived in the database with respect to that needed at a smaller representation scale. This research is focused on a new implementation of a geological database scheme that allows a digital version of the rules to be used by geologists and cartographers in the generalization process. Additionally, a system to avoid overcrowding of symbols is prototyped.

A review of the major works on multi-scale databases and on the concepts of categories and hierarchies has influenced the generalization model proposed for multi-representation. Geographic Information Systems provide the means to carry out the necessary operations.

The proposed system is based on the application of conventional and artificial intelligence computer techniques for the production of digital geological cartography, from the gathering of geological field data to the printing of a geological map. Four parts comprise the system:

- A support system for the identification and characterization of geological objects based on an *ad hoc* geological and stratigraphic dictionary;
- A GIS system for gathering geological data directly in the field using a hand-held digital device;
- A hierarchical geological database scheme for automated reclassification and generalization;
- A system for avoiding the overcrowding of bedding symbols during the production of a geological map. It considers the geological rules interacting between the geological objects represented in a map.

The research results justify the development of a more complete and general solution to the generalization of entire sets of geological features contained in geological maps. This will facilitate and speed up the production of maps, while helping the cartographer to guarantee a standardized traceable procedure for generalization.

Acknowledgements

I would like to thank my supervisors, Professor Adrian A. Hopgood, who patiently analysed the ideas presented in this thesis when they first evolved and who provided valuable guidance as the work matured, and Professor Andrea G. Fabbri, for the interesting discussions, the valuable comments, advice and support and especially for proof-reading this thesis.

Chapter 6 of this work is part of a joint research project carried out at the Geological Survey of Canada with the support of a NATO Advanced grant. I would like to thank Dr. Boyan Brodaric, supervisor of the research project, who has introduced me to research in automatic generalisation of geographic information and of geological databases and have provided valuable comments and material for this chapter of the work.

During my studies and work on this thesis I have had frequent contacts with the researchers of the Italian National Geological Survey. I would like to thank them and especially Architect Domenico Tacchia for his suggestions and useful advices and Mr. Valerio Vitale for is useful help.

Finally, I would like to thank my family for encouragement during this work and for helping me avoid drowning in thoughts about research.

Contents

List of figures

List of tables

Chapter One

1 Aim of the research

1.1 Introduction

During the last decade the diffusion of computer technology in the Earth Sciences has increased dramatically. Geographic Information Systems (GIS) have enabled geologists to compile a great amount of field observations that were processed, published, and archived into databases with the aid of automated techniques. The design of GIS for the Earth Sciences, however, still presents open problems arising from the very nature of geology, which being historical in character, differs substantially from other fields of geographic applications. The first geological surveys are dated to the 17^{th} century and most parts of the historical records and maps have been irremediably lost, destroyed or deformed. There is no method of recovering most of the data recorded in the past because geological processes such as erosion, deformation, recrystallization, reworking and melting, amongst other ones, have often obliterated past events, formations and other geological records. For this reason, imagination, reconstruction and interpretation are necessary to fill the gaps. Geology is basically concerned with the analysis, classification and description of 3D hidden complex structures that outcrop sporadically and unevenly on the Earth's surface and whose presence and extension is therefore affected by uncertainty and by gaps. The classification of such structures into homogeneous map units is an interpretative and subjective process that leads the geologist to a set of non-unique interpretations. Some important factors that may influence the decision process are the training and the preconceived ideas of an individual geologist concerning the significance of the data gathered, the historical records and the pre-existing classifications of structures or stratigraphies that are popular at the time of surveying, and the scale of mapping. Furthermore, classification schemes are neither unique nor definitive.

The identification or deduction of a geological object is iterative: evidence is gathered and hypotheses and theories are formulated, which are supported or rejected by further evidence. Revision of classification criteria determines the consequent reinterpretation and redistribution of geological objects into the new classes. After interpretation, the geologist synthesizes and encodes the real world geology in the form of symbols, which are displayed on maps using various visual artifices. A geological map is a generalized and abstracted form of synthesized knowledge that is essential in conveying the spatial and temporal aspects of geological history of an area (Schetselaar *et al.*, in press). This process usually involves the generalization passage from a large scale geological map, at which the geology has been sketched and recorded in the field, to the smaller scale of the printed product. This may lead to cartographic problems such as symbol overcrowding and overlapping.

A geological map depicts geological observations and interpreted geological objects that are often inferred from field observations. The representation of these objects as map entities is scale dependent, and the geometry may vary between points, lines, or areas (polygons). The symbolism of colour or text codes must be explained in a legend, which synthesizes the data and associated information (observations, measurements, analyses carried out on samples, sketches) archived into the database. To generate an ideal map directly from the database, the user should formalize the desired content and symbolization of the map that are then applied to the database to generate the new map or retrieve a previous one.

In Italy the 1:100,000 geological map, composed of 278 sheets, was completed and published only in 1976. Geological cartography has always had a vital role in the management of the environment, and just a few years after the publication of the map, the necessity arose for a more detailed and informative cartography. In 1988 the Government launched a new project, the CARG project (*CARtografia Geologica* or Geological Cartography), for the production of a new 1:50,000 digital geological map of Italy, composed of 652 sheets. The CARG project includes a very complex and detailed geological database with high information content. The 1:25,000 detailed geological information archived in the database shall be used for the printing of the 1:50,000 geological map and for the production of derivative and thematic cartography for the protection of the environment.

During the last decade, the Geological Survey of Italy (SGN, now named Agenzia per la protezione dell'ambiente e per i servizi tecnici or APAT) has published 13 volumes on the methodologies to be applied for the production of the geological map, from the gathering of 1:25,000 geological information in the field, to the classification of stratigraphic units, the stratigraphic dictionary, and the printing of the final 1:50,000 geological map (http://www.apat.gov.it/site/it-IT/APAT/Pubblicazioni/Quaderni/, Web reference accesses 30 May 2006). The cost for the survey and printing of each sheet is very high, around 1 million euros, and the problems to solve are still countless. Hence a potentially important research market exits for which solutions are needed.

1.2 Research proposed

This research is deemed to be of high importance in the solution of one of the main complex problems in geological map production, the transfer from the 1:25,000 geological database, at which data are gathered in the field, to the printing of 1:50,000 geological maps. The problems relate mainly to the greater detail of information contained in the database and the smaller printing scale. They can be classified into the design of a geological database scheme that allows the generalization process based on the rules relating the geological objects to one another, symbol overcrowding, and symbol overlapping. The challenge is to specify and implement a digital version of the decision rules used by geologists and cartographers to generate the final map. Often in practice these rules tend to be highly ambiguous, subjective, and inadequate in view of the modern need of automated generalization of geological information.

The proposed system is based on the application of conventional and artificial intelligence computer techniques to the production of digital geological cartography, from the gathering of geological data in the field to some printed product of wide usability.

The objectives may be summarised as follows:

1 A support system for the iterative identification and characterization of geological objects based on an *ad hoc* geological and stratigraphic dictionary;

2 The identification and implementation of a hierarchical geological database scheme for the automated reclassification or generalization of a geological database;

3 A hierarchical expert system for the automated revision and multiple representation of a geological database in view of new interpretation criteria of the geological information or for the production of *maps on demand*;

4 A system for avoiding symbol overcrowding or overlapping during the production of a geological map, which identifies the geological rules interacting between the geological objects represented in a map.

The research carried out for points 2 and 3 is part of a broader research activity that was started in 1996 at the Geological Survey of Canada (GSC) with the support of a NATO Advanced grant *Call 215.28/16 of 29th April 1995*, entitled *Investigation and development of techniques for geological map generalization using Relational Data Base technologies integrated with Geographic Information Systems,* under the supervision of Dr. Boyan Brodaric of the GSC in Ottawa, Canada, and Prof. Andrea G. Fabbri of the International Institute for Geo-information Science and Earth Observation, ITC, in Enschede, The Netherlands. The results of the collaboration, that still continues, are partly in several unpublished manuscripts and congress presentations (Brodaric and Patera, 1997; Brodaric and Patera, 1998; Brodaric and Patera, 2001; Brodaric *et al*., 2000; Brodaric *et al*., 2002; Fabbri *et al*., 1997; Patera and Brodaric, 2006) that are an indissoluble part of this work.

1.3 Thesis organization

This research is intended for anyone involved in the design of geological database systems and especially geologists, surveyors, cartographers, and technicians working at the production of the new 1:50,000 Geological map of Italy (CARG project). This includes researchers in geological database design, cartographic generalization, as well as computer scientists who are interested in the implementation aspects of object-oriented models in GIS.

The work is organized into 8 chapters as follows:

Chapter 1 gives a short overview of the research;

Chapter 2 introduces the concepts of database generalization and includes a short review on the major works on the subject;

Chapter 3 deals with the theoretical fundamentals of hierarchies, categorization, and generalization. Some research results are described that have influenced the design of the generalization model for the multi-representation proposed here. The importance of hierarchies for the modelling of geological multi-scale databases is also discussed;

Chapter 4 focuses on the architecture of Geographic Information Systems and on the operations that can be performed by the system provided in this research. The sections deal with topics related with the design of multi-scale databases, links between multiple representations of data, topologic consistency for spatial objects with multiple representations, and general constraints that should be incorporated into generalization processes;

Chapter 5 describes the geological object model developed in this research for collecting geological data in the field. The system has been implemented on a hand-held device connected to a GPS, according to the specification of the Italian CARG project (*CARtografia Geologica*, or Geological Cartography). Its purpose is the production of the new 1:50,000 geological map of Italy, based on field observations for a 1:25,000 basic representation;

Chapter 6 presents the hierarchical expert system proposed for automated revision and for multiple representation of a geological database in view of the new interpretation criteria of the geological information or for the production of *maps on demand*. A case study where the methodology has been applied is also provided;

Chapter 7 describes the rule-based system developed for symbol generalization and for the resolution of symbol placement conflicts, to preserve map legibility;

Chapter 8 concludes this work with further considerations. The results are analysed and discussed, as well as the main contribution of this research. Promising research areas are also identified and new directions are recommended.

Chapter Two

2 Multiple representations of reality

The chapter introduces the basic concepts of map and database generalization. A review of the major works on the subject is discussed. The approach followed and the results expected are presented and discussed. Commonly, generalization algorithms are based only on the geometric part of a geological object, ignoring the fact that the object may carry some topologic structure or geological information that must be preserved during simplification. Therefore, the generalization procedures should take into consideration metrical, topologic, and especially semantic and geological constraint types. This combination of constraints is often disregarded in the works reviewed to date.

2.1 Concepts of generalization

Multiple representations of geographic objects in a geographic database (often in short *geodatabase*) started to emerge as a research topic within the geographic information community in the 1980s (Buttenfield, 1989a). The amount of geographic data available has grown considerably: they are available in different formats and scales, and are usually generated by a diversity of procedures. Such multiple representations imply a considerable increase in the amount of archived data, introducing additional problems for the maintenance and integration of these data at different levels of detail. Progress in this field has concentrated in three different areas: *database issues, generalization issues,* and *spatial modelling issues* (Buttenfield, 1993).

Research has to focus on these issues to define a comprehensive formalism for the generalization and reclassification of geological relational databases for multiple representations or scale variations.

Database issues include mainly the incorporation of expert knowledge systems to produce spatial rules in order to preserve database consistency (Mark, 1991). Generalization issues are usually related to the simplification of geometric objects and the manipulation of the geographic database, in general with regard to display objectives. It is indeed the investigation of the semantic relationships between geological objects that requires further research.

Out of the multitude of approaches followed for geometric simplification, worth mentioning are the works of Douglas and Peucker (1973) and Lang's (Lang, 1969) for cartographic line simplification, of Brophy (1972) and Chaiken (1974) for line smoothing routines, of Müller (1990) for the post-processing procedure to clean up self-intersections generated by line simplification algorithms lacking topologic control, of Müller and Zeshen (1992) for the automated generalization of area patches over a two-dimensional space, the works of Puppo and Dettori (1995), and Tryfona and Egenhofer (1997) on model generalization and topologic issues, and the research on an integrated approach to the generalization of geological maps proposed by Downs and Mackaness (2002).

Spatial modelling issues are concerned with the scale at which several geographic processes are likely to impact the structure of geographic and geological features. Multiple representations of spatial data encompass changes in the geometric and topologic structure of a geographic object. These changes may occur with the value of the resolution at which the object is encoded for computer storage, analysis, and depiction (Buttenfield, 1989b), or may be the result of different hierarchical levels of details.

The concept of multiple representation in GIS means that the geographic object may be represented in several different ways, each one to satisfy the needs of different users or analysis operations. Spatial representations for different scales can differ both in accuracy and resolution (Dettori and Puppo, 1996). A less detailed representation means that the data contain simplifications of the original representation, but the topology and the relationships between the geographic objects should not change. Indeed, the reduction of the map resolution may change the topologic structure of a spatial object, as well as its shape. Furthermore, a different level of classification or a reclassification of the geological database may yield to topologic modifications. Figure 2.1 shows some possible changes in a multiple representation environment. Variations in resolution and in level of classification may affect the metric and topologic aspects of a spatial representation.

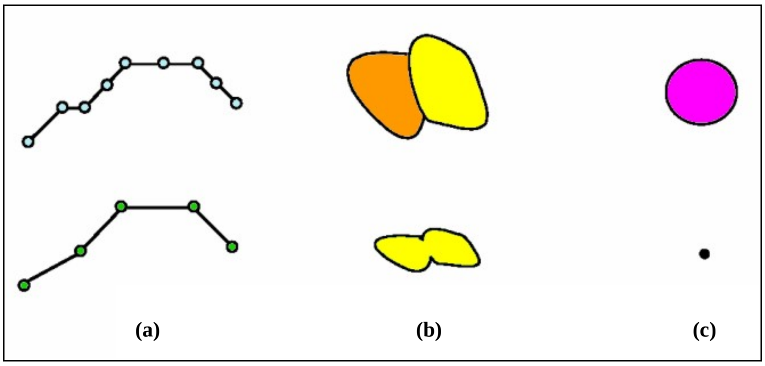


Figure 2.1. Variations in resolution and in the level of classification may affect the metric and topologic aspects of a spatial representation. Multiple representation changes are: (a) metric (simplification), (b) topologic (merge), and (c) topologic (collapse). (Modified after de Carvalho Paiva, 1998).

Metric changes are related to reduction in size and simplification of shape, while database multi-representation, generalization and topologic changes correspond to the recoding and merging of parts and changes in the dimensional representation of a spatial object. Shea and McMaster (1991) consider cartographic generalization operators for simplification and smoothing that are related to changes of the shape of the geographic feature. What is missing, however, is a focus on the aggregation, amalgamation, merging, and collapsing that are related to topologic changes on the geographic feature.

Ideally, multiple representation databases should be automatically derived from a single detailed representation in order to satisfy some specific user queries (Beard, 1988). This automatic approach would avoid the problem of maintaining additional information for the same data.

Müller *et al.* (1995) identify two conceptual levels for map generalization: *cartographic* generalization, which attempts to eliminate visual conflicts, and *model* generalization, which addresses reduction in detail but not the elimination of any object at the representational level, relying on semantic abstraction mechanisms. Within the realm of model-based generalization, Tryfona and Egenhofer (1997) developed a systematic model for the constraints that must hold with respect to spatial objects when two parts of an object are aggregated.

McMaster and Veregin (1996) describe some approaches to provide multiple representation of a database:

- The creation of multi-scale versions for the same data by acquiring the information for different scales. Multi-scale databases have multiple representations for one object, each one for the respective scale;
- The development of robust data structures to support multiple representations, such as hierarchical data structure;
- Application of generalization algorithms to create multiple versions of a database.

The last two approaches are the foundation of the work carried out at the Geological Survey of Canada, and the seeds of new research, while the first one does not fit very well the intrinsic nature of the geological information.

Multiple resolution databases have a close relationship with cartographic generalization. By applying generalization algorithms, new data can be generated, and it is important that the generalization procedure preserves the general structure of the data in order to avoid incorrect results for queries performed at different levels of detail. Database integrity should be optimized between different levels of information for a multi-scale database.

The creation of multiple representations of geological data derived from automated generalization procedures requires a better knowledge of the semantics of these operations. Clearly it becomes necessary to develop computational tools that permit verification of the overall quality of the generalization result in terms of topologic, directional, semantic, and geological properties.

The generalization operations should rely on a relational data model that represents a spatial scene as a hierarchy of graphs. This relation-based model should be built from the topologic relationships between the spatial object representations (de Carvalho Paiva, 1998).

As stated earlier, the term *generalization* can be associated with cartographic generalization, which is concerned with shape of the geometry, or it can be associated with model generalization, which is concerned with qualitative topologic information. It is therefore evident that model generalization must be more closely related with new qualitative models that need to be developed.

Users have diverse needs that require geographic and geological data at different levels of detail. Geological maps at different geographic detail are examples of applications that need multiple representation levels. One critical point in geological databases with multiple levels of detail is to maintain the topologic consistency between the spatial objects. The term consistency is abstract and depends on the constraints applied. Inconsistencies among multiple representations may be fatal where high-level decisions, on one model of geographic reality, are passed down to detail planners who have contradictory information at hand, or vice versa. In this case, recommendations are made with map information that does not agree with the information available at the decision level (de Carvalho Paiva, 1998).

Current GIS lack methods to maintain consistent multiple representations of geographic objects, especially geological objects. There has been research in the last decades on various aspects of multiple representations. Some of them are related to data models (Bruegger and Frank, 1989; Timpf *et al.*, 1992), cartographic generalization (Buttenfield, 1991), and modelling and querying (Rigaux and Scholl, 1994), but all of them are weak in the analysis of the geological and topologic consistency of objects related with their spatial relationships. It is important to have consistent object characteristics through different levels of representation to allow a query at a coarser level to give the same or at least a very similar result as on a more detailed level.

2.2 Main works on model generalization

Model generalization has been the subject of numerous contributions in the discipline of cartography. For this research more than 220 articles have been collected and analysed. Recent literature has addressed the subject with regard to issues in GIS and digital databases. Müller (1990) outlines the underlying *motivations* for generalization in today's environment in terms of various requirements. The economic requirement controls the amount of data populating the original ungeneralized database, and has direct bearing upon the extent of necessary or desirable generalization. Data robustness is addressed through generalization as data errors are smoothed out and basic trends emerge. Graphics generated by modern GIS and spatial decision support systems often are utilized for decision-making, and make up the display and communications requirements for generalization. Finally, modern digital databases are generally designed for multiple applications at a variety of scales, and generalization is necessary to fulfil these multipurpose requirements.

The question on *why we generalize* in the context of a digital environment was first posed by McMaster and Shea (1988). Their categorization of philosophical application and computational objectives provides a checklist of guidelines or goals for generalization. Philosophical objectives include reducing complexity, maintaining both spatial and attribute accuracy, maintaining a logical hierarchy, consistently applying generalization rules, and maintaining aesthetic quality. The selection of the appropriate scale given the map purpose and intended audience, and the maintenance of clarity make up the application objectives. Their computational objectives stress maximising the performance of algorithms and amount of information retained while minimising data storage and the requirements of the algorithms memory. A follow-on paper describes mapping situations when conditions warrant generalization (Shea and McMaster, 1991). The authors define six conditions that may occur with scale changes:

- Congestion
- Coalescence
- Conflict
- Complication
- Inconsistency
- Imperceptibility.

Because these conditions are often highly subjective and difficult to quantify, certain measures are available to aid in their determination. Measures such as distance, length and density are quite distinct, but categories of distribution, shape, and abstract measures are seemingly just as subjective and vague as some of the conditions. Many researchers have sought to refine the broad concept of generalization into manageable pieces.

The aspect of generalization most relevant today is the digital generalization of a geological database, defined as the application of both spatial and attribute transformations in order to maintain clarity, with appropriate content, at a given scale, for a chosen map purpose and intended audience.

With digital databases emerging as the backbone of current cartographic and GIS applications, the formalizing of digital generalization methods will most likely occupy much of the literature in the near future. Automated map design systems will rely upon a hierarchical knowledge base to perform generalizations upon digital databases when necessary. The challenge is to design a geological database scheme that allows the generalization process on the rules relating the geological objects to one another and to specify and implement a digital version of the decision rules, often highly ambiguous, subjective, and inadequate for the world of automated generalization of geological cartography.

Other distinctions have been made within the realm of digital generalization. Brassel and Weibel (1988) consider *cartographic* generalization to encompass only those operations affecting the displayed version of the database. Operating upon the stored information is termed *statistical generalization*. Alternatively, statistical generalization could be thought of as primarily emphasizing the positional accuracy while cartographic generalization worked on *visual effectiveness or recognisability* (Buttenfield, 1989a).

Other works on the generalization process deal with the application of the proper generalization operator. The literature abounds with operator descriptions (Buttenfield and Mark, 1991; Weibel, 1987; Shea and McMaster, 1991; Beard and Mackaness, 1991).

The notion that generalization for multiple representations should be applied using criteria specific to the present geographic and geological phenomena is prevalent in the recent literature. The dominant rule in Mark's (1991) geographic generalization is that the preservation of geographic relationships among features is paramount during generalization.

Once an operator has been selected, digital generalization is performed through a particular algorithm. Because the majority of cartographic information is represented as lines (note that the term *line* is often used in a GIS as a shorthand for *polyline* and it has been used with this meaning throughout this work), most published algorithms work on linear features, besides geological objects are mainly polygons. A good summary of line generalization algorithms can be found in Zoraster *et al.* (1984). Generalization of the detailed database may serve the needs of future users for data views at multiple scales.

2.3 Approach proposed

This research focuses on how reality is abstracted into maps, and how the same reality is abstracted differently in different maps, even though the categories in the different maps are part of the same geological database. The concern is therefore how to generalize a geological database in the view of new classification criteria or for multiple representations of the archived geological information. This will be performed through an *ad hoc* structuring of the database scheme and a hierarchical expert rule-based system based on SQL queries for the physical extraction of the required information. In the proposed system, the generalization operations rely on a relational data model that represents a spatial scene as a hierarchy of graphs. This relation-based model is built from the topological and geological relationships between the spatial objects representations.

A system based on traditional rule-based technique will also be developed in order to avoid symbol overcrowding and overlapping due to change in scale or to the presence of aggregated information that may lead to an ambiguous product or with poor aesthetic map properties.

In this context, consistency across multiple representations refers to the lack of any logical contradictions within a model of reality. Databases with multiple levels may be a result of complex transformations, termed *generalization operations* in cartography. This work will focus on the aggregation, amalgamation, and merging that are related to topological changes on the geographic feature. Each transformation reduces the complexity of a representation level and generates a representation level that is at most as general as the original representation. Each representation level represents a spatial scene, which corresponds to a set of objects that are related by geological and topological relationships. Given two spatial scenes, they can represent at a fixed or variable scale the same area with a different level of geological details. Therefore, the generalization procedures of a geological database or map should take into consideration metrical, topological, and especially in this work, semantic and geological constraint types, together with the elimination of visual conflicts between the geological objects plotted on a map.

The hypothesis of this research is that a qualitative spatial data model is needed and can be developed for querying and multi-representing the information stored in a geological and topological database. The hypothesis is proven by a hierarchical and topological qualitative model that supports the multiple representations of spatial objects, and by designing and implementing an algorithm to query the hierarchies in the database. The major task is to identify what the geological components of this hierarchy are to provide, the qualitative model that supports the development of tools, and the identification of the hierarchical expert rule-based system for the generalization process.

This research proposes and develops a new formalism to model spatial objects and spatial relationships between several objects that may be represented at multiple levels of detail. This work focuses on the topological consistency constraints that must hold among the different representations of geological objects. However, the research is not concerned with generalization operations related to deriving one representation level from another as in Beard and Mackaness (1991), or McMaster and Shea (1992). Topological consistency is considered here at a higher level, dependent of the way spatial objects are encoded. Usually, topology in a GIS is concentrated at the conceptual level of nodes, lines, and areas and the topological consistency is treated by counting and analysing the number of arcs and nodes and their relationships to guarantee that a map topology is complete. This method is appropriate to evaluate topological structure changes by metric changes on the object. However, it does not capture the relationships among the geological objects, such as a change in the dimension of a geological element, the aggregation of several parts into a single object, or the elimination of an object. Often works in multiple representations have focused just on geometric generalization, like the algorithms of Douglas and Peucker (1973) to derive a coarser line from a line with more detail, while there has been a lack in the database generalization research.

The terms *layer* or *feature class* in this research apply to the spatial object representations for a geographic area. These representations may be points, lines, or areas (polygons). Every line has at least two points (with two of them being end points), and each polygon is composed of a list of (or just one) connected lines. The set of lines and points of a layer form a planar graph, and the polygons of the scene correspond to faces of the graph.

Normally a GIS organizes the information about objects using a data structure that stores the points, lines, and polygons of a layer with additional topological information that make it possible to derive adjacency, connectivity, and inclusion relationships between objects, without needing to use the geometric information. In a graph representation layers are described through a set of graphs having connected elements and isolated elements. The graph nodes represent the objects and their attributes, while the graph arcs store the spatial relationships between these objects.

2.4 Expected results

A comprehensive formalism to generalize geological relational databases for multiple representations and for reclassification purposes or for scale variations through the use of a hierarchical expert rule-based system and SQL statements is one of the results of this research. The method employed is based on the categorization of the hierarchically restructured geological information. This generalization supports consistent topological changes for objects like areas and regions, and complexly structured objects such as areas included in other areas (*island polygons*) and objects with separations. The result of this research work is important in the process of developing multi-representation of geological databases as it frees database developers from the tedious task of manually comparing geological databases that are represented at different scales, and finding discrepancies among the different representations. It also enables database designers to test whether the implementations of new generalization operations perform as desired. Furthermore, in geology classification criteria and schemes are not everlasting. The introduction of new encoding rules may modify a geological classification scheme. The proposed system can accommodate any change in the classification scheme in an easy and logic fashion.

3 Categories, hierarchies and generalization

This research provides a new system to automatically generalize the information from a geological database to obtain multiple representations in map form. The maps are designed using a hierarchical rule-based modelling system that will be described in Chapter 6.

How the human mind conceives geological, and generally speaking, geographic information at various scales is an important aspect of how the model should be designed. This chapter documents research results from cognitive science that have influenced the design of the model proposed.

The second section of the chapter deals with the theory and the types of hierarchies, that are investigated on a theoretical level. First, why hierarchies are important for the modelling of multi-scale geological databases is discussed. Then, a hierarchy is defined mathematically and three different types of hierarchies are considered. Finally, it is examined how these hierarchies can be combined.

The generalization of spatial data is analysed in the third section of the chapter. Several different theoretical and practical approaches that have been found in the literature offer the ground for constructive considerations.

3.1 Categories

Categorisation is an important aspect in cartography as well as in hierarchical modelling. Lakoff (1987) states that *without the ability to categorise, we could not function at all.* How humans treat categories in general has implications on how categories in geological information vary with scale. He also claims that there are two main views in the category theory: the *classical approach*, which can be traced back to Aristotle, and the modern approach, termed *prototype theory* (Rosch, 1973). This work will deal only with the classical approach, in which there are no members in a category that represent the category better than other members.

In the classical approach categories have the following characteristics, as summarised by Dunkars (2001):

- Categories are believed to exist independently of human beings. Since the categories already exist all we have to do is to discover and define them;
- Categories act as containers and a particular thing is either inside or outside a container;
- Things are assumed to be in the same category, if and only if they have certain properties in common;
- The properties that things have in common define the category;
- All members of a category are considered to be equal members. There are no members that are better examples of the category than other ones.

There are similarities between this view on categories and how object classes are defined in an object-oriented modelling. How the real world is abstracted into object classes is, however, a matter of design and always depends on the application used (Rumbaugh *et al.*, 1991).

The following is a short list of the main types of categories and their relationships with geological objects.

3.1.1 Extendable boundaries of categories

Wittgenstein (1953) points out that different mathematicians provided different definitions depending on their goals. This point fits very well to geological data, where the geologist's interpretation of geological objects and structures is strictly a subjective process. Furthermore, categories in geological and geographic information are extended as humans make new discoveries. For instance, the category *chemical elements* evolved during the 19th century to incorporate *radioactive elements.*

3.1.2 Conceptual embodiment

Conceptual embodiment is the idea that human biological capabilities and human experience of functioning in a physical and social environment influence how categories are formed (Dunkars, 2001).

If the idea of conceptual embodiment is applied to geological information, we realise that the categories have been formed through several different experiences. In the case of the category *geological formation* it can consist of: interactions with the environment such as walking in different areas in the field, studies in geology, and through looking at different maps that depict the geology of the area.

3.1.3 Basic-level categories

Basic-level categorisation (Dunkars, 2001) is a concept that further illustrates how human experience influences how categories are formed and organised. Categories are organised not only in a hierarchy from the most general to the most specific, but also categories that are cognitively basic are *in the middle* of a general-to-specific hierarchy. An example of such a hierarchy in geology is: *supergroup* → *group* → *formation* → *member* → *bed*, where *formation* is cognitively basic. Generalization proceeds *upward* from the basic level *formation* and specialisation proceeds *downward* from the lower level *member*. See Sub-section 6.2.1 for a full explanation of general and lithostratigraphic hierarchies in geology.

3.1.4 Multiple representation

Classical categorisation assumes that there always is a single correct way to categorise any phenomenon. *Prototype theory* (Rosch, 1973) on the other hand presents a more flexible view that allows for multiple representations of individual concepts. An individual often holds more than one kind of representation of a concept suited to different applications. A cartographer, for instance, may accept digital geographic databases as being *maps* at a conceptual level but, when looking in a bookstore for tourist maps, he will surely look for a printed map.

3.1.5 Human pattern recognition

The human visual system is very efficient at recognising shapes and bringing up knowledge into the consciousness about what is seen from the *long time storage* in the brain. Consider, for instance, the case where we collect in the field a rock that we have not seen for years. We are usually able to recognise it, which implies that there is some form of visual memory. The brain then immediately retrieves all kinds of information about the rock. This knowledge may not have been in the consciousness for years.

The human ability to recognise image patterns seems particularly interesting for the field of cartography, geology, and geographic information science. Map reading is to a large extent a matter of interpreting shapes displayed on a 2D surface to extract knowledge about the 3D real world environment.

MacEachren (1995) says that it is equally difficult to transform knowledge in the opposite direction, from image to procedural, and therefore should be equally difficult to transform knowledge that is stored in an image form into propositional knowledge, and the reverse. The rock picking example above illustrates this, and another example can be constructed for different types of rocks. I have a detailed knowledge of what a dolomite rock looks like, because I am able to immediately recognise a dolomite when I see it in the field. This recognition process is fully automatic. It is, however, very difficult for me to describe a dolomite rock using propositional knowledge, in words, with such detail that someone who is not familiar with this particular rock should be able to recognise it. How this ability to recognise patterns influence modelling of geological information will be elaborated further on in this work.

3.1.6 Categories in cartography

Robinson *et al.* (1995) describe the basic characteristics of a map:

- All maps are concerned with two elements of reality, *locations* and *attributes*, where the attributes contain information about qualities and magnitudes;
- All maps are reductions and a map is smaller than the region it portrays;
- All maps involve geometric transformations through a map projection;
- All maps are abstractions of reality in such a way that maps only portray the information that has been selected to fit the use of the map;
- All maps use signs to stands for elements of reality. These signs consist of various marks such as lines, dots, colours, tones, patterns, shades, icons and so on.

It is natural to agree with Robinson *et al.* (1995) when they say that it is necessary to study and analyse the characteristics of perception as they apply to maps so that symbolisation and design decisions can be based on objective rules**.**

The aim of cartography is communicating geographic knowledge, as shown in Figure 3.1. The knowledge about the geological information exists and is utilised by the geologist-cartographer to design a map. The knowledge portrayed in the map is acquired by another geologist through map reading. At each stage in this process there is a risk that knowledge might be lost and efforts have been made to measure this information loss. Furthermore, the knowledge that can be retrieved from a map depends on the previous experience and training of the map reader. MacEachren (1995) states that *the map is examined here, then, not as a communication vehicle, but as one of many potential representations of phenomena in space that a user may draw upon as a source of information or as an aid to* *decision making and behaviour in space*. This seems to be a constructive view worth adopting. In Chapter 5 the role of the geologist in the system proposed will be discussed.

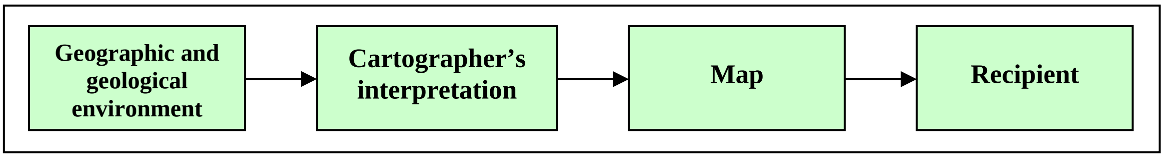


Figure 3.1. A schematic depiction of cartography as a process of communication. (Redrawn after Dunkars, 2001).

3.2 Hierarchies

Current Geographic Information Systems (GIS) lack the structures, tools, and operations to handle multiple representations and especially representations with multiple levels of detail (Timpf and Devogele, 1997). One reason for this is that very little is known about using hierarchies for the description of ordered levels of detail. Hierarchies appear in many different spatial contexts, for instance, geology, road networks, political subdivisions, landuse classes, hydrological watersheds. But hierarchies appear also in non-spatial situations such as organizational hierarchies. It is the intrinsic nature of a hierarchy that has not yet received much attention and this lies at the basis of the problems with hierarchies in GIS.

The assumption seems promising that many individual object-systems with simple behaviour form a whole object-system with complex behaviour. For instance, a map series is a complex object-system composed from many maps. A map in its turn is also composed of many elements. It can be also assumed that the organization of the individual objects is hierarchical, the complex object being on top of the hierarchy. The work by Brodaric and Patera (1997) provides an instance in geology where stratigraphic information has a clear hierarchical origin.

Literature on the theory of hierarchies in geographic information is scarce and the main works have been published in the 1980s and the 1990s. There are two areas in hierarchy research that contribute to the questions examined in this research. In *cognitive science*, hierarchies are examined as a way of how humans represent the world. In *system theory* the observation is made that most biological systems are hierarchically structured and this structure is applied to non-biological systems, such as to a geological system.

3.2.1 Hierarchies in cognitive science

Hierarchies are fundamental to human cognition and have been studied in cognitive science (Timpf *et al.*, 1992). Humans arrange information hierarchically and use hierarchical methods for reasoning. *Hierarchization* is one of the major conceptual mechanism to model the world, the other ones being mainly *prototypes* or *relationships*. The idea is to deduce knowledge at the highest (coarsest) level of detail in order to reduce the amount of facts taken into consideration. Too much detail in thinking means long and inefficient reasoning.

Humans construct hierarchies by abstracting information, that means by building ordered classes of information. For instance, when seeing a tree, one recognizes that the brown long trunk in combination with the green leaves fall into the object category *tree*. In this example, the spatial arrangement of the entity from the class *leaves* and the entity from the class *trunk* suggests that the aggregate entity belongs to the class *tree*. The corresponding hierarchy is an aggregation hierarchy. Hierarchies of entities in the world of geology result in multiple representations within a spatial database.

What makes the conceptual task of modelling hierarchies so difficult is the fact that humans are able to switch between different types of hierarchies (attributes, classes, instances, tasks etc.). Humans do not even notice that they are using different types of hierarchies simultaneously. It is assumed that this fact is the main impediment to the investigation of representations with multiple levels of detail.

3.2.2 Hierarchies in systems theory

In systems theory the observation is made that most biological systems are hierarchically structured and this structure is applied to non-biological systems.

Complex systems are usually hierarchically structured. There are several advantages to a hierarchical structure. The system has a number of interrelated sub-systems that are themselves hierarchically structured. Each sub-system is a stable intermediate form and can function without the *help* from the complex structure. All forms in evolution are stable intermediate forms.

Three types of hierarchical systems can be distinguished by the types of levels (Timpf, 1998):

- Level of abstraction;
- Level of decision complexity;
- Organizational level.

The level of abstraction in a hierarchical system expresses the fact that some objects in the system may be more abstract than others, and the level imposes an order on the objects. The level of decision complexity creates a hierarchy of decision layers, meaning that decisions in a system are broken down to decisions of sub-systems. The original decision is made with a certain margin of error, because not all sub-systems may be able to decide. The organizational level creates a set of organizational hierarchies as in a human formal hierarchy.

3.2.3 Definition of hierarchy

A hierarchy is an ordered structure. Order can be established between individuals or between classes of individuals. The partial ordering can be depicted as a tree with the vertices denoting the individuals of the domain and the edges representing the ordering function between individuals.

The notion of levels is introduced through the idea that vertices V_i at the same depth of the tree belong to the same level of the hierarchy. Thus, there are as many levels in the hierarchy as the tree is deep. The highest level is the most abstract level of the hierarchy, the lowest level is the most detailed level, as depicted in Figure 3.2.

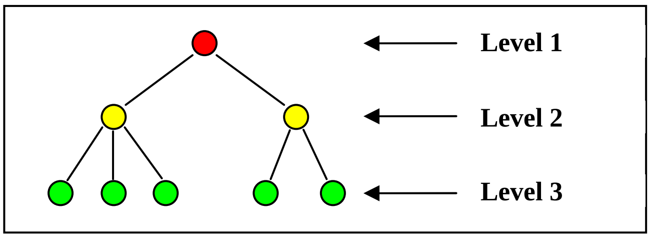


Figure 3.2. Vertices (circles) and levels (colours) in a hierarchical tree**.**

A hierarchy is intricately linked to the idea of levels (or ranks). Individuals on the same level share a common property, e.g., *formations* have the same level in a geological classification tree, or map objects have the same level of detail. The order of the levels is always total, although the order between individuals in the hierarchy is only partial.

Hierarchies can be distinguished by the way they are constructed (Timpf, 1998). The distinction lies in the ordering function between individuals or classes of individuals. The most common function to build a hierarchy is the aggregation function. Classes of individuals are aggregated because they share a common attribute.

In the next section several distinct types of hierarchies will be investigated. A hierarchy is an ordered structure with a total order between its levels, but with a partial order between individuals or classes of individuals. The structure has sub-structures that are also hierarchies. The function that establishes the order must be reflexive, antisymmetric, and transitive.

3.2.4 Types of hierarchies

Hierarchies are formed through abstraction, e.g., through factoring out commonalities in the description of several concepts into the description of a more general concept. In software development three abstraction mechanisms can be identified (Timpf, 1998):

- *Aggregation*;
- *Generalization* or classification;
- *Filtering*.

The abstraction mechanism of classification is a prerequisite for all other abstraction mechanisms. It is necessary to classify objects before applying to them operations like *aggregate*, *generalize*, or *filter*.

3.2.4.1 Aggregation

We term *aggregation hierarchy* (Timpf, 1998) the type of hierarchy that is constructed by aggregating sets of area features in close proximity into new single area features: for instance, in stratigraphy a geological bed can be aggregated with other beds to form a larger one if it is spatially adjacent and belongs to the same member. The possibility of aggregation depends therefore solely on a given attribute of the individuals. Many geological data types such as units, rock types and time scales are commonly categorised and organized into hierarchical arrangements formed by many levels of components that are ranked according to a specific scheme and that can be aggregated according to specific rules.

The aggregation hierarchy is the most common type of hierarchy. The aggregation function maps a set of individuals to a single individual, or it maps a set of classes of individuals to a single class of individuals. The end of the aggregation is reached if there is only one individual or class of individuals left as argument of the function. The type of the individuals is the same throughout the hierarchy. Only individuals of the same type can be aggregated.

3.2.4.2 Generalization

The *generalization hierarchy* (Timpf, 1998) defines classes as the more generic the higher the level of the class in the hierarchy. E.g., *members* belong to the generic class *formation*, or *groups* belong to the generic class *supergroup*. This type of hierarchy has also been called *classification hierarchy* by Molenaar (1993).

In few words, the generalization hierarchy relates a class to a superclass. The generalization function states explicitly which classes generalize to which generic classes. This can be visualised as a hierarchy of classes with the most generic classes at the top level (as for *Level 1* in red in Figure 3.2). Individuals change their type when generalized, e.g., individuals represented in green (*Level 3*) become individuals represented in yellow (*Level 2*) after the generalization**.**

Aggregation and generalization are the abstraction mechanisms that have been used in the hierarchical rule-based expert system proposed in Chapter 6. The system generalizes the information archived in the geological database at a higher hierarchical level without modifying the shape of the geological objects in the geological map.

3.2.4.3 Filtering

The *filter hierarchy* (Timpf, 1998) applies a filter function to a set of individuals on one level and generates a subset of these individuals on a higher level. The individuals at the higher level are always represented at a lower level. Individuals pass the filter at one or more levels of detail. Individuals that do not pass the filter disappear from the representation, as shown in Figure 3.3. This is the most striking difference between aggregation and generalization hierarchies and the filtering hierarchy**.** The class and the type of the individuals stay the same.

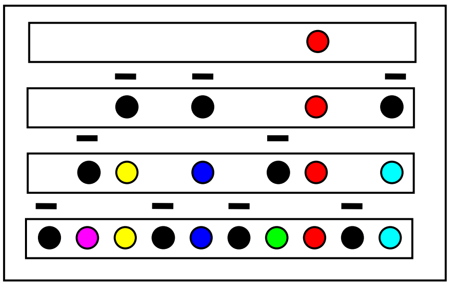


Figure 3.3. Filter hierarchy (Redrawn after Timpf, 1998). Circles flow from the bottom to the top. Only coloured circles pass the filter. Black circles are coloured circles that have been blocked by barriers (black dashes) acting as a filter and cannot flow from a lower level to an upper level.

3.2.5 Combining

It can be noted that the three types of hierarchies (aggregation, generalization and filtering) have a relationship. For instance, a filter hierarchy can be deduced from a generalization hierarchy, and the filter hierarchy is the mechanism that creates the aggregation hierarchy.

3.3 Generalization in digital systems

In comparison with generalization in conventional cartography, generalization in digital systems has to be taken with a wider meaning: each transition from one model of the real world to another, which comes with a loss of information, requires classification and *generalization*.

3.3.1 Database design

Database issues in multiple representations are concerned with how to accommodate the different sources of information in a single or multi-version data management strategy. These multiple sources of information need to be maintained consistently, and it is important to organise the multiple topological and metrical information for efficient access and to implement links between these multiple representations (Buttenfield, 1993).

A transformation from a large-scale map (such as a geological sketch drawn in the field on a 1:25,000 topographic map) to a small-scale map (such as the final 1:50,000 geological printed map) involves changes that may introduce inconsistencies among representations, which may affect the outcome of queries. Due to the inadequacy of automated generalization software, especially in the field of geology, it may not be feasible at this time to store a single representation and then derive other representations that satisfy user queries for specific scales and a specific level of geological detail (Beard, 1988). As a result, multiple representations for the same data have to exist, and we expect consistency among them. Multi-scale databases generate multiple representations of data, and some main goals during the design of a multi-scale database are the following (Jones *et al.*, 1996):

- Maximise the database integrity with multiple representations;
- Reduce the need of interactive intervention in update operations;
- Automate the retrieval of spatial information relating to phenomena with multiple representations.

Most current Geographic Information Systems use only one level of abstraction to represent the real world. This single level of abstraction reduces the system utility as topological queries can take a long time to be satisfied due to the large amount of data archived. A solution is therefore needed that allows GIS to support multiple levels of abstraction by linking the different representation levels through hierarchical relationships.

3.3.2 Automated generalization

The need to keep the consistency at different levels of detail in a multiple representation database introduces additional constraints on the process of automating cartographic generalization. The latter requires the application of both the spatial and the attribute transformations to maintain data integrity and appropriate content for a resultant scale. Digital generalization includes intrinsic objectives like *why we generalize*, situation assessment like *when we generalize*, and spatial and attribute transformations like *how we generalize*. The process of how to generalize corresponds to a set of generalization operators to be applied to maps in order to solve possible spatial conflicts.

Operators to reduce the number of objects, spatial operators, attribute operators, and display operators have been proposed in the literature to specifically respond to conflict resolution. Those operators are referred to as *structural operators*, which simplify or abstract the level of detail, and *display operators* which adjust the graphic display to ensure legibility. Figure 3.4 shows some generalization operators that may affect the general topological structure of the data. Following is a description of the most commonly used operators:

- *Aggregation* corresponds to joining a group of different features into a higher-order feature, when for instance we generalize from a lower to a higher rank in a lithostratigraphic units tree (for instance, *bed* → *member* → *formation* → *group* → *supergroup*).
- *Merge* means to represent a feature as a lower-order feature, such as representing all the formations belonging to a group.
- *Amalgamation* joins features of the same class into a larger element of this class, for instance different beds belonging to the same member.

All these operations should correspond to the objectives of new research. For instance, collapse, simplification and smoothing may change the general shape of a line or of a polygon, which may cause changes in the relationship of the geometric feature with other components of the map**.**

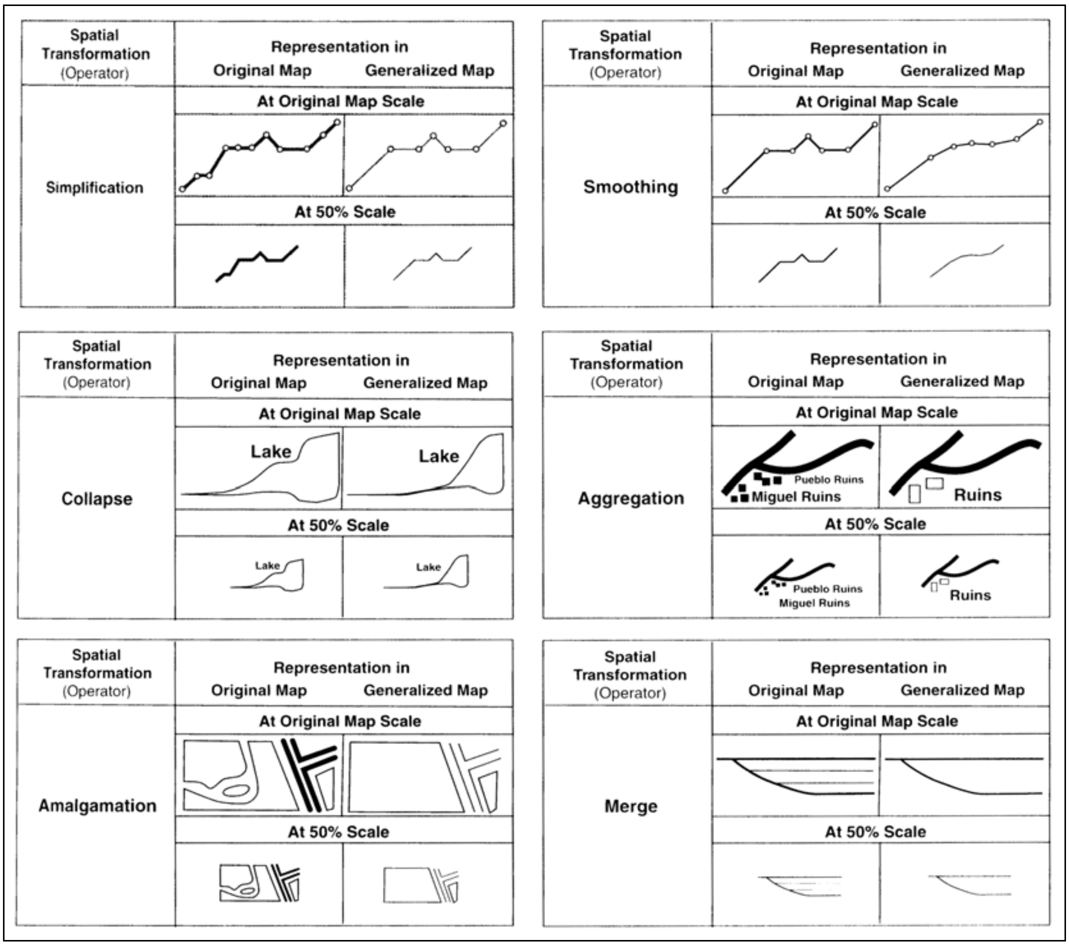


Figure 3.4. Some generalization operations (Longley *et al*., 2001).

Generalization can be viewed as a set of metric transformations on the geometric representations of spatial objects, intended to improve data legibility, understanding or the level of geological detail. It is also viewed as an interpretation process that leads to a higher level view of some phenomena (Müller *et al*., 1995). These two different views would be the motivation to the use of the concepts for *model generalization* or *model-oriented generalization*, that deals with the development of data models to support spatial data at multiple scales and levels of detail, and *graphic generalization* or *cartographic generalization*, that deals with geometric information.

3.3.2.1 Model generalization

Generalization of geological information can be seen from two different perspectives: *model oriented generalization* and *graphic generalization*. *Model generalization* is seen as the transformation of data between geographic data models defined at different spatial and semantic resolution. These transformations can be performed independently of the graphic representation. They can be performed to facilitate data access in a GIS and are also driven by analytical queries. Database generalization can be considered a form of model generalization and can allow multiple representations of the archived information. *Graphic generalization* can be viewed as transformation of objects in a cartographic representation of spatial information, intended to improve data legibility and understanding. An example of graphic generalization is the simplification of cluttered symbology described in Chapter 7 of this work. Müller *et al*. (1995) also suggest that model oriented generalization can be the precursor to graphic generalization.

An important research aspect becomes how to generalize a geological database for multiple representations through analytical queries and how to generalize graphic objects, e.g., punctual symbols, in order to preserve data legibility.

Queries can be used to perform different analyses using different levels of generalization as well as to obtain information by looking at the screen or printed map. The process that extracts, generalizes, and inserts geological data into the data model is treated as a one-step process and not divided into model and graphic generalization (not intended in this case as e.g., the simplification of overcrowded symbology that will be treated later). The main reason for this is the difficulty to explicitly define where the model generalization part of the process ends and the graphic generalization begins. It is believed that the geological knowledge of a geologist has an important impact on how the categories or object classes in a particular map are defined. If the generalization process is to be divided into model and graphic generalization, the data model that defines the result after the model generalization has to be defined neglecting the geological knowledge. The geological knowledge is only utilised during the graphic generalization and it impacts on how the model generalization shall be performed. Dividing the process into model and graphic generalization introduces additional complexity to the problem. Kilpeläinen (1997) tried to divide the generalization process for geographic data in general into two steps. He noted as well that the distinction between model and cartographic generalization is not always sharp.

A new research approach should be that the database queries are a matter of creating a view of the database that is optimal to the user’s needs, while symbol simplification is performed at any scale to preserve legibility.

Model generalization is new and specific to the digital domain and its goal is to control the reduction of data or details. The reduction of data is desirable in order to save storage space and to increase computational efficiency or to extract the required information from a very detailed database. Model generalization is concerned with map reduction and derivation of spatial data at multiple levels of accuracy and resolution. As in cartographic generalization, different applications of model generalization require different methods.

Weibel (1995) specified some general requirements that should be met by all the procedures for model generalization:

- Produce predictable and repeatable results;
- Minimise deviations from original model;
- Maximise data reduction;
- Do not violate topological consistency of spatial objects;
- Minimise procedure complexity;
- Minimise computations.

Generalization should be seen as a process that allows us to perform a change in the perception level of geological data, and it must preserve as much as it can the geometric properties, spatial relationships, and semantic relationships, while respecting graphic limitations. Related to geometric properties are the needs to identify specific algorithms for generalization based on the characteristic of the geological objects, to describe the elements based on the nature of the objects that they represent, and to apply geometric and topological modelling for the whole elements or just part of them.

Related to spatial relationships are the issues of connectivity and spatial arrangement relationships. Related to semantic relationships, the modification of object geometry may generate conflicts that may be solved through aggregation, elimination, or change in the dimension of objects. Scale variations may cause changes on geometry and topology, and it is important to note that a model to support transformations between scales of *1:x* to *1:y* may not be appropriate for changes between scales *1:z* to *1:w*.

3.3.2.2 Graphic generalization

This is the term commonly used to describe the generalization of spatial data for cartographic visualization. It is the process most people typically think of when they hear the term *generalization*. By means of spatial and attribute transformations, it is used to counteract the unwanted effects of scale changes or the level of detail in order to produce aesthetically acceptable maps.

Most cartographic algorithms for generalization are line simplification algorithms that analyse only the vertices of a line. In that way they do not take into consideration that a line may be part of a polygonal subdivision, which is the common approach of commercial GIS.

Categorical maps, such as geological maps, are made up of a set of polygons. A work developed by Weibel (1996) attempts to identify further constraints in relation to established cartographic principles in order to form a basis for the development of extended line generalization algorithms that try to preserve the general structure of the data. Four different types of constraints are discussed in terms of an individual line, in terms of a feature class (represented by polygon), and in terms of different feature classes:

- *Metric constraints*: mainly influenced by aspects of perceptibility such as minimal separation, minimal size, or minimal width;
- *Topological constraints*: maintenance of topological consistency, including avoidance of self-intersections, mutual overlaps, containment of point features;
- *Semantic constraints*: relates to semantic modelling, preservation of class memberships, or the domain of existence in the spatial context;
- *Gestalt constraints*: can only be met if the other constraint types are satisfied. Maintenance preservation of original line character or of the distribution and arrangement of map features.

Table 3.1 summarizes the basic constraints defined by Weibel (1996) and identifies which types of constraints affect a set of feature classes.

Table 3.1. Weibel's (1996) constraints for cartographic generalization within feature classes.

Description	Type
Preserve ratios between feature classes	Metric
Preserve proximity relationships	Metric
Preserve polygon containment	Topological
Preserve shared lines	Topological
Preserve domain of spatial context	Semantic
Preserve interplay of elements	Gestalt

Constraints between feature classes include preserving the ratios between classes, preserving distance relationships (parallel lines, point in polygon), preserving polygon hierarchy, preserving shared boundary lines, preserving the domain of existence in the spatial context, and maintaining the interrelationships between the elements.

Hierarchical methods for line generalization have been proposed in order to speed up the visualization of maps at different scales (Cromley, 1991).

3.4 Management of geological mapping proposed

This research is focused on how reality is abstracted into maps, and how the same reality is abstracted differently in different maps, even though the categories in the different maps are part of the same geological database.

Categorisation is fundamental in the map making process. Moreover, as Robinson *et al.* (1995) say, symbolisation and design decisions should be based on objective rules. Some characteristics of how humans form categories, such as fuzzy borders, conceptual embodiment and multiple representation, have also been described. In this work, this view on categorisation, together with the classical approach, has been adopted, because it has impacts on how the abstraction process can be seen. For instance, a map category, such as *geological unit*, has been formed in the human mind through experience. For the category *geological unit*, this might consist of experience from walking in different areas, studies in geology and palaeontology, experience from reading various maps, etc. The category *geological unit* is fuzzy and subjective and acquires different meanings in different contexts. Furthermore, most Geological Surveys, like the Geological Survey of Italy, have their own coding conventions for the definitions and characterization of geological objects.

The ideas presented in this work concern mainly the levels of conceptual and logical data modelling. The main focus is on how geographic reality can be abstracted into an object-oriented data model. The approach is based on the cognitive aspect of how humans reason about geological information. The following assumptions form the basis on which the object-oriented model presented in Chapters 5 and 6 of this research can be constructed:

- Several categories used in geological information are rather fuzzy. Examples that illustrate this are given in Chapters 5 and 6. Since the categories are usually transformed into object classes in a GIS, there is a need to handle fuzzy as well as crisp categories in a system;
- The categories have different meaning in different contexts. The context is set by the application discipline and the application within the GIS;
- The human pattern recognition ability has impacts on the meaning that a particular category in a map acquires. The category in a map has a much narrower definition than when a category is discussed. It is the pattern that the category forms in the map that influences the meaning that is given to the category;
- A map that is a view of a database should have the possibility of containing object classes suitable for analytical queries as well as object classes that are only used to visualise information in the map;
- Categories with the same name displayed in different maps are defined within different contexts and thus have more or less different meaning. The categories are most likely overlapping, but whether associations between individual members of the two categories can be explicitly defined has to be decided in each individual case;

- The map presents a view of reality for a particular application. The meaning of the categories included in the map and the design of the map are an optimal compromise to convey the information required by the user.

The work by Brodaric and Patera (1997) provides an instance in geology where geological and stratigraphic information has a clear hierarchical origin. Hierarchical thinking is intrinsic to the classification of geological objects and rules any generalization process. Any geological object may be composed of a set of objects that in turn may be composed of other objects (for instance, the lithostratigraphic sequence *supergroup* → *group* → *formation* → *member* → *bed*). In Chapter 6, it is proposed a solution that allows GIS to support multiple levels of abstraction by linking the different representation levels through hierarchical relationships. The system allows to generalize a geological database for multiple representations through analytical queries, which create a view of the database that is optimal to the user's needs.

We have seen that model generalization is the transformation of data between geographic data models defined at different spatial and semantic resolution. These transformations can be performed independently of the graphic representation. It can be performed to facilitate data access in a GIS and is also driven by analytical queries. Database generalization can be considered a form of model generalization and can allow multiple representations of the archived information. Graphic generalization can be viewed as transformation of objects in a cartographic representation of spatial information, intended to improve data legibility and understanding.

These two different views have motivated the concept of graphic generalization or cartographic generalization that deals with geometric information, and model generalization or model-oriented generalization that deals with the development of data models to support spatial data at multiple scales and levels of detail. Both these operations correspond to the objectives of this research. However, the hierarchical generalization methodology proposed in this research deals only with polygon generalization. Collapse, simplification and smoothing may change the general shape of a line or of a polygon, which may cause changes in the relationship of the geometric feature with other components of the map, and they have not been considered in this work.

In Sub-section 3.1.6 the human ability to learn how to automatically recognise different patterns has also been described. The difficulties in transforming this *visual* knowledge into a propositional or procedural form needs to be coded in an automated system for generalization. It seems reasonable to assume that cartographers and experienced map readers have developed such *visual* knowledge and that this is used when interpreting different maps. The meaning that a map category, such as a geological unit, acquires in a particular map context is influenced by this visual knowledge, and the visual knowledge gives the category a more narrow definition. It is therefore of paramount importance the definition of the constraints that rule the generalization process performed by the geologist-cartographer. The rules have been applied to the expert system proposed in Chapter 7, which is an example of graphic generalization for the simplification of cluttered symbology, where the simplification operation is performed at any scale to preserve legibility.

Chapter Four

4 The architecture of Geographic Information Systems

This chapter introduces the concepts and typical components of a Geographic Information System, provides a brief reference of some important milestones of their development and of their probable future. The backbone of a GIS is the data model based on a spatial data structure. The requirements that are more or less specific for a GIS are discussed. The system should allow the storage of geometric, topological and thematic data in a single undivided unit in order to avoid the drawbacks of a dual architecture, the data model must possess good spatial capabilities, and in the data model it must be possible to archive the data in a form suitable for the use at several levels of detail.

The different GIS formats are analysed and a justification for the system selected is provided. The chapter is directed to scientists not experienced with the subject. However, its target is the understanding of the geological model that will be presented in Chapters 5 and 6.

4.1 The development of Geographic Information Systems

4.1.1 Brief history

The development of Geographic Information Systems was influenced since the 1960s mainly by key groups, companies and individuals in North America. Several factors caused a change in cartographic analysis, besides the improvements in hardware, graphics and computer technology in general (Berry, 1995):

- the development of theories of spatial processes in economic and social geography, anthropology and regional science;
- the increasing social awareness, education levels and mobility and the awareness of environmental problems.

One of the earliest examples of GIS was the Canada Land Inventory Geographic Information System developed in the mid 1960s, whose development provided many conceptual and technical contributions. At the time there was no previous experience in how to structure data internally and no precedent for GIS operations of overlay, area measurement and computerized analysis.

Another example of GIS application was the SYMAP system developed by the Harvard Laboratory for Computer Graphics and Spatial Analysis. The system sparked enormous interest in a previously unheard-of technology besides it was developed as a general-purpose mapping package with an output exclusively on line printers, with poor resolution and low quality, but simple to use and seen for the non-cartographer as a new way to make maps. The GRID application followed in the late 1960s. It was the first example of raster GIS and it allowed multiple input layers of raster cells for landscape analysis.

The early 1970s saw computer mapping automate map drafting. The points, lines and areas defining geographic features on a map began to be represented as an organized digital set of *x,y* coordinates, which could be rapidly updated and redraw using pen plotters at a variety of colours, scales and projections. The pioneering work during this period established many of the underlying concepts and procedures of modern GIS technology. The main advantage, but a radical conceptual change, of this new system for producing maps was the format of mapped data, from analogue inked lines on paper, to digital values archived on disk.

During the early 1980s, spatial database management systems were developed that linked computer mapping capabilities with traditional database management capabilities. A user was now able to point to any location on a map and instantly retrieve information about that location. Alternatively, a user could specify a set of conditions and direct the result of the geographic search to be displayed as a map.

Increasing demands for mapped data focussed attention on data availability, accuracy and standards, as well as data structure issues. Hardware vendors continued to improve digitizing equipment, with manual digitizing tablets giving way to automated scanners. A new industry for map encoding and database design emerged, as well as a marketplace for the sales of digital map products. Regional, national and international organizations began addressing the necessary standards for digital maps to ensure compatibility among systems.

During the 1980s the first release of ARC/INFO® software by ESRI was launched. The system, the ancestor of the ArcGIS® family of products, was the first successful implementation of the idea of separate attribute and locational information. It was also a successful marriage of standard relational database management system (INFO®) to handle attribute tables with specialized software to handle geographic objects stored as geometric objects (ARC), a basic design that has been copied in most other systems. ARC/INFO® was also the first GIS to take advantage of new mini hardware. GIS could now be supported by a platform that was affordable to many resource management agencies and was independent from specific platforms and operating systems.

In the 1990s GIS was at a threshold that was pushing beyond mapping, management and modelling to spatial reasoning and dialogue. In the past decades, analysis models had focussed on management options that were technically optimal. In reality, there was another set of perspectives that had to be considered, the social solution (Berry, 1995).

Among the main textbooks produced during these decades, it is worth mentioning the works of Aronoff (1989), Bernhardsen (1996), Burrough (1986), Burrough and McDonnell (1998), DeMers (1996), Fabbri (1984), Maguire *et al.* (1991), Star and Estes (1990), Tomlin (1990) and Worboys (1995) on the theory and concepts of Geographic Information Systems, the article of Tomlinson (1987) on the potential of GIS, the first compendium on three-dimensional applications in GIS of Raper (1990) and the works on environmental modelling, spatial analysis and quantitative geography of Chow (1997), Fotheringham and Rogerson (1994) and Goodchild *et al.* (1993).

4.1.2 Probable future

There are several different prospects for the future of GIS. Almost all forms of use of geographic data can today be automated, so that maps and atlases can be queried also using the Internet with seamless browsing and geographic information can be analyzed and used in models.

Looking at Geographic Information Systems in the view of the next decades, it therefore seems probable that the adoption of GIS society-wide and worldwide is inevitable and that GIS users will be advantaged in their work while non users will be relatively disadvantaged. The technology will advance in concert with the increases in capability and lowered costs of computer hardware, operating systems and communication bandwidth for the Internet. With these assumptions made, the factors that will have the most impact on GIS development in the future years can be broadly grouped into the three categories of *functionality*, *communications*, and *management* (Tomlinson, 2000).

Geographic Information Systems are spatial analysis engines. The current set of analysis functionality provided by commercial GIS software products does not include the functionality tailored for specific types of fields, like for instance geology. These added functionalities are where new GIS development will make the most societal impact. GIS functionality needs to have the ability of modelling processes that will allow the behaviour of complex spatial systems to be examined, leading to the ability to predict outcomes and, above all, to understand them.

What is also very important is simplicity of operation. Simpler interfaces must be developed that will allow access to the full range of functionality. Software tools such as the ModelBuilder® interface of ArcGIS® 9 software are a huge step forward. The additional step necessary is to incorporate training for spatial problem solving in the software so that users can employ the system to find out how to solve their geographical problems and not only to exploit it in the mechanics of their work.

Perhaps the major development in the next decades will be the increased ability to communicate quickly all forms of data. Internet bandwidth is increasing by at least 300 percent per year at the moment, and this rate can be expected to accelerate to the point where physical access to all data is essentially local (Tomlinson, 2000). This will dramatically increase the data sources available for analysis and hence enrich the ability to produce information of benefit to users and to society. This has huge potential ramifications to the way that society operates, for citizens to become involved in their community decision making and for organizations to cooperate in order to solve multifaceted problems. There will be, however, very real issues of data security, data quality, data integrity, archival policy, privacy, and even ethics that increased physical access will bring to the fore (Tomlinson, 2000). As with other aspects of new systems, the problems to be overcome are those of management rather than technology.

In the last decade many researchers have expected GIS to produce fundamental changes in the ways people think about geographic information. However, even today the magnitudes of its future effects on affected natural sciences is not clear but it is very evident that much research still remains to be done. However, the level of public funding of GIS research and development has never been high and it has been mainly funded by vendors, driven by strong market forces that are not necessarily consistent with the needs of scientific research. Geographic information is used infrequently compared to text or numerical information (people use maps only in certain limited contexts. But the potential of automated geography may lead to much greater levels of use. People might use geographical data more frequently if they had better access to it, and if it was easier to use. What is therefore needed is investments in education and training to raise awareness of GIS technology and its applications among people.

The concept of a GIS software seat and this client/server computing model has been so popular in the last decades that many only think of GIS within this context. However, the GIS vision is expanding. The future of Geographic Information Systems is strictly connected with the developments in computing. The growth of the Internet, advances in

DBMS technology, object-oriented programming, mobile computing, and widespread GIS adoption will lead to an evolving vision and role for GIS, in which GIS software will be centralized in *application servers* and *Web servers* to deliver GIS capabilities to any number of users over networks. Focussed sets of GIS logic will be embedded and deployed in custom applications and increasingly GIS will be deployed in mobile devices for field use.

4.2 Definitions

Database software packages (network, hierarchical, or RDBMS - *Relational Data Base Management Systems)* can be used for long-term and structured storage. The drawback of most of these packages is that they do not handle geological and geographic data very well, because they only support one-dimensional search structures. It is impossible to formulate queries like: *Which cities with a population greater than 100,000 lie within 10 kilometres from the river Tiber* in the Data Manipulation Languages (DML) of these RDBMS. Even if it were possible to construct such a type of queries, they could not be satisfied efficiently, because these RDBMS lack the proper multi-dimensional search structure. This explains why most commercial GIS have a *dual architecture.* The thematic information is archived in a relational database and the spatial information is stored in a separate sub-system capable of dealing with spatial data and spatial queries. By means of a unique identifier (*ID*), the two components of a geographic entity are linked together. Besides not being elegant conceptually, this dual architecture has also practical disadvantages: the ID must be kept consistent, *mixed* multi-dimensional search structures are impossible (e.g., two dimensions used for the spatial location and the third dimension used for a thematic attribute), and performances are reduced because objects have to be retrieved and compiled from components that may be stored far apart. Therefore, it would be worthwhile to select a data model that does not have this dual architecture.

Before providing the definitions of the data types that can be found in a GIS, the term GIS itself needs to be defined first. According to the work of the International Geographic Union, IGU (Tomlinson, 1972), a GIS is *the common ground between information processing and the many fields utilizing spatial analysis techniques*. This quite general definition of a GIS is refined by Burrough and McDonnell (1998) as *a powerful set of tools for collecting, storing, retrieving at will, transforming, and displaying spatial data from the real world.* A similar definition is given by the National Center for Geographic Information and Analysis (NCGIA, 1987). The NCGIA defines a GIS as *a computerized* *database management system for capture, storage, retrieval, analysis, and display of spatial (locationally-defined) data*. Cowen (1988) puts more emphasis on the integration aspect: *a GIS is best defined as a decision support system involving the integration of spatially referenced data in a problem solving environment*. Jack Dangermond (Ormsby *et al.*, 2004), founder and president of ESRI, the ArcGIS® software producer used in this research, states that *a GIS is an organized collection of hardware, software, network, data, people, and procedures*, as shown in Figure 4.1.

From these definitions it should be clear that the data model plays a central role in a GIS, and that the current GIS are the result of the combined efforts in many disciplines.

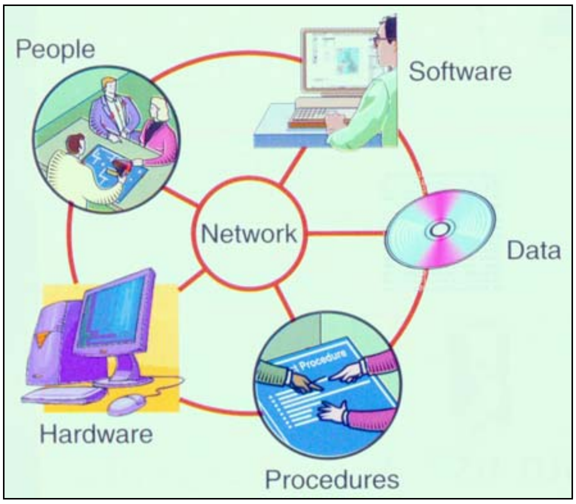


Figure 4.1. The components of a Geographic Information System (Longley *et al.*, 2001)

The geographic entities or objects in a GIS are based on two different types of data: *spatial* and *thematic* (*attributes*). In turn, spatial data have two components: *geometric* and *topological*.

The terms that will be used here are defined as follows. *Geometric data* have a quantitative nature and are used to represent coordinates, line equations, etc. Basically, there are two formats: *raster* and *vector*. The primitive of the raster format is the *cell* (or *pixel* - Picture element). With the raster model, features are represented as a matrix of cells in a continuous space. A *point* is one cell, a *line* is a continuous row of cells, and an *area* is represented as continuous adjacent cells. Cells are usually square, but they may also be rectangular or hexagonal.

The two-dimensional vector format has three subtypes, *point* (position, 0-Dimension) *polyline* (line, arc, chain, 1D) and *polygon* (area, region, 2D), that are termed geometric primitives. Other primitives such as multipoint, polylines or regions are possible.

Topological data describe the relationships between the geometric data. There are several types of topological relationships, for instance *connectivity*, *adjacency*, and *inclusion*. Examples of queries concerning topological relationships are:

- Adjacency: e.g., which areas (or cells) are neighbours of each other;
- Connectivity: e.g., which polylines (or cells) are connected and form a network of roads;
- Inclusion: e.g., which lakes lie in a given country.

Topological data are not always stored explicitly, because in principle they can be derived from geometric data. For instance, topological relationships among the cells of a raster are explicit: each cell can have from three (when it is positioned in a corner of the raster) to eight adjacent cells. Often GIS software store topological rules as database tables, as shown in Figure 4.2. Figure 4.3 summarizes and depicts the hierarchy of geographic data types.

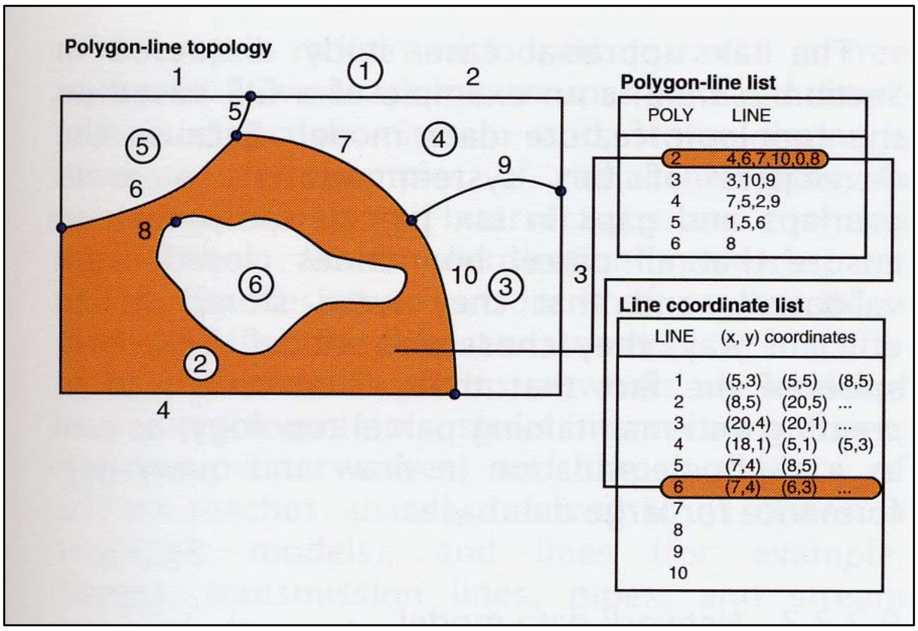


Figure 4.2. Shared topological polygonal model of ArcInfo® Workstation data format. Each polygon is related to the information about the lines composing its borders (Courtesy of ESRI Italia).

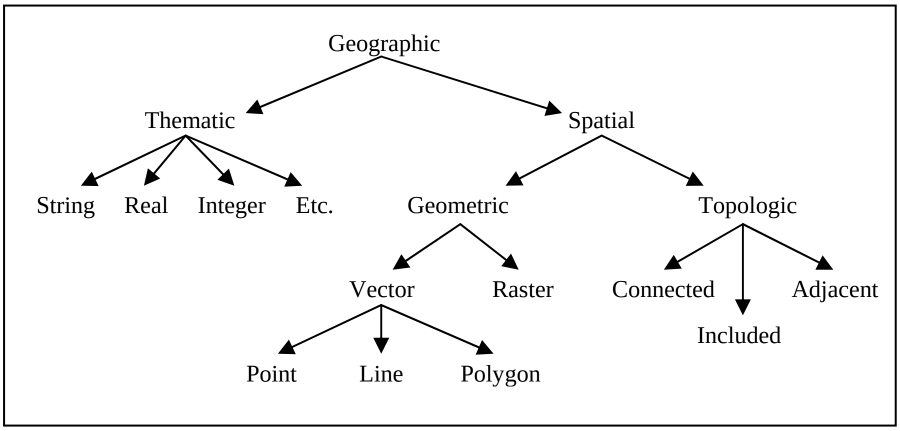


Figure 4.3. The hierarchy of geographic data types. (Redrawn and modified from van Oosterom, 1990).

A geographic database is a set of geographic entities. It is often organised in layers, each describing certain aspects of the mapped real world, as shown in Figure 4.4.

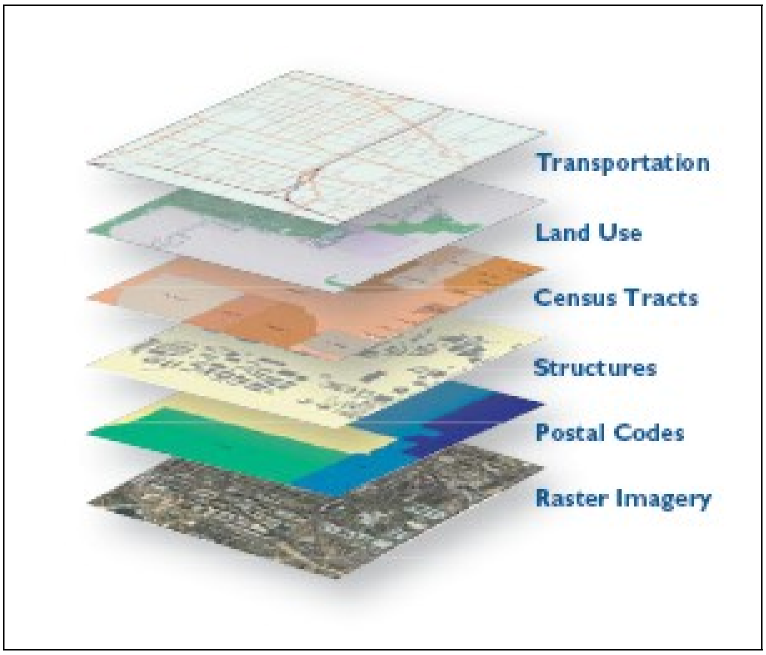


Figure 4.4. Different layers of geographic information, each depicting a real word phenomenon.

Thematic data (application-dependent *attributes*) are alphanumeric data related to geographic entities: e.g., the name and capacity of a road. Thematic data may be any kind of data that can be found in the traditional databases, e.g., strings, integers, and reals. Another term frequently encountered in the context of GIS is *graphic*, which may refer just to the visualization of the geographic entities.

The next section explains why this research concentrates on the vector format instead of the raster format for the geometric data. Note that this discussion is about the internal storage and representation and not about the display system, which is always based on the pixels of the screen.

4.3 Raster based systems

An advantage of the raster format is that it is appropriate for analysing continuous data such as remote sensing (satellites), scanning of existing documents (maps or aerial photographs) and image processing in general, which all deal with raster data. The raster format has some good spatial properties, inherent to the direct addressing of the cells. Some applications of these properties are:

- *Select* a certain (rectangular) region by using all the cells with the x and y indices in proper range;
- Find the *neighbours* of a cell by using all the cells that have indices one lower or higher in comparison with the original cell;
- If each polygon is represented by a (connected) set of cells with the same attribute value and every polygon has a different value, then the *point-in-polygon* test is established by retrieving the attribute value of the cell;
- If two maps are based on the same raster then *map overlay* is performed by a simple cell by cell algorithm (this algorithm is also well suited for hardware implementation).

The fact that a raster algorithm is simple does not mean that it is faster than a more complex vector algorithm, because raster data have the tendency to be very voluminous. Although the raster format possesses good spatial properties and performs spatial analysis in a faster way, it shows serious disadvantages. Different sources of raster data use different models (sometimes a cell does not represent a square but a rectangle or an hexagon). A rectangular raster may not even be rectangular when using a different projection and geometric data should never be dependent on a specific projection. Raster data models are more suitable to represent and analyse continuous physical and environmental phenomena (e.g., air pollution, precipitation, etc.).

In spite of these arguments, any good GIS possesses the capability to use raster data as well as vector data, because a user often has no control over the format in which data are delivered. Raster data can be incorporated in a vector based GIS by treating these data by vectorising them through specific software. For instance, a satellite image may be classified for land use and converted into vector polygons. The selection of one of the two data models depends on the nature of the phenomenon being investigated and the analysis that the user wants to perform.

4.4 *Vector based systems*

The vector model is extremely useful for describing discrete features (e.g., geology, landuse, etc.), but less useful for describing continuously varying features.

Vector spatial data include *points*, *lines*, and *areas*. *Points* represent anything that can be described as an *x*, *y* location on the earth surface, such as beddings, survey stations, springs, etc. *Lines* represent anything having a length, such as faults, tracks, lineaments, etc. *Areas* or *polygons* describe anything having boundaries, whether natural or artificial, such as the boundaries of a geological unit, a survey area, a landslide, etc.

With a vector model, each feature defined by more than one *x*, *y* location in space is connected by the GIS to draw lines and outlines, creating lines and polygons.

4.5 *The GIS architecture*

A GIS is more than just a data model in which different types of data structures are incorporated. In this section important aspects like the database, the user interface and exchange standards will be treated. There seems to be a consensus in the literature about the architecture of a GIS. Burrough and McDonnell (1998), Goodchild (1987), and Smith *et al*. (1987) describe the following five components:

- The user interface;
- Data input;
- Storage;
- Analysis;
- Output.

The way these five components are implemented distinguishes a GIS from other information systems.

4.5.1 *User interface management*

The Graphic User Interface (GUI) is an important layer that is situated between the core of the system, the other four components, and the user. In order to be useful, the user interface should be intuitive and therefore requires a careful design. The operations are meant to be applied in the first place by the user. The user interface consists mainly of an input (*queries*) and an output (*results*) part. An example of GUI is the one created for the gathering of geological information in the field using a hand-held digital device presented in Chapter 5.

Another example is the new ModelBuilder® interface of ArcGIS® 9 software that provides a new framework for working with geoprocessing tools. In a GIS a model is a representation of a system of processes that performs operations on GIS datasets. Through the visual ModelBuilder® interface, the analyses proposed are more easily translated into ordered steps. Models allow data and operations to be linked together in a user defined sequence that structures and automates geoprocessing tasks such environmental analysis, selections, and conversion operations. Figure 4.6 shows an example of an overlaying model built with ModelBuilder®.

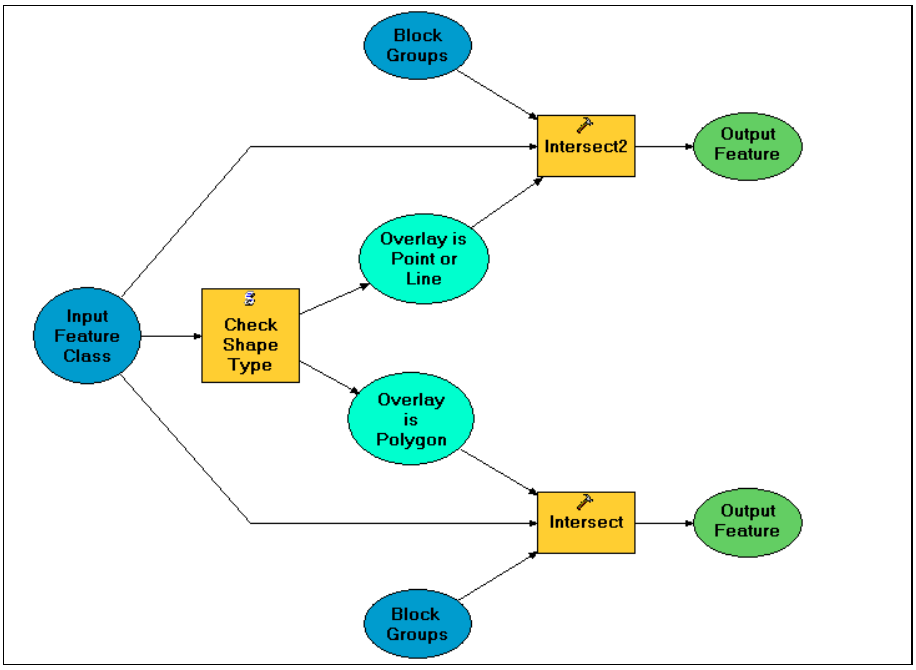


Figure 4.5. An overlaying model built with ArcGIS® 9 ModelBuilder®.

4.5.2 Data input and verification

Some possible sources for the input of data are: sensors, existing maps, and field observations. The data can be entered and verified by using one or more of the available tools: scanners, digitizers, graphic displays driven by appropriate software. Format conversion, error detection and editing, topology reconstruction, generalization, and registration are sometimes also part of the data input process. The cost of data capture in GIS is usually high. An obvious solution to reduce this cost is the multiple use of the same dataset. Unfortunately, there are some practical problems. What categories of data should be collected? How accurate should they be? Which conceptual structure should be selected, and what transfer format should be used? There are several exchange standards available that try to solve some of these problems. Just to mention a few of them, the DXF and DWG exchange format of Autodesk for CAD files (www.autodesk.com), the DLG standard of the United States Geological Survey (www.usgs.gov), and the shapefile, E00 and Grid formats of ESRI (www.esri.com). International agencies, such as ISO (www.iso.org), IEEE (www.ieee.org), the Open GIS Consortium (www.opengis.org), and the Italian Intesa GIS (www.intesagis.it) play an important role in the standardization process.

4.5.3 Data storage and database management

Tasks of this part of the system include traditional RDBMS facilities such as support of multiple users and databases, efficient storage and retrieval, non-redundancy of data, data independence of applications, security, and integrity. To store the thematic data (attributes), generally an RDBMS is used. By using a standard RDBMS, the portability of the GIS is enhanced. However, the database should also be used for the storage of the geometric and topological aspects of the geographic entities, like the ArcGIS® *geodatabase* model by ESRI used in this research, besides probably the best choice would have been the use of Oracle® Enterprise RDBMS with the Spatial extension, discarded here because not available at the time the research was carried out. In general, standard DBMS are not suited for this task.

4.5.4 Data transformation, manipulation, and analysis

This part of a GIS is traditionally regarded as the most important one. Of course, analysis is impossible or not useful without the other components of the system. The following analytical operations can be used in many GIS: geometric calculations, map overlay computation, network analysis, and several forms of simulation. These operations will be described in more detail in the next sections.

4.5.5 Data output and presentation

This can be performed with the help of several different hardware devices, such as displays, plotters, and printers. A number of different presentation formats are available for this purpose: maps, tables, graphs, and figures. By using a standard graphic software package, the output part of the GIS becomes less device dependent and much programming may be avoided.

Table 4.1 shows the main GIS producers and their GIS software.

Table 4.1. Main GIS producers and their GIS software.

	Autodesk	ESRI	Intergraph	MapInfo	Smallworld	Manifold
URL	www.autodesk.com	www.esri.com	www.intergraph.com	www.mapinfo.com	www.gesmallworld.com	www.manifold.net
Viewer	AutoCAD LT	ArcReader	GeoMedia Viewer	ProViewer	Custom	Custom
Desktop	World	ArcView	GeoMedia	MapInfo Professional	Spatial Intelligence	Manifold Professional
Professional	AutoCAD/ Map	ArcEditor ArcInfo	GeoMedia Pro	MapInfo Professional	Smallworld GIS	Manifold Enterprise
Hand-held	OnSite View	ArcPad	IntelliWhere	MapXtend	Scout	Custom
Database server	Design server	ArcSDE	Oracle Spatial	SpatialWare	Part of Smallworld GIS	Enterprise Server
Component	In several products	Map Objects	Part of GeoMedia	MapX MapJ	Part of Smallworld GIS	VBScript JScript
Internet	MapGuide	ArcIMS	GeoMedia Web Map GeoMedia Web Enterprise	MapXtreme MapXSite	Smallworld Internet Application Server	Manifold IMS
CAD	AutoCAD Map	In several products	In several products	In several products	Part of Smallworld GIS	Part of Manifold

4.6 Operations in a GIS

This section describes the operations that should be available to the user of a GIS. Most, but not all, operations described in this section are part of the *analysis* sub-system of a GIS. Two sets of operations are identified. The first set consists of the operations that must be present in every GIS, here termed *fundamental* operations. The second set consists of the operations specific to a given application, the *additional* operations. All operations are meant to be used in an interactive mode by the user. This section discusses all the fundamental operations and a few examples of operations from the second group.

4.6.1 Fundamental operations

The spatial data structures should allow for efficient implementation of the operations.

There are three types of fundamental operations:

- Display a map;
- Select entities from a map;
- Perform spatial calculations with one, two, or more geographic entities as operands (*map overlay*).

4.6.1.1 Displaying the map

The *map display* operation is the most essential GIS operation and seems trivial: visualise what is archived in the geographic database. This implies that a number of more or less complex steps have to be performed, for instance, the type of *projection* has to be selected. A different example is the required transformation in a navigation system: the display can be *north-up* or *heading-up*. A GIS contains several layers of information, so that for which layers will be used has to be decided. Furthermore, the region that has to be displayed and the scale to be used has to be selected.

After the map has been drawn the user may want to move to an adjacent part of the map, an operation termed *panning*. It is also possible that the user wants to take a closer look at a part of the map, the *zoom-in* operation. In this case not only the objects are enlarged on the display, but also more details are drawn. The reverse operation of zoom-in is *zoom-out*, where details are removed. This type of zoom-in (and zoom-out) operations is termed a *logical zoom*.

In many situations it is possible to generate different kinds of maps using the same data or derivations thereof. To produce a thematic map one could use for instance a choropleth, a dot-chart, an isoline map, a trend surface, a graph map, etc., to visualise a specific theme. Some GIS provide a very powerful display set of operations.

4.6.1.2 Selecting entities

There is a strong relationship between the *select* and the map display operation. On the one hand, the entities selected are to be displayed on the screen. On the other hand, entities may be selected from those already displayed on the screen.

The selection queries in a GIS include those found in a traditional RDBMS. However, the user may also want to pose *spatial* queries and *hybrid* queries, the latter being a combination of the traditional non-spatial and the spatial queries. Traditional queries are entered in an alphanumeric way using a query language like *Structured* (or *Standard*) *Query Language* (SQL). In GIS, selection criteria may also be based on topological relationships and on geometric calculations. For instance *Select all polygons with lithology equal to clay*, or *Select all springs adjacent to the San Andrea's fault that are inside a buffer area of 2 km*.

There are two basic types of spatial queries. Those based on the *geometric* properties of an object and those based on the *topological* properties. Queries dealing with adjacency, connectivity, and inclusion are topological spatial queries. Queries dealing with co-ordinates, area, length and other sizes are geometric spatial queries. Spatial queries can be made more easily by using the *pick* graphic input device. The pick device itself has two parameters: *shape* (the pick primitive, usually a point or a rectangle) and *aperture* (the maximum distance between the pick primitive and the primitives that are to be selected). Geometric queries that are based on the locations of the geographic entities are termed *proximity* queries. A few examples of proximity queries are *range* query, e.g., *Select everything that overlaps the search area,* which can be a specified rectangle, circle, or polygon, and *nearest neighbour* query, e.g., *Find the nearest neighbour of a given geographic entity*.

4.6.1.3 Map overlay

The ability to *overlay* or *combine* different maps is one of the main strengths of a GIS. The first variant of this operation is the *visual* overlay of different maps using the map display operation with the correct projection and scale. An example of this is *first draw a polygonal map with soil types*, *then draw the network map of roads*, and *finally draw the point map representing the cities*, as shown in Figure 4.4. A special type of the visual map combination operation is the display of a map projected on a digital terrain model.

A difficulty arises when two polygonal maps, covering the same region, are to be combined, as the second map would obscure the first map. The second map could be drawn in a semi-transparent mode, but often this is not a satisfactory solution.

The second variant of map overlay operates on two polygonal maps. It first computes the resulting map and then displays the result. This is the *polygon-overlay* problem and several algorithms are described in the literature (Doytsher and Shmutter, 1986; Franklin, 1987). Because polygon-overlay requires time consuming computations, it might be useful to store frequently used map overlays (Frank, 1987). Note that polygon-overlay is also used to solve the query *Compute the total area of calcarenites that lie within 2 kilometres of a fault*. A buffer zone is created around the fault resulting in a polygon layer, which is used to perform the overlay with the geological layer.

4.6.1.4 Network Analysis

For map layers with a network topology there are several *analysis* operations that can be performed, which anyway will not be considered in this research because they are beyond the scope of the research discussed here. Some examples are:

- **Shortest path**: Calculate the shortest path between an origin and destination. The minimum path problem is a modification hereof that minimises the sum of the weighted values of the arcs, rather than their geometric length;
- **Location of service centre**: Determine the best location of a service centre, e.g., a survey station. Try to minimise the total (or maximum) distance between the service centre and the laboratory for analysis; and
- **Travelling salesman**: Determine the best or shortest route for a geologist who has to collect samples along sampling tracks.

Network analysis may require a lot of computation, especially if the analysis has to be performed on a large dataset.

4.6.1.5 Analysis

The most important function of a GIS is the analytical capability of geographic data. As already stated before, there are two main GIS data models: *vector* and *raster*. Each of the two data models has specific types of data, analysis, and display that can be handled better by one than the other model by the system. This distinction is mainly based on the way data are stored and processed in the two models.

Generally, a vector data model focuses on discrete spatial objects, which means that there can be *empty spaces* between these objects within the study area. A raster data model describes the whole study area with no *empty spaces*, e.g., continuously, within its coverage (data-carrying cells exist in all places in the raster study area).

4.7 The GIS data model for generalization

As mentioned earlier, the backbone of a GIS is the data model based on a spatial data structure. The requirements that are more or less specific for a GIS, are discussed below. The *geodatabase* model of ArcGIS®, selected for this research, fits these requirements:

- *Geometric, topological and thematic data* should be archived in a single undivided storage system in order to avoid the drawbacks of a dual architecture. Because of their different nature, each of these types requires a specific data structure. These data structures have to be tightly integrated in the GIS data model. The chosen geodatabase format of ArcGIS® software by ESRI is a relational databases that contains geographic information. It organises geographic data into a hierarchy of data objects. These data objects are stored in feature classes, object classes, and feature datasets. An object class is a table in the geodatabase that stores non-spatial data. A feature class is a table containing a collection of features with the same type of geometry and the same attributes. A feature dataset is a container of feature classes sharing the same spatial reference. Relationships between feature classes or object classes are modelled as tables;
- The data model must possess good *spatial capabilities*, allowing efficient implementation of the three fundamental operations listed and discussed in Section 5.1. Geometric properties are necessary for the efficient implementation of operations such

as selection of all objects within a rectangle, picking an object from the display, map overlay computations, and so on. Topological properties are required for efficiently solving network analysis problems and for topological selections, such as *Select the geological bodies that are adjacent to a given fault*;

- In the data model it must be possible to archive the data in a form suitable for the use at several *levels of detail.* This is the main focus of this research and there appears to be a growing interest in multi-scale geographic databases by the scientific, geological, and cartographic community, for instance scientists working in the CARG project (Servizio geologico nazionale, 1997). There are several reasons for this:
    - If too much information is presented to the user at one time, it will reduce the efficiency in perceiving the relevant information;
    - Unnecessary detail increases the access time to the database, and slows down the drawing on the display. The latter is especially true for primitives that become very small after the transformation to screen coordinate system and therefore are not visible to the user. The user looking at a small scale map should not be confused with a high degree of details. Only when *zooming in,* additional details should be added. This operation, termed *logical zooming* in contrast with *normal zooming* that only enlarges the objects, has at least two additional effects. Firstly, the objects that were already visible at the smaller scale map have to be redrawn in finer detail. Secondly, objects that were not visible at the smaller scale map may now become visible. Logical zooming is closely related to map generalization, meaning that the operations of aggregation and desaggregation have to be supported by the database structure. The rule of thumb on *constant pictorial information density* says that *the total amount of information displayed on one screen should be about the same for all scales*;
- In the data model it should be possible to archive data in *layers* of geographic entities, in order to easily add or remove a layer from the display. This requirement is quite obvious, because it is natural to organise the way we perceive the world in manageable and comprehensible units.

Chapter Five

5 The geological object model

This chapter describes the object model that has been implemented for the gathering of geological information in the field using a digital device. Object orientation is a software modelling methodology that facilitates the design and construction of complex systems from individual components. It provides concepts and tools that permit developers to model and represent the real world as closely as possible.

The geological database scheme has been implemented according to the specifications of the CARG project. A geological field survey has been carried out using a PDA computer connected to a GPS receiver to test the proposed system.

5.1 The object-oriented approach

The object-oriented approach has been used in this research to implement the field system on a hand-held device, running ArcPad® GIS software by ESRI Inc., for collecting geological information in the field. The object-oriented model is characterized by objects and abstraction mechanisms to deal with them. Each data object contains operations (or *methods*) that describe its behaviour. Groups of data objects that have the same operations are implemented through classes. A class describes and implements all the operations to manipulate its instances. Abstraction tools such as classification, generalization, association, and aggregation are basic concepts for the design of object-oriented models (Brodie, 1984). The abstraction concept of classification corresponds to the mapping of an object onto a common class.

Generalization groups several classes of objects, with common operations and properties, into a more general class. These abstraction tools, combined with the concepts of inheritance and propagation, permit us to model complex spatial objects and to represent them at different abstraction levels better than the relational model (Egenhofer and Frank, 1989). The concept of inheritance means that the properties and operations of a *superordinate* (parent) class are inherited by all related *subordinate* (child) classes. The inheritance is *simple* when the child class has just one parent class. If the child class has more than one parent class then the inheritance is called *multiple*. Some of the major benefits of the object-oriented approach is that the software components can be easily reused, modified, and extended.

Object-oriented design methods help developers to exploit the expressive power of object-based and object-oriented programming languages, using classes and objects as basic building blocks (Booch, 1994). The object model has been influenced by object-oriented programming languages, and the object-oriented analysis and design represent an evolution for the development of systems. Object-oriented analysis identifies the system requirements in terms of objects and classes, and this result serves as a model for the object-oriented design process. Object-oriented design leads to an object-oriented decomposition and uses different notations to express the different models of the class and object structure. This chapter uses the Unified Modelling Language (UML) (Booch *et al.*, 1996) as a software engineering tool. UML is a third-generation method for specifying, visualising, and documenting the components of an object-oriented system. It represents the unification of Booch (Booch, 1994), Objectory (Jacobson, 1992), and OMT (Rumbaugh *et al.*, 1991) methods.

5.2 Object-oriented modelling of geographic information

A number of books and papers have been published on object-oriented modelling of geographic information, see for instance Worboys (1995). Molenaar (1998) describes four different levels of modelling and states that these levels of modelling have evolved since the way most users of GIS understand information is rather remote from the way the information is handled by the computer. The different levels of modelling have evolved to give users and system developers a comprehensible tool to reason and express their view on geographic information in such a manner that it can later be transformed into machine code. The four different levels are:

- *Spatial data modelling*: spatial data modelling concerns modelling reality within a certain discipline, such as geological mapping or soil mapping;
- *Conceptual data modelling*: concerns which geological features (e.g., *units*, *faults*, etc.) should be represented in the logical data model, which thematic description that they should have and how they should be represented geometrically;
- *Logical data modelling*: this is the level of the database models. One of the best known models is the relational model described by Date (1995). As already mentioned, the object-oriented approach (Rumbaugh *et al.*,1991; Booch *et. al.*, 1996) has been used for this work;

- *Physical data modelling*: this level concerns how data should be organised into bits, bytes, records and pages, structures that a machine can handle.

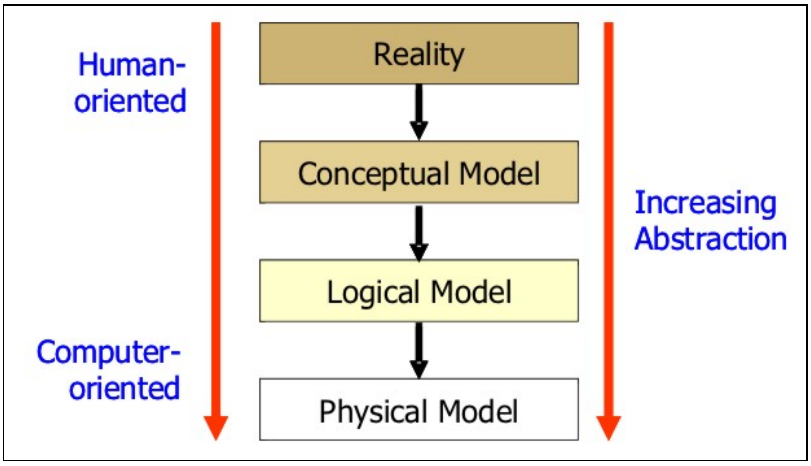


Figure 5.1. The different levels of modelling. (Redrawn and modified after Molenaar, 1998)

Worboys (1995) gives the impression that object-oriented modelling is focussed on modelling individual objects that can later be organised into object classes. This might be true in other applications of object-oriented modelling, such as designing software for an automatic teller machine. There is only one automatic teller machine, but there is a class of customers. When modelling geological information, the focus is on the object classes rather than on the individual objects. It is very rare that an individual geological feature is modelled explicitly.

As Booch *et al*. (1996) point out, a successful model should have a good connection to reality, and it is important to know where there are flaws in this connection. Object classes that contain objects that do not have an easily comprehensible definition are such flaws and should be highlighted. Based on these ideas all object classes defined in this model belong to a map. They are either feature classes containing geographic occurrences or object classes containing descriptive attributes. This implies that each class is defined for a given scale, for instance a lithostratigraphic unit may be represented at 1:25,000 by *beds* and *members* that would be generalized for display purposes at a higher rank, for instance to *formation*, on a 1:50,000 map, as we will further discuss in Chapter 6.

5.3 UML notation

UML, the Universal Modelling Language, distinguishes between the notions of model and diagram. A model contains all the elements of the system and the diagram is a particular visualization of certain types of elements from a model, exposing in some cases detailed information. There are several types of diagrams in the UML definition. In this research only the class diagrams (feature classes and object classes), the domains, and the relationships between classes have been used.

5.3.1 Class diagrams

The class diagram is the core for a UML model, and it shows the important abstractions (*classes* and *relationships*) in the system and how they relate to one another. The basic elements found in class diagrams are *class icons* and *relationship icons*. UML represents individual classes as solid rectangles that may be divided into three parts or compartments. The first part contains the name of the class. The second and third parts are optional and may be used to list the attributes and operations of the class. Figure 5.2 shows the class diagram for the class *Point*.

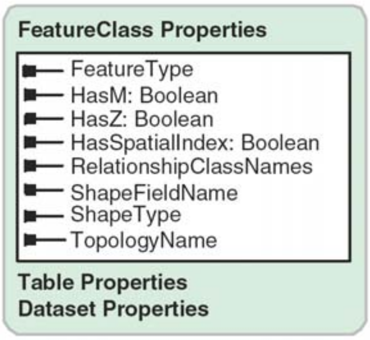


Figure 5.2. Feature class properties diagram with attributes and operations.

Besides the individual classes with their attributes and operations, class diagrams also represent the relationships that exist between dependent classes. UML identifies several types of relationships with their respective graphic representations. An association between two classes is depicted by connecting the classes with a straight line. The values of role-1 and role-2 specify how many instances are to participate in an association (*cardinality* of the relationship).

Associations are bi-directional by default (Figure 5.3a), but UML uses an arrowhead to represent an unidirectional association (Figure 5.3b). Aggregation (or composition) is a special form of association that is used to show that one object is at least partially composed of another. Figure 5.3c shows an aggregation with a hollow diamond, which highlights that the whole object maintains a pointer or a reference to its parts. If the diamond is filled (Figure 5.3d), then the diagram shows that the aggregation is by value, e.g., the whole object declares an actual instance of the part object within itself. When one class shares the structure and behaviour defined by another class, a diagram as in Figure

5.3e is used, showing that the subclass inherits all the attributes and operations of the superclass.

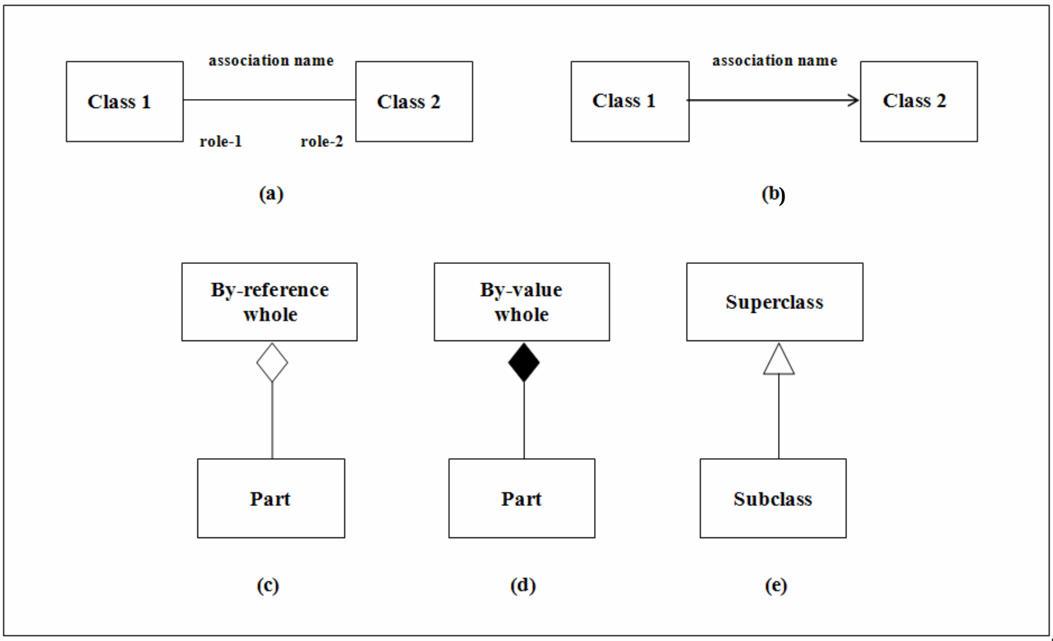


Figure 5.3. Types of UML relationships: (a) bi-directional association; (b) unidirectional association; (c) aggregation by reference; (d) aggregation by value; (e) inheritance (Modified after de Carvalho Paiva, 1998).

5.4 The geological model

This section, extracted and adapted from an unpublished manuscript (Brodaric, 1996) is the theoretical basis of the research work on generalization that will be described in Chapter 6. It has also influenced the system for gathering and encoding geological information with a hand-held device in the field, which will be presented in Section 5.5.

5.4.1 A geological object model for cartographic representations

A model attempts to capture both the cartographic representation of one or more geological maps as well as the core geological content portrayed on these maps and the geological content influencing their construction. In this sense the model describes a repository of data that is largely geological information, some of which is displayed on one or more maps and some of which leads to the inclusion of certain geological entities on these maps. Each component of the repository is a geological object. The types of geological objects that can be described range from geological units, boundaries, structures to a diversity of field observation types, all of which are common to most standard geological maps. The model not only defines the structure of such a repository but also defines how the included geological entities are attributed, and how they interact, though the interactions are relayed largely from an organizational perspective. Overall, it aims to provide a general framework of core geological objects, upon which agencies and individuals can expand.

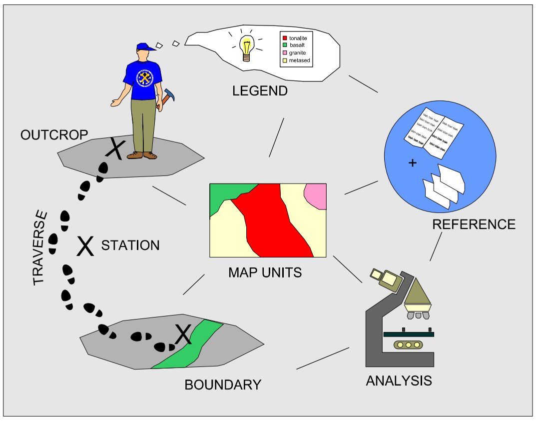


Figure 5.4. The geological mapping process. (Source: Brodaric, 1996).

The properties attributed to geological objects in the model include geological, geometric and geographic components as well as their various display characteristics and legend classifications, which may be exhibited on one or more maps. A model should permit any meaningful combination of geological objects to be aggregated on a map and any geological object can retain potentially many geometric shapes. For instance, a map may treat a geological object as a polygon, line, or point depending on the subjective requirements of the geologist or the scale of representation. To achieve this, usually a model separates geological objects into two archives: a geological object repository that contains geological attributes, and a spatial object repository that contains the geometric shapes and the geographic locations of the geological objects. However, the model used in this research, the geodatabase by ArcGIS® application, archives both spatial and attribute data in a Microsoft Access® *.mdb* database.

It is important to note here that the geological archive contains geological descriptions of both classes and instances of geological objects. A geological unit is a class of geological objects that is not actualized until it is assigned to one or more real world occurrences. In this way a unit is a type of geological object, whereas a specific fault, for instance, is an actual occurrence. The geological object repository contains information about both geological object types, namely units and various generic linear feature types (e.g., faults, contacts, shear zones, etc.), as well as geological object occurrences such as named structures (e.g., the San Andrea's Fault), geological boundaries or field observations. In all these cases, the geological content resides within the geological object archive. The spatial characteristics, most notably geometry and geography, inhabit the spatial map object archive.

Generalization can be considered as another form of classification. It is influenced by the intrinsic nature of the spatial object and often occurs when maps are compiled from detailed to regional scales, or when particular characteristics of the spatial objects are visualised, thus creating a derivative map. In these cases, spatial objects are regrouped according to superimposed criteria. A collection of spatial objects is classified according to some grouping of objects in the data archive. The lumping of several units into one classification and the application of that classification to a collection of spatial objects is an example of this.

We can now more rigorously define a model as a representation of the interplay between three integral geological map components: a *geological data repository*, a *spatial map object repository* and their associations of which the most notable is the *legend archive*, which classifies a subset of the other two repositories on any given map. Using these components a geological map can be said to be composed of a collection of spatial objects located within a fixed geographic extent, and which, through the legend, are not only symbolised but are also described or classified by a some combinations of objects from the geological archive. Segregating the cartographic, spatial and geological content components of geological maps permits any of these aspects to be modified without unduly affecting the other ones. It also permits the coexistence of multiple versions of any component, thus allowing for possibly many cartographic, spatial or geological perspectives on a subject. A practical application of this would be the generation of derivative maps from existing maps, and the ability to alter the geometric representation of a geological object with changes in map scale. Properly applied, the model could act as an invaluable aid to map making, particularly in regional compilation, helping to derive maps at a specific database resolution.

One of the definitive aspects of spatial objects is that they inherently posses spatial associations. Topological relationships are a particular type of spatial association, normally understood as referring to the adjacent nature of objects partitioning a space. In the three dimensional sense this would include the notions of *beside*, *underneath*, and *on top* of, as well potentially other ones depending on the exact implementation. Geologically, these interactions contain a wealth of critical information that has to be captured. Thus a model permits spatial objects to have geological relationships that are usually semantic enhancements to their existing topological relationships.

A legend consists of classifications, which connect spatial and data objects, and visualization parameters for each classification. Each spatial object referred to by the legend has geographic extent, and thus a legend inherently possesses a geographic boundary defined by the perimeter of its spatial objects. A map then simply constrains the legend to a particular geographic region that presumably overlaps with the area covered by the legend's spatial objects. It is therefore possible for a legend to be shared amongst several maps, as each map is simply some subset of the geographic extents of the legend's spatial objects.

If a map is a geographically constrained collection of spatial objects classified by a legend, it is not impossible to imagine several classification schemes for a map. When a new classification scheme is applied to an existing map, the map is often referred to as a derivative map. The alternate classification scheme is simply an additional legend, and thus it is possible to conceptualize a map, a geographic subset of spatial objects, classified by several legends, without being termed a new map. Alternate legends can be constructed in two ways: either the original spatial objects are reclassified or the classifications themselves are re-grouped.

5.5 Collecting data in the field

Geologists usually go out to the field, identify geological occurrences and phenomena, collect samples, and model a geological process that often leads to a report on their findings. Many of the data and notes recorded in the field are often unavailable to subsequent analysis because they reside in inaccessible formats, such as field notebooks, field slips or reports not directly associated with their positional geographic attributes. There is no method of recovering most of the data recorded in the past, let alone deriving alternative interpretations from the same data source (Schetselaar *et al*., 2004). In fact, the information that is easily available often is not current or is in formats that are archaic to modern technology. These hurdles limit easy access and are not sympathetic to the demands of today's rapid and potentially critical decision-making process (Buller, 2004). Furthermore, there is a need to share accurate, up to date information between different groups and disciplines, whose demands continue to grow dramatically.

To meet the above challenges, organizations are looking at the collection, processing and analysis, and final dissemination of information from a business perspective (Buller, 2004). What is needed is an immediate improvement in data quality and a reduction in the time it takes to publish final results, usually in the form of a printed map.

A significant improvement in this information processing can be achieved by reducing the reliance on paper formats at the various phases of the collection of geological data. Evolving from paper field notes to electronic field data capture, the likelihood that transposition or scientific error will enter the data collection process is reduced. Collecting information in this way also increases the ability to search and manipulate the field data. By using an electronic systems, quality assurance and quality control (QA/QC) begin at the reception of data collection (Buller, 2004).

In the last two decades, several groups both nationally and internationally have worked to make data collection applications fit their scientific rules and goals. Usually, field applications have been developed *in house* by manipulating existing software applications to fit into the requirements that geologists demand for data capture. An example of a full information system that captures the geological information is FieldLog field application (Brodaric, 2004), which uses a laptop computer to gather and archive information electronically. The drawbacks of the system are the weight and size of the laptop computer and the battery life that limit its portability in the field.

These systems are often peculiar for a specific geological survey or research organization. This means that there has been no improvement in the level of data access or sharing, because data created with the various different systems is not easily exchanged: we have just altered the format, from paper to various, less accessible formats. Furthermore, the information captured or the geological dictionary being used may be specific to a single geological survey organization. This yields to a lack of interoperability: the information needs to be translated into different formats to enhance communication between organizations (Brodaric, 2004). These data translation activities have met with limited success and are recognised as large consumers of time and resources.

In the last years, there have been other valid initiatives to put geological data into electronic formats and to increase the accessibility of this information also via the Internet, improving the quality of the analytical results and expediting the transfer to the final publication process. One of the most valuable initiative is the LIMS laboratory information system developed by the Geological Survey of Canada (GSC) Terrain Sciences Division in Ottawa for geochemical data collection (Buller, 2004).

In the last decade, the advance of technology has brought to a new family of smaller computers, the personal digital assistants (PDAs), that have become more powerful and more rugged with the latest versions, which may incorporate a digital compass, a GPS receiver, a digital camera, and on-board GSM/GRPS or UMTS module, as the DART® (Data Acquisition & Recognition Terminal) device by the Italian Citec S.p.A. shown in Figure 5.5, that can be considered to date the state of the art instrument, and that is aimed to the Land and Environmental Protection Agencies. This terminal allows the acquisition of several data kinds (spatial, alphanumeric, digital images) that are automatically associated with date, time and location. DART® also sports a wide and easy-to-read display, even in severe environmental conditions. Needless to say, it is equipped with a keyboard, a touch screen device, and with serial (RS232), USB, Bluetooth™ and infrared (IrDA) ports. The acquired data may be stored on removable ROM cards or be sent over the GSM/GPRS link. Its integration with geographic information systems is simple and straightforward. The software environment is based upon Microsoft WinCE® 4.2 (CE.NET), while the integrated devices programming and interfacing is performed with the supplied DLLs.

Figure 5.5. The DART® device by the Italian C.I.T.E.C. S.p.A.

In general, PDA electronic data gathering devices have proved themselves as a reasonably low-cost mobile field system. These devices have the ability of loading collected information directly into a database structure that mimics the data structure found at the corporate level. This database structure concept would greatly facilitate the transfer of information to a corporate data holding and reduce the data manipulation needed to facilitate the transfer (Buller, 2002).

5.5.1 The ArcPad® system

In geology, as in most scientific disciplines, digital methods are increasingly used for data management, analysis and visualization, but are rarely used for data acquisition in the field. Most geoscientists already digitize their field data by transcribing into spreadsheets or databases, and by reproducing field maps on cartographic or graphic packages in the office or laboratory. Capturing geological data directly in the field on a station-to-station basis is an effective way of streamlining the information process, while at the same time capturing vital geological information. The tool that has been selected to capture geological data is

ArcPad® mobile GIS software for field mapping applications by ESRI (http://www.esri.com/software/arcgis/arcpad/index.html).

ArcPad® runs on handheld and mobile devices and provides field-based personnel with the ability to capture, analyze, and display geographic information. Field data collection with ArcPad® is efficient and accurate and can integrate input from GPS receivers, rangefinders, and digital cameras.

Efficiency can be further improved by using ArcPad Application Builder®, the development framework that is used to customize applications and tools for specific field tasks or projects through *ad hoc* graphic user interfaces. Enabling geologists with ArcPad® would allow for more productive and accurate geological data collection through data collection forms and input from a GPS device. Immediate access to the collected data and GIS tools would also enhance the geologist's ability to make critical decisions in the field, to interpret observations during the mapping process and to modify the interpretation as more information is acquired. By incorporating visualization and analysis into the mapping workflow, digital methods can also aid and improve the interpretation process.

The ArcPad® application may essentially give the geologist the ability to plot a variety of geological information in the form of points, lines and polygons, and to directly capture this information from a GPS receiver. ArcPad® allows a digital data capture system as well as a visual display of the map data while out in the field. A further advantage with having a map interface is that other map information such as topography, aerial photographs or administrative data can be accessed using the same device and viewed in the field with newly captured map data. This combination of spatially related geological data and maps means that geologists at the end of the field survey have a preliminary map that is available for printing, as well as a searchable database that is geographically referenced.

Unfortunately, at the time of the field survey test, the DART® device was not yet available. Furthermore, the cost of the instruments has been known to be extremely high, over 3000 Euros. The ArcPad® application has been therefore installed on a Compaq iPAQ® handheld device with a StrongARM® SA-1110 processor, 32-MB SDRAM memory, a 240 × 320 pixels colour TFT display and Windows Pocket PC® operating system. The device has been connected through a serial cable to a Garmin eTrex Vista® GPS unit, which has been proved to have an accuracy in the field ranging from 2 to 3 metres in *x*, *y* positions. The GPS unit is a generic hiking model rather than a differential GPS. For the purpose of a geological survey test at a scale of 1:25,000 or 1:50,000 with all errors (accuracy of topography and interpretations, graphic error, and size of features) taken into account, the GPS accuracy may be considered sufficient. The system is shown in Figure 5.6.

Figure 5.6. The system used to collect geological data in the field.

As a mobile component of ArcGIS®, ArcPad® integrates with desktop GIS technologies to allow field edits to be incorporated into the geodatabase through disconnected editing. The ArcPad® toolbar for ArcGIS® provides tools for preparing data for use with ArcPad®. ArcPad® tools for mobile geodatabase editing allow to check out data using ArcGIS® Desktop, edit in the field with ArcPad®, and post changes back to the central geological GIS geodatabase.

Using the ArcPad® tools in ArcGIS® it is possible to create customised input forms, using the domains and subtypes defined in the geodatabase to generate pick lists.

5.5.2 The CARG database scheme

The database scheme is based on the CARG model, the official data model for the geological-geographic information system of the Geological Survey of Italy (SGN). This national programme foresees the realisation of a new Italian Geological Map at the 1:50,000 scale and its digital database (see Chapter 1, Section 1.1).

The database scheme, modelled by CARG using Entity/Relationship (E/R) diagramming techniques, is shown in Figure 5.7.

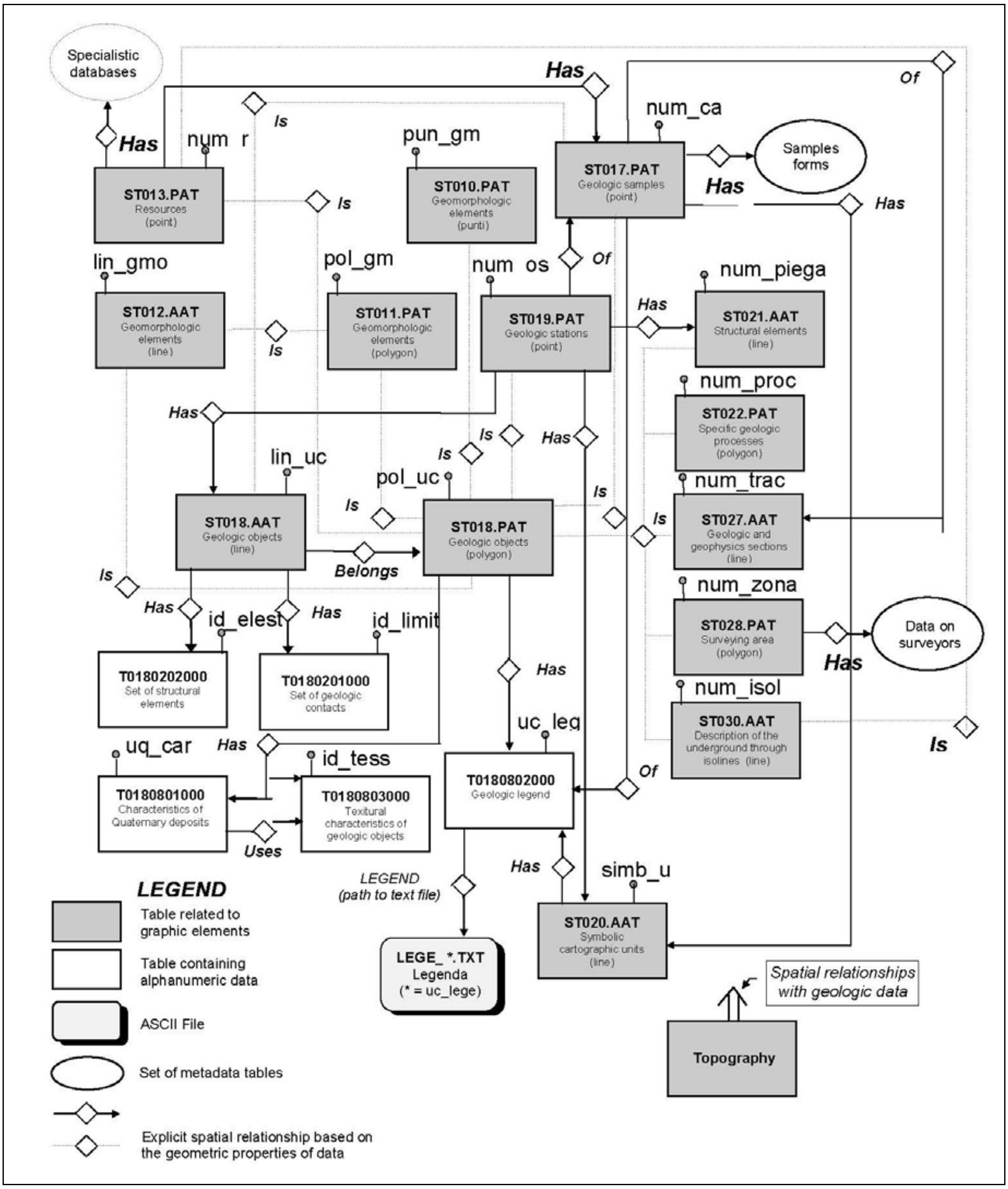


Figure 5.7. The CARG geological database scheme modelled using E/R diagramming techniques.

The CARG project has benefited the geological community by providing the first common structure in Italy for managing the spatial and attribute information, and for describing geological phenomena and their genetic origin through a standardized scientific dictionary. Although national geologists do similar activities, they do not often share the same language for describing the same geological phenomenon or object. Therefore the first step to implement a geological database scheme has been the standardization of common terms and dictionaries.

Common terms are used in several different ways and are mostly non-scientific words that are used in daily speech. These words are often applied to objects or phenomena specific to geology or to the geologist during the various phases of the geological field survey. Between the geologists the translation of a daily-speech word into a specific geological term is common practice, but because there is no such intrinsic translation between computers, this level of ambiguity causes havoc when dealing with databases. In order to facilitate the input of data in a relational database system, terms that have specific definitions must be agreed upon a variety of users.

In the ArcGIS® and ArcPad® systems, this has been accomplished by using one of the most powerful functionalities of the application, the *domains*, which facilitate data input to a common model and reduce data ambiguity both now and in the future. Essentially a domain is a set of valid values for a particular geographic or tabular element. In a geodatabase it is also a mechanism for enforcing data integrity. Attribute domains define what values are allowed in a field of a feature class or of a non-spatial attribute object class. Two different types of domains have been implemented in the geodatabase: *coded value domains* and *range domains*.

A coded value domain consists of a descriptive code and its equivalent value. For example, for the *Geological objects* (line) feature class (*ST018Aat*) the codes 1000, 2000, and 2100 correspond to three types of geological features: stratigraphic contact, tectonic contact and generic fault. Codes are archived in the geodatabase, and corresponding descriptive texts appear in any drop-down list and in the attribute table.

A range domain is a type of attribute domain that defines the range of permissible values for a numeric attribute. For example, for the *Geological station* (point) feature class (*ST019Pat*) the permissible range of values for the bedding strikes can only range from 0° to 360°, while the dips value can only be between 0° and 90°.

In Figure 5.7 it is not evident that the CARG database schema does not fully comply with the rules of a normalized database design according to the forms of Codd (1970). The conceptual and logical design of the CARG database scheme started in 1989 and THE SGN chose ARC/INFO® software (the ancestor of ArcGIS® and now a module of the ArcGIS® family of products named ArcInfo® Workstation) as Geographic Information System. At that time there were limited capabilities both for the hardware and the software. ARC/INFO® (see Sub-section 4.1.1), for instance, did not directly support one-to-many relationships and there was a sleight-of-hand to solve the problem. The design of the system had therefore to cope with these limitations and was a compromise among a good database design and the requirements of the system. An example of an inadequate database scheme are the relationships between the St018Pat polygon layer and its related tables T0180801000 (Characteristics of quaternary deposits), T0180802000 (Lithostratigraphic information) and T0180803000 (Texture). For instance, the T0180802000 table contains the hierarchical lithostratigraphic units data (*x supergroup*, *x group*, *x formation* and *x member*. See Sections 6.2 and 6.3 for a full explanation on the conceptual modelling of geological hierarchies) in the SIGLA*n* items. SIGLA1 contains the lower lever of information, for instance *x member*, while SIGLA2 to SIGLA4 contain the data of the higher lithostratigraphic units, if present. This structure of the database does not allow performing a hierarchical query on the archived information and therefore it is not possible to query the hierarchical tree to find a parent or a descendant of an item as indeed proposed in the system of Chapter 6. In Figure 5.7 another example of a not fully normalized design is the T018080300 table, which contains the texture characteristics of the lithostratigraphic units and that is related to St018Pat by a relationship with a 1:1 cardinality. In T0180803000 the percentage of gravel/sand/clay is stored in the *Tessitura* (texture) item in a form that is not atomic, e.g. the different percentages are inserted together in the same item as text, separated by a comma.

Nevertheless, the SGN asserts in the guidelines for the digital encoding of the Italian geological map (Servizio Geologico d'Italia, 1997) that the CARG geological database is not a *strict relational database*, but it is indeed a *model* for the delivering of geological data collected by the surveyors in the field. In Italy the field mapping is not done directly by the SGN but it is contracted out mainly to universities or research institutes. The geologist-surveyor often works alone in the field, collecting data on the basis of a topographic sheet, without having any contact with the surveyors of the adjacent geological sheets. The main duty of THE SGN is therefore the control of the congruence of the surveyed geological information between adjacent sheets, of the referential integrity constraints and of the topological relationships. To this end, after uploading the data into the SGN central system, *ad hoc* queries are performed to control the referential integrity of the archived geological data. The scripts control as well the topological relationships inside the objects in a single feature class and between different feature classes. For instance, a fault in St018Aat (structural elements) that is also a border of adjacent lithostratigraphic unit in St018Pat (geological information) must be coincident with the border of these polygons.

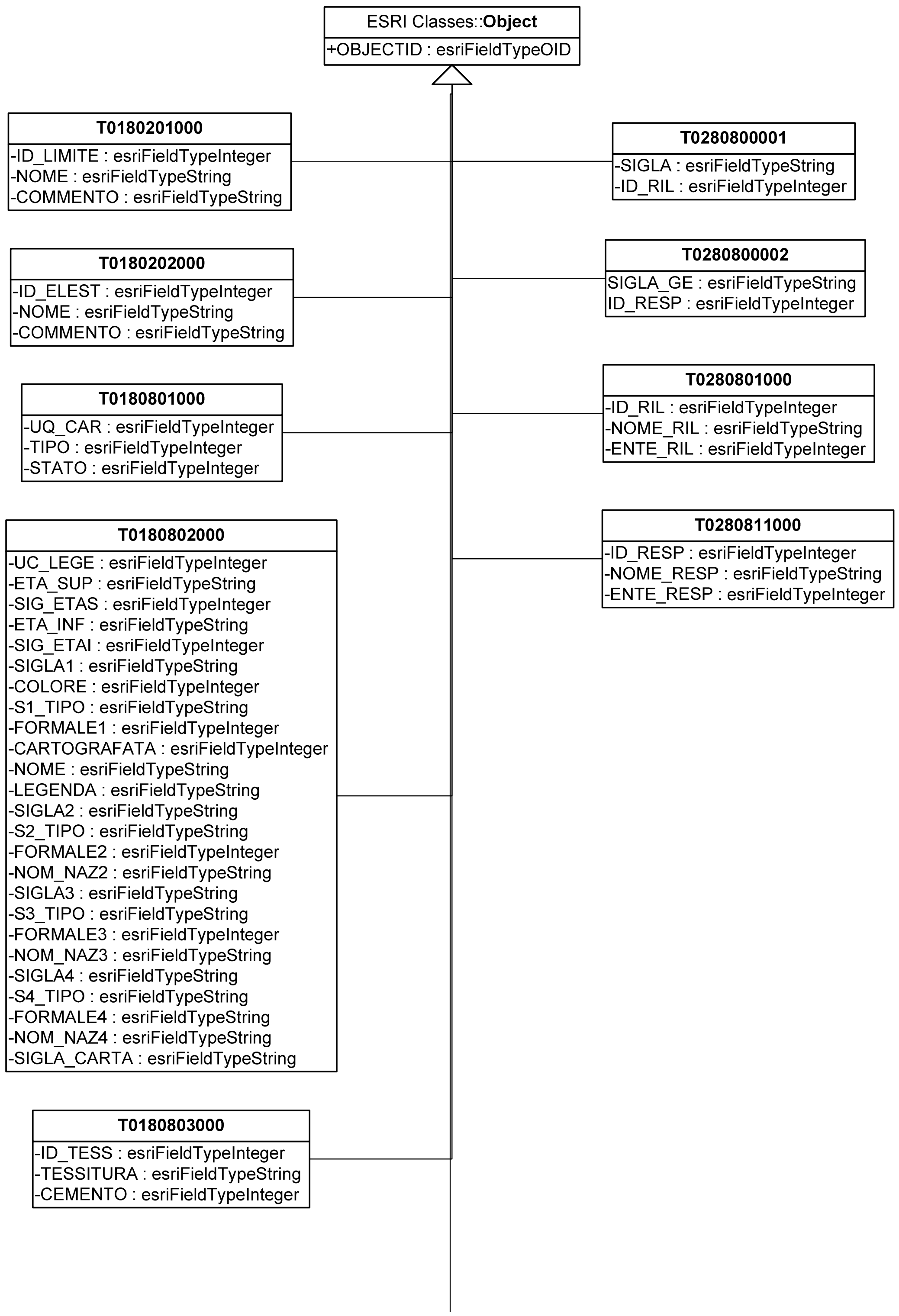
However, during the last years, the SGN has been working on a new database scheme and on new tools for the management of geological data that would take into account both the new developments in software technologies and the results of the last research on the design of geological database and the management of geological mapping.

5.5.3 Implementing the CARG database scheme into the geodatabase model

The CARG geological database scheme, modelled using Entity/Relationship diagramming techniques and shown in Figure 5.6, has been transposed into an object-oriented (O-O) model using Unified Modelling Language™ (UML) software. ArcGIS® allows the definition of the content and structure of a geodatabase using third-party Computer Aided Software Engineering™ (CASE) tools like Microsoft Visio®, the application that has been used in this research. Visio® tools allow to create a visual UML diagram, or model, of the geodatabase, then use the Scheme Wizard™ tool of ArcCatalog™ to read the model and generate the corresponding geodatabase elements (object classes, feature classes, domains, subtypes and relationships) from it. The CASE tools cannot create certain types of geodatabase elements, like annotation feature classes, raster datasets, spatial reference and topology rules. However, they may be also used to manage the database over time. For instance, you can add new object classes (tables) or feature classes to the model, then re-apply the model to an existing geodatabase to create the new elements.

The geodatabase is a Microsoft Access® file system of the *.mdb* type that organises data into a hierarchy of data objects. These data objects are stored in feature classes, object classes, and feature datasets. An object class is a table (or class) in the geodatabase that archives aspatial data. A feature class is also a table in the geodatabase but it contains a collection of features with the same type of geometry and the same attributes. A feature dataset is a collection of feature classes that share the same spatial reference.

The 15 geographic entities shown in the CARG database diagram have been modelled in Visio® as *feature classes* containing geographic elements and descriptive attributes, while the 9 tabular entities have been modelled as *object classes* containing descriptive attributes. From the conceptual point of view, a feature class is just an object class containing geographic features. It is also a subordinate of an object class and inherits from this its properties and methods. The type of geometric element and of the attributes of any feature class and object class correspond to those implemented in the CARG database scheme. Figure 5.8 shows the feature classes and object classes implemented in Visio® for the geodatabase.



Continues in Figure 5.9

Figure 5.8. *Object classes* implemented in the geodatabase according to the CARG database scheme. Both object classes and feature classes have the same ancestor: *Class*. The upper part of each table contains the name of the class, while any row in the lower part of the tables is a property of the class mapped as an attribute field in the geodatabase object class or feature class. Figure 5.8 continues in Figure 5.9.

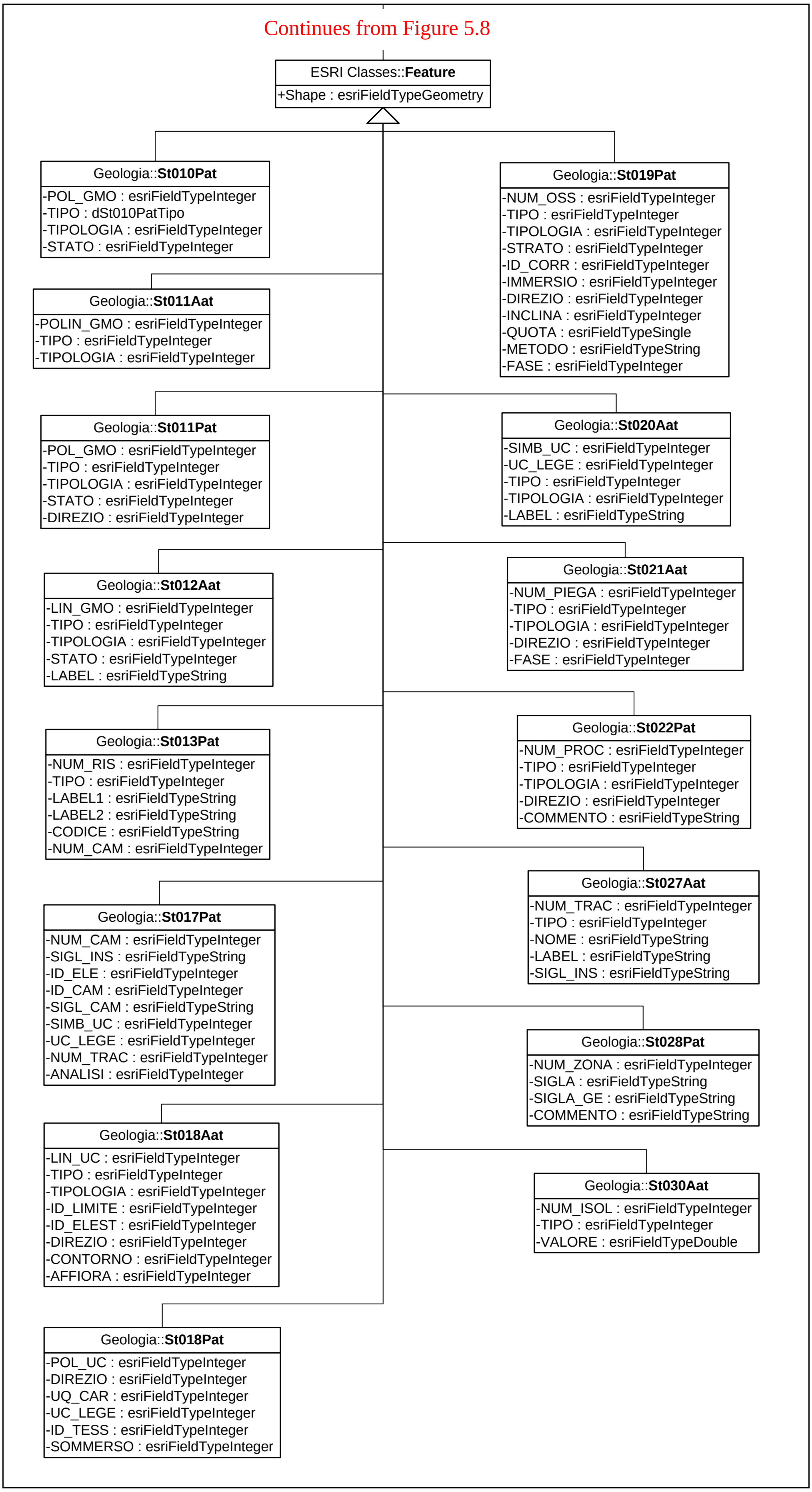


Figure 5.9. *Feature classes* implemented in the geodatabase according to the CARG database scheme. Note that *Feature* is a subordinate of *Object* and inherits properties and methods from it (see Figure 5.8). Figure 5.9 is the continuation of Figure 5.8.

Using Visio® tools implemented by ESRI for ArcGIS® to model the geodatabase, relationships between feature classes and object classes have also been modelled as a special type of class: the *relationship* class. Relationship classes define relationships between objects in the geodatabase (e.g., feature classes and object classes). These relationships can be simple one-to-one relationships, or more complex one-to-many (or many-to-many) relationships. Some relationships specify that a given feature, row, or table is not only related to another, but that creating, editing, or deleting one will have a specified effect on the other. These are called *composite relationships*, and they can be used to ensure that the links between objects in the database are maintained and up to date, preserving referential integrity. For instance, deleting a feature, such as geological path, can trigger the deletion of other features, such as the geological stations along the path. Figure 5.10 lists the relationships created according to the geodatabase scheme.

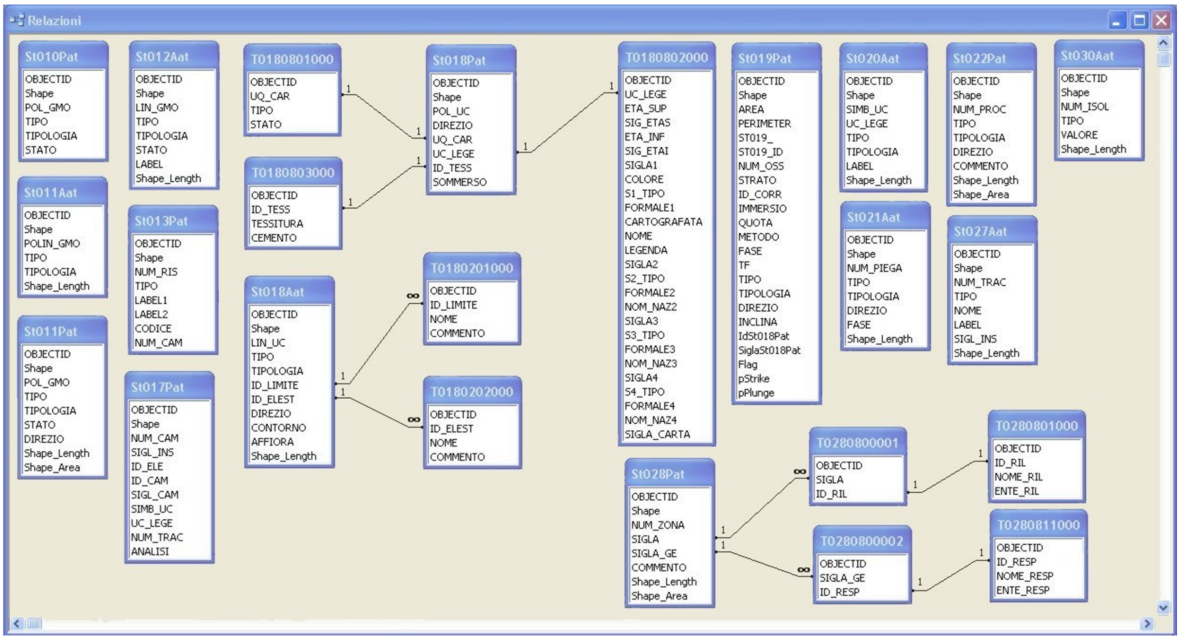


Figure 5.10. Relationships between feature classes and object classes in the geodatabase, modelled as classes in Visio® and tables in Microsoft Access®, as they appear in Microsoft Access®.

In Visio® 32 domains have been modelled as classes. Two different sets of domains in the geological model have been identified: domains specific for an attribute of a single feature class or object class and domains valid for any feature class or object class present in the geodatabase. For instance, to the first set belongs the domain *ST021AatTipo* for the attribute *Tipo* (Type) of *ST018Aat* (line) feature class, while to the second group belongs the domain *Stato* (Condition) for the attribute *Stato* that is present in most of the feature classes in the model. In fact, the domain is a property of the entire geodatabase and therefore it may be applied to any feature class or object class that is part of the model. Figure 5.11 shows an example of the two different sets of domains.

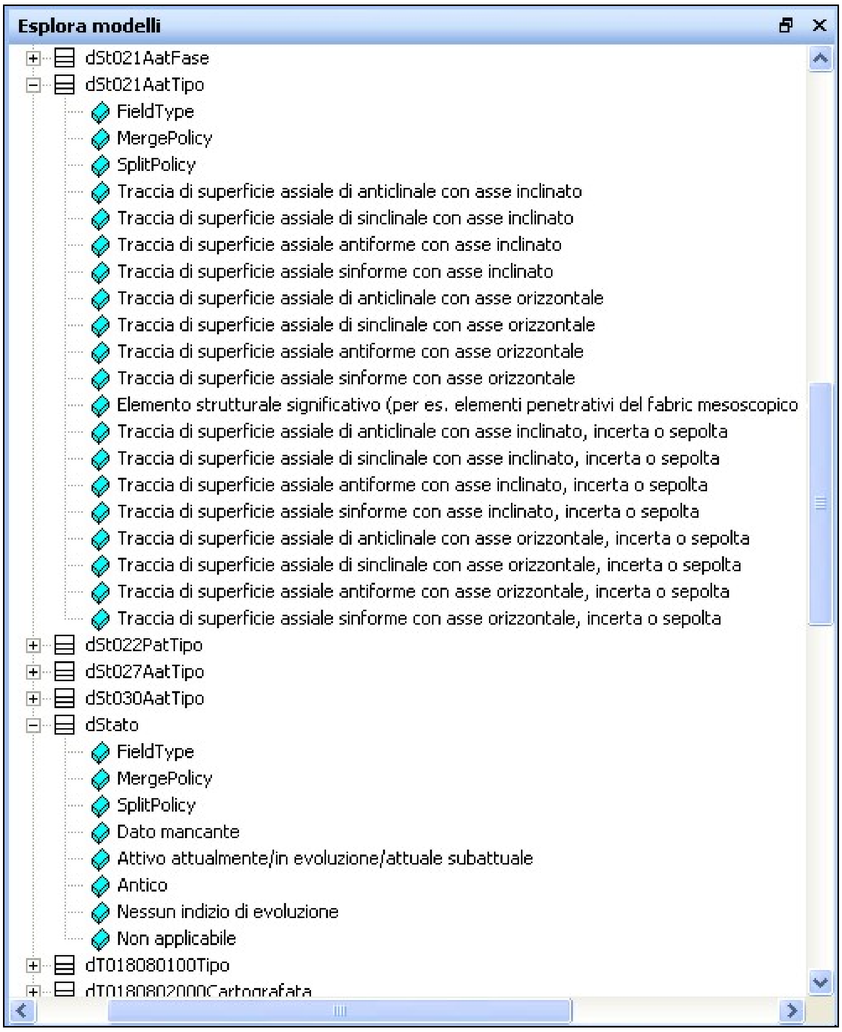


Figure 5.11. *ST021AatTipo* domain describes the type of linear structural occurrence, while *Stato* domain describes the condition of a geographic feature.

The CASE tools expect UML models to be created following a set of modelling rules. After creating the UML model in Visio®, the Semantics Checker™ tool has been used to verify that the model had been correctly defined. The following phase has been to export the UML model to a Microsoft Repository®, an intermediate step before creating the final scheme of the geodatabase. Figure 5.12 shows the geodatabase created using the Scheme Wizard™ in ArcCatalog™, the browsing and organising application for geographic data of ArcGIS®, while Figure 5.13 shows the same geodatabase in Microsoft Access®.

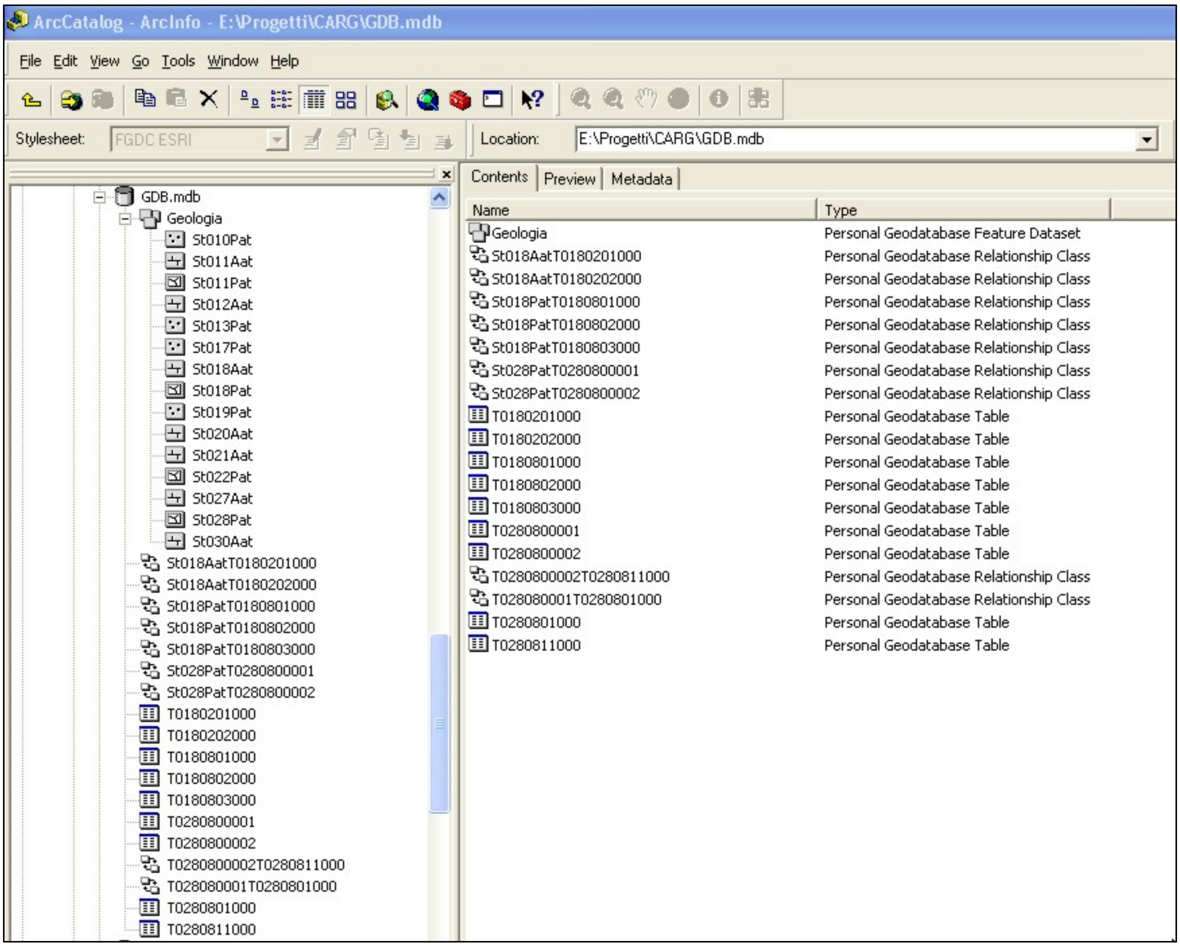


Figure 5.12. The CARG geodatabase created using the UML model implemented in Visio® as it appears in ArcCatalog™.

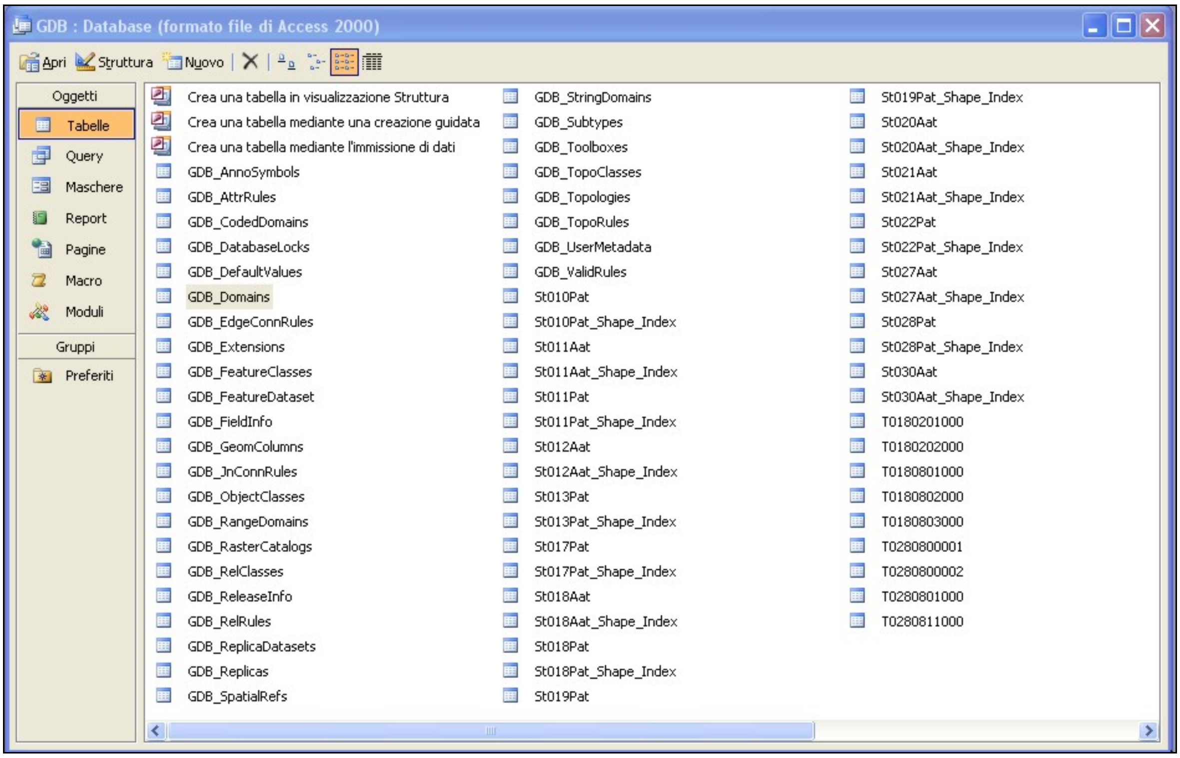


Figure 5.13. A view of the CARG geodatabase as it appears in Microsoft Access®.

One of the most powerful tools available in ArcGIS® is the possibility to build topology rules between the feature classes contained in a geodatabase. Many vector datasets have features that can share boundaries or vertices. For instance, in a map a fault can represent a structural element that can also be part of a boundary of a geological unit. Faults are archived in the geodatabase in the *ST018Aat* (line) feature class, containing linear geological elements, while geological units are stored in the *ST018Pat* (polygon) feature class. Therefore the fault line in *St018Aat* must be coincident with the boundary of *ST018Pat*, containing polygon geological features. Creating a topology in a geodatabase, it is possible to set up rules defining how features share their geometry. Editing a boundary or vertex shared by two or more features updates the shape of each of those features. Topology rules can govern the relationships between features within a single feature class or between features in two different feature classes. For instance, moving a geological boundary in one feature class would update a fault in another feature class.

Unfortunately, as well as spatial reference, topology cannot be modelled in a Visio® UML diagram, and therefore it has been necessary to implement it in ArcCatalog™. Figure 5.14 shows some of the topology rules set up between the geodatabase feature classes.

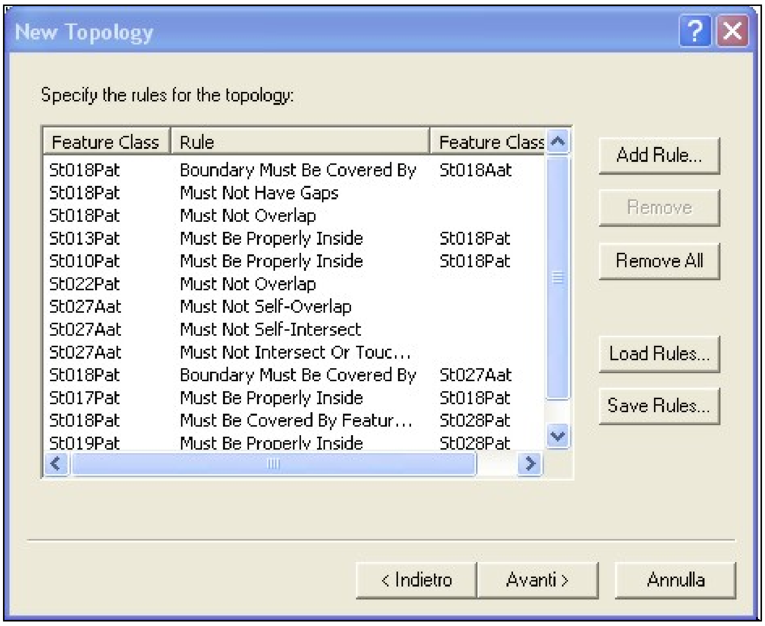


Figure 5.14. Some of the topology rules set up in ArcCatalog™.

After creating the geodatabase scheme, the following step has been the implementation of a map project containing the required feature classes and tables for a test in a field. The ArcGIS® application for organizing data for display, analysis and printing is ArcMap™. Topography of a test area has been added to the map document and the required symbology implemented according to the standards of the Geological Survey of Italy

(Servizio Geologico d’Italia, 1996) for the CARG Project. The final map project ready to be used for collecting geological information in the field is shown in Figure 5.15.

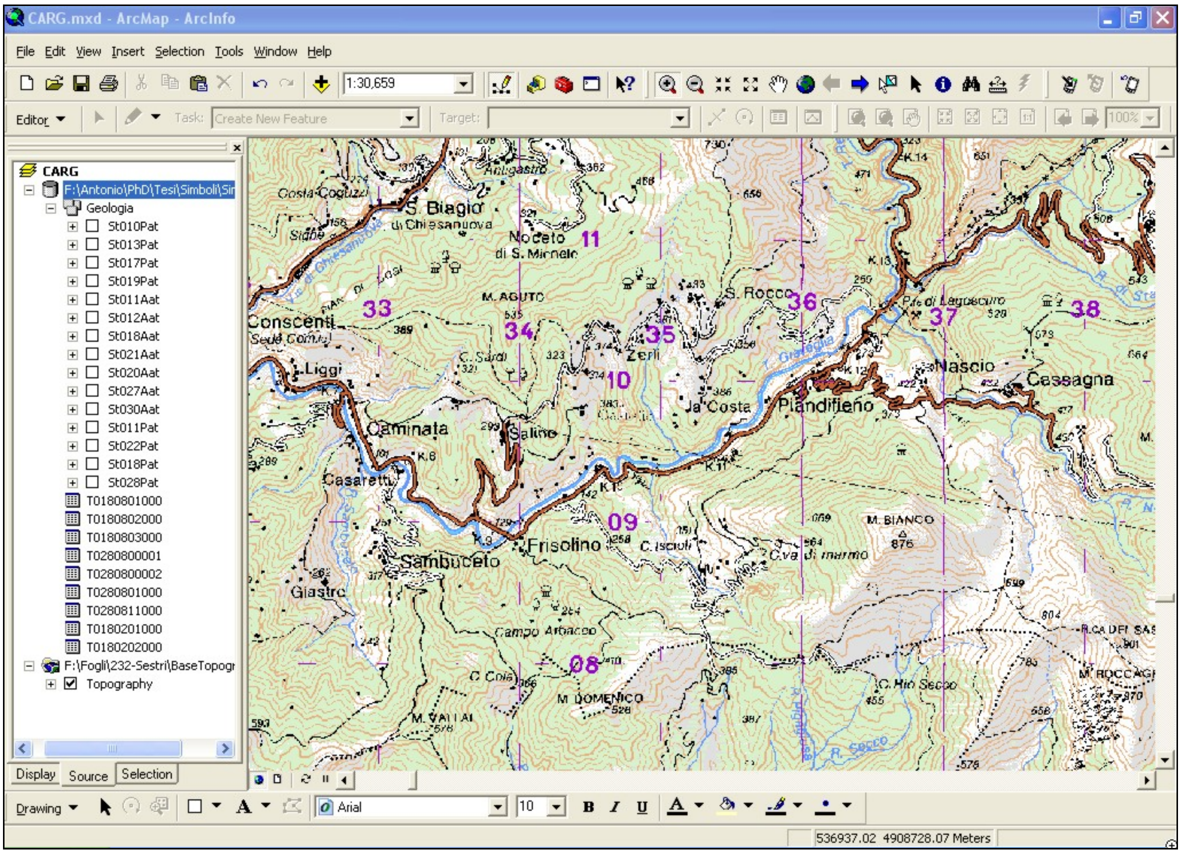


Figure 5.15. Map document set up in ArcMap™. Feature classes and tables are shown on left and are still empty. Only the topography is visible in the display area on the right.

5.5.4 *Test in the field*

ArcGIS® contains specific tools to export a map project to an ArcPad® mobile application. Geographic and tabular data and the geological database scheme have been therefore transferred to the iPAQ® system to be filled and edited in the field with ArcPad®.

The test area has been chosen in the Liguria region, selecting a portion of the *Sestri Levante* topographic sheet at scale 1:50,000, enlarged and validated by the Italian Military Geographic Institute (IGMI) to a scale of 1:25,000 for the field survey.

The Sestri Levante sheet is one the key areas in the comprehension of the complex stratigraphic and structural evolution of the Interior Ligurian Units of the Northern Apennines. In this area crop out the stratigraphic sequences of the Vara Supergroup, that are formed by the ophiolitic rocks of the substrate and their sedimentary cover represented by the pelagic deposits. The sequences represent the remains of the ancient oceanic basin, named western Tethys, formed during the Mesozoic between the African and European plates and closed between the Upper Cretaceous and Eocene following the Alpine orogenesis.

The Sestri Levante sheet covers a sector of the Ligurian coast between Lavagna and Framura and its hinterland for about 15-20 km. In the area can be identified the lower section of the Sturla Torrent, the Graveglia Valley, the Petronio Torrent, the upper section of the Vara River and several minor basins flowing directly to the Tyrrhenian Sea. Figure 5.16 shows the Sestri Levante topographic sheet at scale 1:50,000.

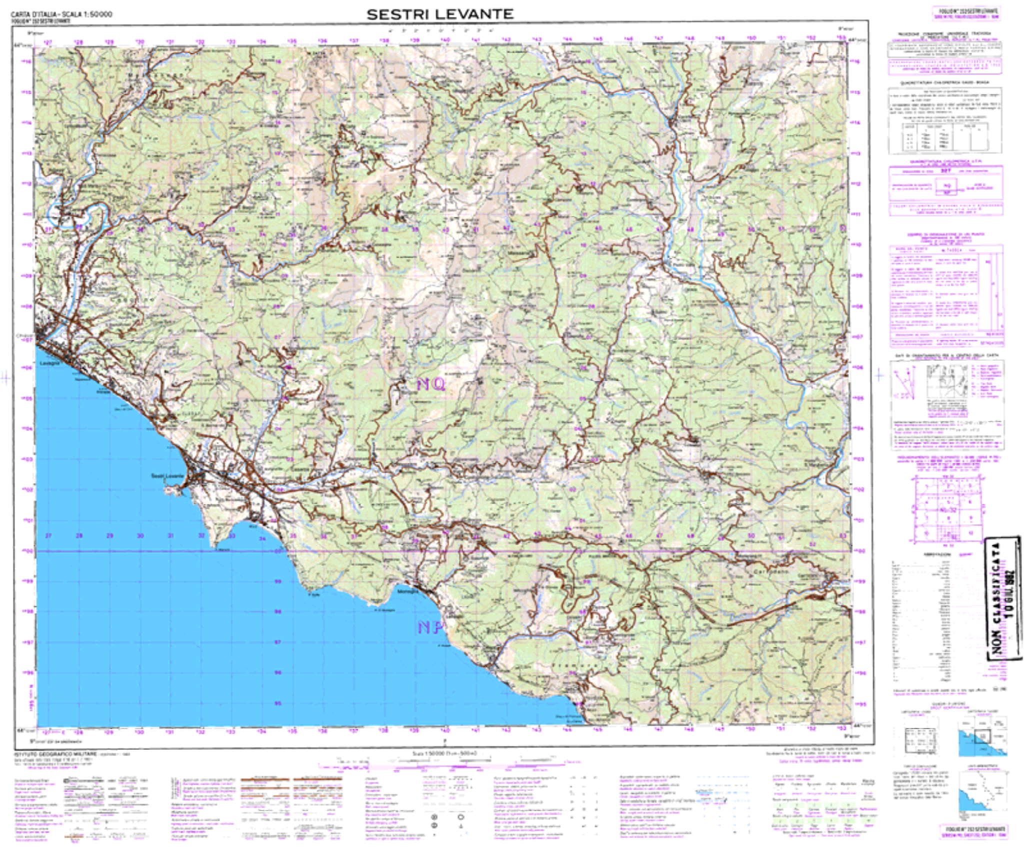


Figure 5.16. The Sestri Levante topographic sheet.

Together with a group of survey geologists and stratigraphers, the data gathering system shown in Figure 5.6 has been used for several days during a geological field trip, and digital geological mapping has been carried out over a small part of the Sestri Levante sheet. It is worth noting that the field survey has been just a field test to evaluate the efficiency of the system and not a full mapping exercise. Positional data for each observation have been automatically recorded from the GPS locational fix. Tectonic contacts (*St018Aat*) have been mapped as lines and structural data, essentially bedding dips and strikes, have been collected as point measurements in *ST019Pat* feature class. Polygons have been drawn to represent geological formations (*ST018Pat*). Digital photographs of the key outcrops have been also taken. Figure 5.17 shows the area of the test, while Figures 5.18 and Figure 5.19 are an example of geological data management and editing in the field. Dotted lines highlight editing elements.

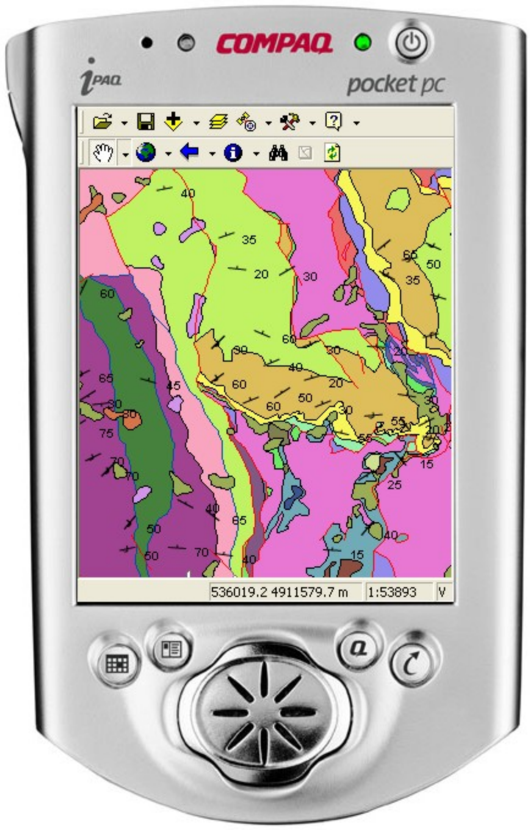


Figure 5.17. The portion of the Sestri Levante sheet where the digital geological mapping has been carried out.

Figure 5.18. Editing of *ST018Aat* (line) feature class, containing linear geological elements, such as faults and stratigraphic contacts. Left: from a dropdown menu, the type of stratigraphic contact is selected. Right: the proper description for the same object is chosen.

Figure 5.19. Left: Editing of ST018Pat (polygon) feature class containing geological objects such as geological formations. Right: Structural data (bedding deeps and strikes) are inserted in *ST019Pat* (point) feature class.

After the geological survey, field data have been transferred back to the desktop ArcGIS® system using the check-in functionality, and the geodatabase has been loaded with the collected data in the field. Figure 5.20 shows the map document in ArcMap™ application, while Figure 5.21 shows the attribute table of *ST018Aat* (line) feature class with all attributes populated with the proper domains.

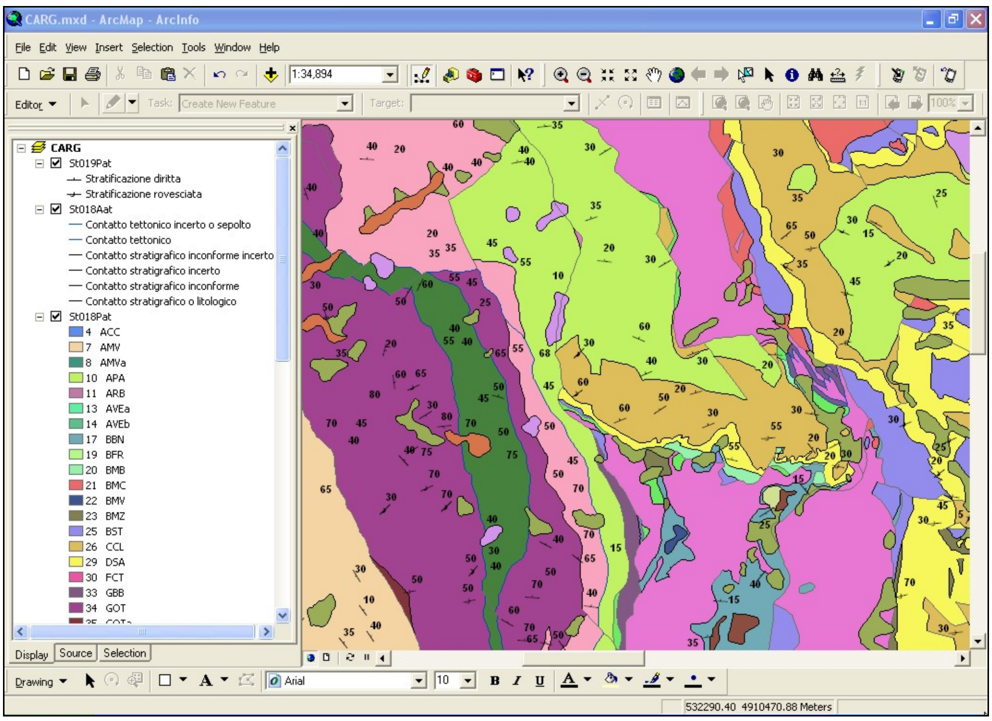


Figure 5.20. The map document in ArcMap™ application.

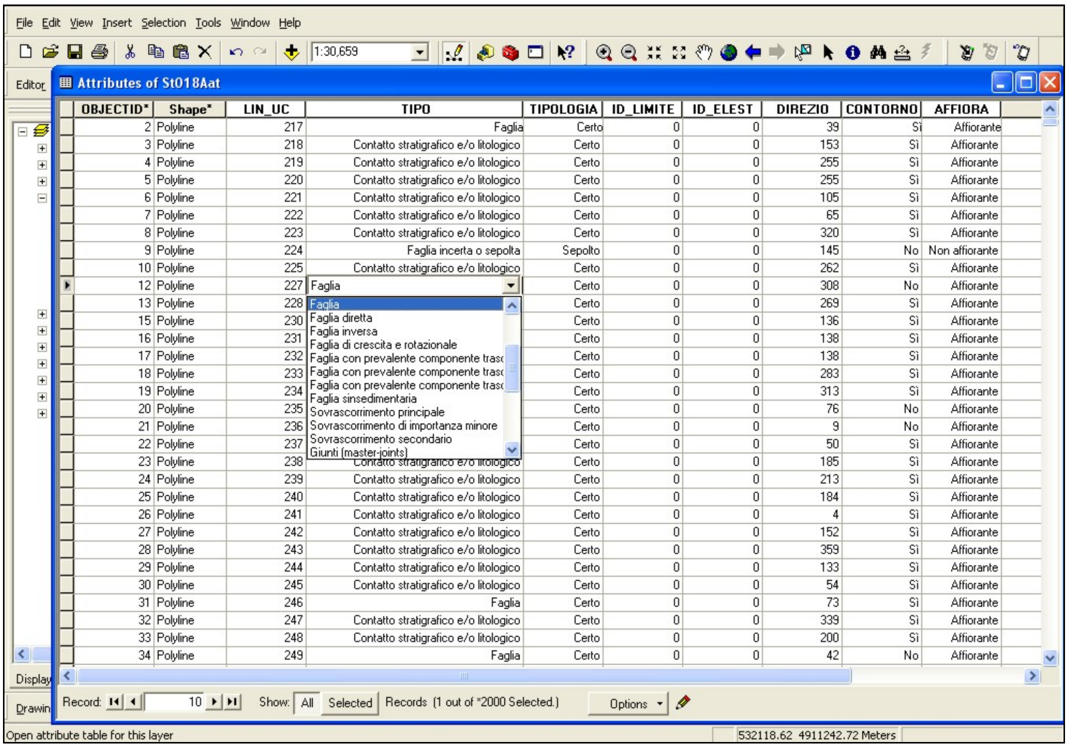


Figure 5.21. Attribute table of *ST018Aat* (line) in ArcGIS® desktop application.

After loading data into the desktop application, the feature classes have been draped onto a digital terrain model (DTM), in a form of a surface fitted to a raster map of elevation values, to produce a display of a 2.5D representation for further visual structural analysis. (In a 2.5D representation it is possible to assign only a single *z* value for any *x*, *y* position, while in a real 3D representation different *z* values can be assigned to the same *x*, *y* position as, for instance, in a stratigraphic log.) The resulting digital geology may be also displayed on a variety of topographic, photographic or other bases, and the model may be zoomed or rotated to various vantage points. Digital photographs have been linked to their location with a hot-link and within the GIS may be accessed by clicking on specific points on the map. Viewing the geology in 2.5D provides a much better appreciation of how geology interacts with topography and has been shown to enhance geologists 3D understanding in complex areas (McCaffrey *et al.*, 2003). However, using real 3D applications like EarthVision® by Dynamic Graphics, would provide much more sophisticated immersive capabilities for data interpretation. True 3D volumetric data can be incorporated to build solid geological models rather than a series of stacked surfaces or parallel cross-sections (Kessler and Mathers, 2004), which may then be exploded to examine details of the model.

5.5.5 *Assets of the systems*

During the field test we have asserted that a number of technological advances have increasingly helped to make methods of digital field data acquisition a practical, low-cost alternative to paper-based fieldwork systems, besides several severe technological flaws still need to be solved. In addition, these methods offer new types of spatial analysis that were previously impossible or impractical to achieve by conventional mapping methods.

Digital methods can improve the quality and efficiency of field data collection because they have potentially better spatial accuracy than traditional methods, they can help streamline the workflow from data collection in the field to the published map product, they allow better visualization of data in two dimensions and three dimensions, they yield further geological insights because of the enhanced ability to perform geological analysis, and they can help re-use pre-existing data during renewed phases of fieldwork.

An affordable, flexible system suitable for most general geological field data acquisition can comprise just three key components: a handheld computer, a GPS receiver and some mobile GIS software. The main advantage of digital mapping over conventional paper-based mapping lies in the automatic recording of positional data for each observation, meaning that the geospatial context is maintained. Additional benefits include the ease with which data are recorded in formats that are compatible with widely used relational databases, the opportunity to map at varying scales, and the ability to map onto different base layers, such as a remote sensed image, aerial photograph or topographic data layers.

The precision or error of the GPS position has been estimated by making observations at the same location over a given length of time. The precision achievable by GPS receivers generally varies with its cost. The accuracy (how close the calculated position is to the true position) can be determined by making observations on a known survey trigonometric point. Using GPS to locate field data leads to a significant reduction in uncertainty regarding location errors. We have tested the Garmin eTrex Vista® receiver and found that the level of precision range from 2 to 3 m, much less than the acceptable graphic error of 0.2 mm that at a the 1:25,000 scale of the survey is equivalent to 5 m.

Digital geological databases allow many different types of geological data to be stored together, so that the geologist has a visual interface to all of the data collected for an area. Examples of data that may be included are field photographs, regional geophysical maps, aerial photographs, satellite images, topographic data, previously digitized geological information, sample catalogues, geochronological data, geochemical data, etc. A properly managed digital database offers considerably improved data retrieval, database searching, archiving, and remote accessibility compared with conventional paper-based methods.

Many of the raw field data recorded in field notebooks and field slips are inaccessible to anyone else who wants to use them. This leads to an enormous amount of replication of expensive data collection each time a new study takes place in any particular location. Digital mapping and survey methods can also be used to standardize field working practices and help to ensure that data collection may fit institutional database formats. Furthermore, setting up standards will provide a framework for the long-term storage of data and will lead to a reduction in expensive primary data reproduction. These developments can be viewed as a positive step for the long-term sharing of field data compared with analogue methods whereby data remain hidden in field notebooks, field slips and reports.

The ability to reproduce observations and measurements is of paramount importance in scientific methodology. Often different observers have difficulty in replicating previous observations. When mapping in remote areas, the precision with which a position is located using sighting compass and field slip may be poor, because standard compass-based transect methods are not enough accurate and may make it difficult to revisit old field observations. Digital mapping has powerful features that improve the capability to visit the exact location where an observation was made. We have made a test where a geologist collected a fault dataset into the iPAQ® PDA device connected to the Garmin eTrex Vista® GPS receiver and another geologist, who had not collected the data, had to navigate to the same fault sample location using the ArcPad® application and the GPS locational fix. On reaching the position stored in the database, the sampled location was less than 1 m far from the original position. The accuracy level of a digital device is a considerable improvement over the analogue methods. Furthermore, arguments about interpretation are less likely to be affected by uncertainty regarding where exactly the observation was made.

The efficiency of fieldwork can be thought in terms of the time it takes to collect geological data in the field. In our test, the time savings made during acquisition of field data in digital form was nil compared with traditional methods of mapping. After training, a significant improvement in the time saving should be assessed. However, the digital nature of the acquired data gives large time savings when subsequently carrying out analysis or producing maps and reports.

It is indeed evident that the adoption of digital fieldwork practices will provide the geologist with significant advantages, such as a better data management on projects, with much better reproducibility of observations, and the ability to carry pre-existing data into the field to provide supplementary information to aid data collection, interpretation and hypothesis testing. Geological data collected in the field can be easily integrated into a single georeferenced database that agrees to national or international database scheme standards. It is also possible to implement a more streamlined digital workflow from the initial data acquisition stage to the final map product.

5.5.6 Drawbacks of the system

Two major constraints were accepted at the beginning of this effort. The first was that the learning curve of ArcGIS® software, in the short time of the test, was too steep to expect geologists in general to utilize this application as a tool without the presence of a higher-level interface, which would implement all the geodatabase capability, e.g., relationships, domains and topology. The second was that geological field mapping is a very broad and subjective field. Therefore the system developed was focussed on the specific geological scheme and model of the CARG project.

Discussions with survey geologists who used the system in the field have resulted in a list of concerns and operational issues, which have highlighted the limitations of the system and the instruments. The major drawbacks are discussed below.

5.5.6.1 ArcPad® and iPAQ® field-based digital visualization

The 2D screen on the handheld iPAQ® computer was considered by most geologists as too small, and the limited graphics capabilities of ArcPad® mapping application largely restricted data visualization to simple map-type displays in the field. The graphics display was however capable of visualizing raster data at high resolution and this has allowed an aerial photograph and a digital terrain model in 2D (*hillshade*) to be used as a backdrop onto which new data have been portrayed. Furthermore, a digital display allows more flexible methods of visualization that can be easily tailored to individual requirements. For instance, on-screen data may be viewed at different scales in two dimensions using zoom and pan functions with different combinations of data layers displayed as required. Unfortunately, to date no handheld computers incorporate 3D viewer capability that would allow 2.5D models to be viewed in the field while data are being collected.

Another major issue of the ArcPad® mobile system was the incomplete display of the attribute domains in the dropdown lists as shown in Figures 5.18 (left) and 5.19 (right). In the dropdown window an horizontal scrollbar is not available and any string exceeding the length of 15 characters is truncated. Therefore it is not possible to choose the proper domain, which would constrain choices and reduce data entry errors, because the name of the domains is not fully visible, for only the first part is displayed in the dropdown list.

The problem could be overcome using the 4-digit numeric code archived in the TIPO (type) field instead of the textual description, but this would force the geologist to go to the field with a list on paper (in the CARG database there are more than 500 codes) or storing the list as a separated file on the PDA. According to ESRI, the problem should be solved using the next version of ArcPad Application Builder® that should be released at the end of 2007. ArcPad Application Builder® is the development framework for building custom ArcPad® applications. With it is possible to build *applets* for field specific applications and tasks, write scripts using VBScript™ that interact with the internal objects of ArcPad® application and design custom forms to streamline data collection and ensure data integrity in the field.

Another major issue that has surfaced transferring a map project from the ArcGIS® desktop system ArcMap™ to the ArcPad® field application is the impossibility to directly export object classes and the loss of the relationships established in the geodatabase without significant customization and third-party software.

To transfer an ArcGIS® map project to ArcPad®, the map must first be *checked-out* from within ArcMap™. To check-out a map, ESRI provides a specific toolbar that can be added to ArcMap™. The commands on the toolbar allow the user to specify the layers to be exported as well as whether to export all the data associated with those layers. When a map project is exported form ArcGIS® to ArcPad®, the geodatabase feature classes are converted in *shapefiles*, the native geographic data format of ArcPad®.

A drawback to this approach is that there is no programmatic connection between the ArcPad® version of the data and the ArcMap™ version. When a user checks-out a version of the map for ArcPad®, it is simply a copy of the data. If changes are made to both versions of the map (the handheld version and the desktop version), the changes made to the desktop version will be overwritten when the handheld version is checked-in. Additionally, ArcPad® does not support multiple check-outs of the same map. If the same map is checked-out multiple times, each check-in of the data will overwrite the previously checked-in data. ArcPad® provides no support for merging changes in a personal geodatabase made on multiple PDAs to the same desktop map.

Another severe concern with the ArcPad® check-out procedure is its inability to transfer tables since the toolbar commands export only feature classes and do not check-out object classes. Since there are usually many object classes in a geological database, like the CARG geodatabase, a procedure needs to be developed whereby these tables are manually exported to DBF format (the only format supported for data tables) using ArcCatalog™. After entering data into those object classes using ArcPad® on in the field, another procedure needs to be developed to allow them to be re-imported into the geodatabase.

But probably the most severe issue was the lack of support for relationship classes that are defined in the geodatabase. If changes or editing made in the ArcPad® version of the map violate any of the referential integrity constraints defined for the relationship classes in the geodatabase, these change must be manually corrected during the check-in process, or programmatically accounted for in an ArcPad® customization. A way to overcome this problem would be the use of a third-party external database. Several software packages on the market provide the user with a means of interacting with databases on a PDA. These products, like HanDBase® by DDH Software (www.ddhsoftware.com/handbase.html) or Visual CE® 10 by SYWARE (www.syware.com/visualce.php), would still require the development of an interface in much the same way as with ArcPad® or VBScript™, but the coding necessary to connect to the various geodatabase feature classes and object classes and maintain referential integrity is hidden from the user and the programmer alike.

Object model enhancements to ArcPad® to support relationships related tables (highly anticipated by ESRI) such as relationships with 1 to 1 and 1 to many cardinality will be included in the new release of the software expected for the end of 2007. ArcPad 7.0 does have a SUBTABLE control, which can display records in a 1 to many relationship, but its functionality is limited to read-only access for now. This control will be enhanced to support write access (to create new records or edit existing records) in the future release of the product. The new release should also include a built-in support for exporting directly object classes from ArcMap® to ArcPad® using *ad hoc* commands and functionalities.

5.5.6.2 Field-based digital analysis tools

Spatial statistical and analytical tools have not yet been developed for direct use in the field on a handheld computer (McCaffrey *et al.*, 2005), besides they may easily be used on a laptop computer at the field base where the desktop application runs. It is indeed true that on-the-outcrop analysis tools such as rose diagrams, frequency plots, dip analysis, structure contour estimation and intersecting plane calculations would significantly ease the work of the survey geologist.

5.5.6.3 GPS receiver

The positional precision and accuracy that may be achieved using a GPS receiver is dependent on variations in the input satellite configuration (an error summarized by the Dilution of Precision statistic calculated continuously by GPS units). By obscuring the unit from direct line of sight to satellites, steep topography or sometime the foliage or the crown of trees can limit the number of input satellites available to a GPS receiver and degrade, or even prevent, a locational fix. This means that accurate positioning near cliffs, under vegetation or in deep valleys may be difficult to achieve.

Another possible source of error known as *multipath* can occur when locating near a metallic object (e.g., a chain link fence) and is due to the satellite signals travelling through the object before encountering the receiver.

Furthermore, GPSs have poor resolution in the z direction. Alternatively, 2D data may be converted to 3D by locating the positions on a digital terrain model.

5.5.6.4 Operational efficiency

Geologists have generally perceived disadvantages of digital acquisition methods, including poor integration and compatibility of software and hardware, and bulkiness and ruggedness of field equipment. They have also had the perception that the complexity of PDA computer with on-board mapping connected to a GPS receiver means that the simplicity of paper-based methods is lost and could lead to a loss of focus on the geological problems at hand.

5.5.6.5 Operational issues

The cost of robust, weather-resistant equipment is still relatively high, although prices are falling rapidly. PDAs are largely designed for office and personal use, although with care they may be used in the field. Specific systems designed for the field, like the DART® handheld computer, are extremely expensive. Low-cost equipment is generally not robust enough for long-term use or expedition fieldwork.

Developments in battery technology have played a key role in the usability of digital geological mapping and survey equipment. Lightweight, long-life rechargeable batteries usually power handheld computers and GPS equipment. We have noticed a maximum of 6-8 hours use for our system, meaning that extra power cells are required for long days. Recharge times must be taken into consideration when planning fieldwork, particularly when camping. Wireless communications protocols now allow field units (e.g., the GPS receiver and the PDA computer) to transmit data to each other and transfer also files to laptop and desktop computers, and thus remove issues associated with cables and connectors between the various parts of the equipment. This, however, to the detriment of battery life.

There is always potential for data loss or corruption in the event of equipment failure so a systematic data back-up strategy is essential. Loss of a complete digital database that has not been backed-up is just as disastrous as losing a field notebook. However, it is easier to copy data to a laptop computer at the field base each evening than routinely backing-up a field notebook.

The physical size and weight of the amount of equipment that must be carried is another major consideration. The digital geological mapping system used is relatively compact and portable and will fit into a small backpack. A laptop computer is bulky and is not easily transported far from a vehicle, placing limits on the outcrops that may be surveyed at high resolution.

Many of the core technologies used for both digital geological mapping and survey are not currently fully integrated with one another, so that workflows for digital mapping are not fully optimized. Problems remain with compatibility of hardware, and especially of software, when the desktop application does not belong to the same family of products as the field application, and with different data formats required between successive stages in the workflow from field acquisition to visualization and analysis. Software vendors are attempting to use more open formats or are providing tools that allow data to be converted from one format to another, usually to the detriment of value added of any format.

5.5.6.6 User resistance

The perception of most geologists has been that traditional fieldwork methods are easier to use than the digital alternatives, probably because they are familiar with these from their training. This distinction is much less marked with younger geologists, for whom digital devices have always been a central aspect of their educational and social life. With any technological advance there will always be a part of the user community who would prefer to continue with the old tried and tested methods.

There have also been concerns that there will be a demise of generic mapping skills. However, most of the important skills, such as observation, interpretation, analysis and continuing hypothesis testing should be enhanced by using digital methods. For instance, the ability to plot an instant rose diagram in the field, call up an old dataset, or see how a contact mapped at one particular place would project through the whole field area, must enhance the interpretation process. There could be a loss of cartographic skills in the sense that there would no longer be a need to use pencils and colouring pencils, but these can be regarded as mechanistic rather than generic mapping skills.

Nevertheless, it is important that geologists will still be trained in traditional paper-based mapping methods, so if the batteries of the field system run out or there is no satellite coverage they can still perform in the field.

5.6 Conclusions

There is some resistance among the geologist community toward the new way of collecting data in digital form directly in the field. It must be kept in mind that, at one time, the use of paper forms in the field were considered just as inconvenient to the geologist, but they are now often seen as an indispensable aid to the systematic capture of information in the field. Creating electronic forms allows the geologist to retrieve, share and examine data more easily, and in turn allows the geologist to think about geology rather than being concerned with the input of raw information into standard computer systems.

Computerized mapping is finally gaining popularity for field use. Continued advancements in technology will make data collection systems commonplace and will be an even greater asset to geologists in the future. As the cost of running a field survey increases, it is essential that we do not have data in a multitude of formats that are not interoperable or easily accessible.

Data collected by the geologist in the field, together with observations and indications, can add clarity to a geological model at the time of data capture or when contrary models are introduced. Furthermore, field data that today may seem unimportant may in the future become extremely useful.

Any data gathering system that is developed, regardless of operating platform or run application, must have interoperability of data as a main goal. This means that some of the focus of any development should be centred on a data storage structure that allows geologists to use any data capture tool available. This data storage needs to be able to extend the availability of data to geologists and also allow for single queries to access multiple, seemingly disparate datasets.

The geological information collected in the field for the specific use of a single geologist limits the sharing of data and ultimately does not advance in scientific analysis. Information must be accessible by others, now and in the future, in order to serve for science and the geological community.

However, there are still severe technological concerns and limitations that need to be overcome. The proposed ArcPad® application has proved to fail when it is used to manipulate a moderately complex database structure. ArcPad® facilities for interacting with object classes are limited at best. There is no built-in support for exporting object classes from the geodatabase to the PDA. Furthermore, all rules for referential integrity must be maintained by custom-written VBScript™. The quirkiness of many of the tools available both in ArcMap® and ArcPad® make displaying and editing data much more of a chore than is expected with modern database management systems. If the project design can be reduced to a small number of feature classes with few related object classes, the project is still manageable, but trying to maintain a more complex geodatabase design like the CARG database needs significant high-level customization that is not within everyone's grasp.

Aside the present limits of ArcPad®, McCaffrey *et al.* (2005) state that in 5-10 years time digital mapping and survey systems will be much easier to use in general, more streamlined physically, durable, with long-life batteries and wireless connectivity. Extensive analysis software will be available in the field on handheld devices. The iterative interpretation cycle will be shortened and will possibly take place largely on the outcrop. Three-dimensional screens will be available on PDAs. Fieldwork will become more dynamic: remote databases could be updated on the fly via a wireless link from a computer at base, and this would permit to carry out live sensitivity analysis on field-based 3D models. Common repositories of field data will be developed so that field geologists can make use of, and add to, a common body of geological field data, rather than having only their own field notebook.

Chapter Six

6 Representing geological hierarchies in the relational data model

This chapter presents the hierarchical rule-based expert system proposed for the generalization of the geological database, for both the multi-thematic and the multi-scale representations of the information generated and archived.

Sections 6.1 to 6.4 provide the justification of why a hierarchical approach has been selected. They have been extracted and adapted from an unpublished manuscript co-authored by Brodaric, Patera and Boisvert (2000)[1]. Many geological data types such as units, rock types and time scales, because of their intrinsic nature (see Section 3.2), are commonly categorised and organized into hierarchical arrangements. Computer-based techniques must be capable of effectively manipulating such hierarchies. Most databases and digital mapping systems, such as Geographic Information Systems, rely on the relational data model as a paradigm for data management. The relational data model, however, does not inherently support recursion and thus hierarchical queries cannot directly operate on hierarchical structured data. Three approaches are commonly employed to overcome this problem: the *encoded*, the *algorithmic*, and the *set-theoretic* ones (Brodaric and Patera, 2000). Each approach has advantages and limitations and significantly impacts the design of a geological database containing hierarchical information. The set-theoretic method has proved to conform with the relational data model and is advantageous in managing geological hierarchies. The method has been applied to several case studies where the methodology and the geological object model proposed in this research are validated.

The second part of the chapter illustrates the structure of the geological database scheme and introduces the SQL queries used for the database manipulation and generalization.

[1] The work is part of a broader research activity that was started in 1996 at The Geological Survey of Canada with the support of a NATO Advanced grant *Call 215.28/16 of 29th April 1995*, entitled *Investigation and development of techniques for geological map generalization using Relational Data Base technologies integrated with Geographic Information Systems.*

The last part of the chapter shows two case studies where the expert system has been applied.

6.1 Classic modelling of hierarchies

The representation of geological hierarchies in relational databases is related to two classic problems in relational database design: the *exploding parts* and the *classification hierarchy* problems.

6.1.1 Exploding parts

In traditional database literature, the issue of managing membership hierarchies has been termed the *exploding parts* (Date, 1995) or the *bill of materials* problem (Blaha *et al.*, 1990). This label seems to be a historical artefact arising largely from the engineering task of managing complex machinery composed of many discrete parts. Each part possesses unique properties, and in turn is composed of other discrete parts. Generating a *bill of materials* thus requires the listing of all parts making up any component of the assembly. An example of this construction is depicted in Figure 6.1.

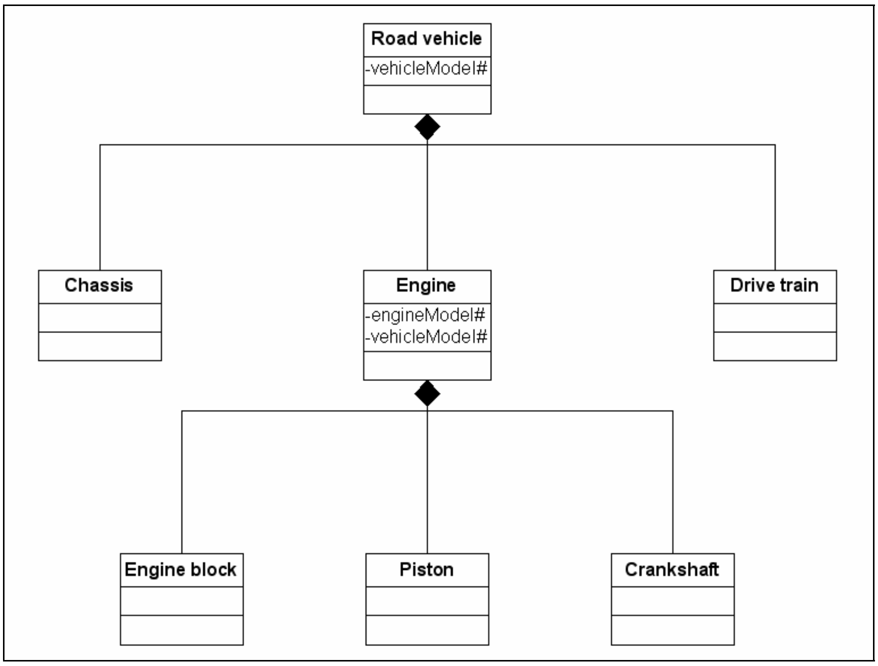


Figure 6.1. The *exploding parts* of a road vehicle is one of the most famous examples of hierarchy in traditional database literature. The black diamond indicates *composition.*

One of the more noticeable things about this structure is the individuality of each object within successively larger assemblies. Each object contains unique properties but has access to the details of its parent assemblies: e.g., the properties attributed to a piston are quite different from those attributed to an engine, but a particular piston would have knowledge of the engine it composes, and an engine would know of the road vehicle it propels. Organizing these parts structure into a relational database typically involves the transformation of each object into a separate database table (Rumbaugh *et al.*, 1991; Date, 1995). Each table would naturally possess a part number uniquely identifying each part in the table, and comprising the primary key for the table. Each table would also contain its most immediate assembly part number, as a foreign key, to establish its membership within the larger assembly. The properties of the assembly *propagate* to its components using relational operations on these keys. The road vehicle and engine objects in Figure 6.1 illustrate this.

6.2 Conceptual modelling of geological hierarchies

What has been described in the previous section can be applied to geological data. *Classification hierarchies* (or *Isa hierarchies*) model the classification of object types. For instance, the *classification* hierarchy in Figure 6.2 classifies rocks into *subtypes* such as *calcareous* and *arenitic*. Each is in turn subdivided into subtypes. The immediate parent to each subtype is referred to as its *supertype*. A supertype may be refined into more than one subtype (e.g., a calcarenite may be both a calcareous and an arenitic rock), in which case the subtypes are said to *overlap*. A supertype that is refined into only one subtype is said to be *disjoint*. In both circumstances subtypes *inherit* the attributes of their supertypes.

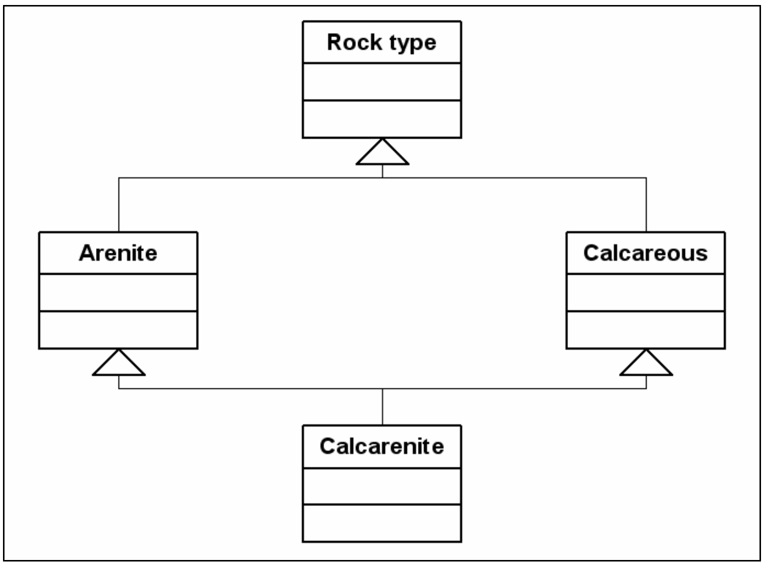


Figure 6.2. Rock *classification* hierarchy. The triangle indicates *generalization*.

Each object in an *classification* hierarchy becomes a table in a relational database and each object also possesses an identifier that becomes its primary key. Maintaining connections between supertypes and subtypes requires the subtype to contain the identifier of the supertype as a foreign key (Rumbaugh *et al*., 1991; Hughes, 1991). Inheritance is dynamically maintained through relate operations on the tables. In the case of multiple *inheritance*, where a subtype may actually inherit from one or more supertypes (e.g., in Figure 6.2 a calcarenite may be classified as both an arenitic and a calcareous rock), then the simple linkage between subtypes and supertypes is extended to contain a foreign key reference to each possible supertype, permitting join operations with each supertype table. The disjoint property of a supertype determines its update behaviour: e.g., deletion of a disjoint subtype entails deletion of its supertype, whereas supertypes are retained in the deletion of non-disjoint subtypes (Hull *et al*., 1987).

Hierarchical thinking is intrinsic to the classification of geological objects like *rock types* (e.g., igneous rock classification schemes), *geological time scales* (eon, era, period, epoch, etc.), *lithostratigraphic units* (group, formation, member, etc.), *lithodemic units* (suite, lithodem, etc.) and other geological units such as *biostratigraphic units* as illustrated in Figure 6.3.

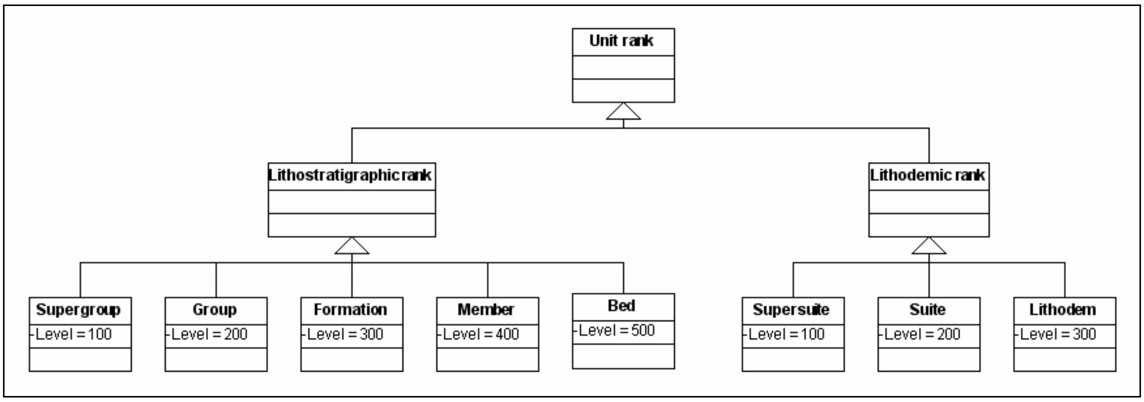


Figure 6.3. Unit ranking as supergroup, group, etc. and supersuite, suite, etc.

Lithostratigraphic or lithodemic units, for example, may have many levels of components: units are composed of other units, which in turn may be composed of units, and a group may consist of several formations, each of which may comprise one or more members. Rock type hierarchies, on the other hand, are innately classifications: a granite *is a* granitic rock type, which *is a* plutonic rock type, which *is an* igneous rock type. Time scales also follow this pattern as Neoproterozoic *is a* Proterozoic time period, etc. Where geological hierarchies diverge from the classic structures is in their explicit recognition of rank, in a tendency towards uniform description of the hierarchical components, and in the lack of a common root origin for the hierarchy. Geological hierarchies are additionally often semantically mixed, e.g., a unit hierarchy may contain both lithostratigraphic and lithodemic units.

6.2.1 Rank

The notion of rank explicitly connotes a hierarchical organization of items, e.g., ranking implies existence within a stratified scheme in which elements potentially exist above or below any other element in the scheme. As modelled in Figure 6.3, lithostratigraphic hierarchies are traditionally ranked, in descending order of generality, according to the *supergroup*, *group*, *formation*, *member* and *bed* levels, and lithodemic units are ranked according to the supersuite, suite, lithodem, etc., levels. Likewise time scales are ranked according to eon, era, period, epoch, etc., levels.

These rank concepts possess a semantic value that is geological and not simply hierarchical, e.g., items at the same tree level may not be identically ranked, as shown in Table 6.1. For instance, a hierarchical arrangement of units might find the highest rank for a related collection of units to be *group*, and for another to be *formation*. When the two unrelated collections reside within a single hierarchy (e.g., in a lithostratigraphic lexicon), then from a purely hierarchical point of view their topmost units exist at the same level of the hierarchy, despite the semantic difference. Related to this is the discontinuity of ranked items, where an item may be ranked several semantic levels higher than some of its immediate descendants: e.g., in circumstances where our understanding of the geology is evolving, a supergroup may contain groups that possess formations, and the supergroup may also contain other formations not yet collected into groups. Here the hierarchical level below supergroup will thus contain both groups and formations. The introduction of *ad hoc* intermediary rankings into a formal ranking scheme may also cause such a behaviour, e.g., a group consisting of formations A, B and C, may partition A and B into a *complex* that is semantically ranked between group and formation.

Table 6.1. Table of conceptual units. Rank varies at first level. This is a diagrammatic portrayal of the table to illustrate the *A* and *Y Groups* (highlighted in colour) as synonyms, sharing descendants. In practice, *Y Formation* would not be duplicated in this table.

Unit Name	Rank
Unit	Top
X Group	Group
X Formation	Formation
X Member	Member
X Bed	Bed
Y Supergroup	Supergroup
A Group	Group
Y Formation	Formation
Y Group	Group
Y Formation	Formation

It is often useful to distinguish between the hierarchical and the semantic levels by assigning numeric values to the rankings, increasing from the most general to the more specific as shown in Figure 6.3. This becomes particularly important in semantically mixed hierarchies (e.g., containing both lithostratigraphic and lithodemic units, and perhaps even biostratigraphic units) where the rankings intrinsically differ irrespective of their hierarchical level. Procedures such as map generalization can then take advantage of the numeric rankings by equating semantically disjoint concepts such as *Suite* and *Group*. In effect, the disparate semantic rankings can be normalized to a neutral scale that can be used to prioritize hierarchical items in generalization procedures.

6.2.2 Recursion

Recursion, which occurs when a procedure or function calls itself, is a well known and powerful concept of mathematics and programming. Recursion is evident in hierarchical geological classifications, as objects in successive levels of the hierarchy repeat the pattern of those above them. In some cases, where the ranking sequence is predetermined (e.g., unit or time), the number of iterations in a recursion is fixed and equal to the number of rankings. In other cases (e.g., rock type) ranking is not formally attributed to the concept, implying that the hierarchy can be extended indefinitely as required. In practice, even ranked hierarchies often need revision and expansion of ranking levels. It is not unheard of to introduce sub-ranks such as sub-beds or sub-members as intermediary ranks into working unit descriptions. Therefore the logical modelling of hierarchies must accommodate rank expansion.

6.2.3 Origin

Unlike classic hierarchies that tend to originate from some root object (e.g., road vehicle in Figure 6.1), geological hierarchies tend to be collections of hierarchies with no specific tangible origin. The origin for the geological case is in fact abstract: *igneous*, *metamorphic* and *sedimentary* can be considered tangible origins for their respective families of rock types, but collectively they can only be grouped from some abstract *rock type* concept, as illustrated in Table 6.8 in this chapter. This holds for lithostratigraphic and lithodemic units, time scales, and particularly for semantically mixed hierarchies where the root cannot possibly be semantically consistent with all the diverse hierarchical items.

6.2.4 Multiple inheritance

From the mapping of geological units it becomes evident that an object in a hierarchy (e.g., a unit) may contain synonyms, e.g., more than one name for a unit. Multiple inheritances thus become essential to implement within a geological hierarchy, as each synonym must be propagated to each of the components of a unit. Reversing this perspective may clarify the issue: a unit, whose parent has multiple names, effectively has multiple parents. Multiple naming may occur because of the parallel concept evolution (e.g., simultaneous mapping of a unit by two or more geologists, probably in disjoint areas), or because of alternate naming schemes. These two semantically different situations can be equated to the synonym case, because in both cases the object has effectively more than one name, as shown in Table 6.1.

Apart from synonyms, geological multiple inheritance may also resemble the traditional case where an object is classified in more than one way: e.g., are obsidian or pitchstone rock types rhyolitic, dacitic, or both? In some cases it may be preferable to classify them in both ways. This situation is distinguished from the synonym case in that the same name (e.g., pitchstone) could exist in two very different places within the classification scheme. Likewise a unit could be part of more than one higher ranked unit.

Another multiple inheritance consideration involves objects with many ranks. For instance, a unit may be initially defined as a bed, but through further field investigation and mapping may evolve to a formation. In such evolutionary scenarios, it may be desirable to include both units, separately, in the database: e.g., *X Formation* and *X Bed* would coexist in the database. However, the manner of this coexistence requires inspection. If *X Formation* and *X Bed* are identical then they can be treated as synonyms, albeit with varying rank. As synonyms they would share composing units, and thus it is important to verify that the rank of the composing units does not exceed the rank of its parents, the synonyms. If they in fact refer to different concepts, perhaps earlier and later interpretations, then they may be treated as individual items. Unique identification then becomes an issue, as unit names are no longer unique, the combination of unit name and rank is in fact unique. It is perhaps often simpler and formally correct (IUGS Subcommission on Stratigraphic Classification, 1961, North American Commission on Stratigraphic Nomenclature, 1983) to also include the ranking within the unit name. Thus *X Formation* and *X Bed* are distinguished by name. During implementation this permits the hierarchical object name to be used as a primary key in the hierarchy. To circumvent these situations, a numeric identifier is assigned to each unique unit and used as a primary key.

6.2.5 Operational requirements

The conceptual issues confronting geological hierarchy development require translation into database operations for creating, updating and querying individual hierarchy objects as well as branches of the hierarchy. This functionality should be achieved with standard relational operations to ensure generality of method. Conceptually this means that it must be possible to express the methods in terms of relational algebra or relational calculus (Date, 1995; Ullman, 1988) to conform with the relational model. From an implementation perspective this requires the operations to be executed with standard SQL statements, as SQL is the leading commercial data definition and manipulation language for relational databases. In order to avoid implementation-specific irregularities, two SQL database environments have been used in this research: Microsoft Access® 2002 for the Windows XP® operating system and Oracle® 8 for the SUN - UNIX operating system.

Hierarchical queries must also satisfy *isa* and *hasa* queries. An *isa* query is a specialization, in that it recursively returns all subtypes and compositions of classification and hierarchies, respectively, once a root object has been specified. For instance, every rock type within a database that *is an* igneous rock might be sought, or every unit composing *X Formation* (e.g., for which *X Formation* is a parent) might be sought. On the other hand, *hasa* queries are generalizations where all parents (supertypes and assemblies) of a specified object are returned: e.g., querying all higher ranked units to *X Bed* would in this case return *X Formation* and maybe even *X Group*. Generalization and specialization queries can be performed on two fronts: with the hierarchy or within a set of geological data that makes reference to a hierarchy. In the former, the structure of the hierarchy is queried, whereas in the latter, a set of geological data is queried for conformance with the hierarchy.

6.3 Logical modelling of geological hierarchies

The geological literature documents three methods of organizing hierarchies within relational databases. They have been labelled by Brodaric *et al.* (2000) as *encoded*, *algorithmic*, and *set-theoretic*.

6.3.1 Encoded modelling

In the encoded method each object in the hierarchy contains within itself a record of its parent. For instance monzogranite might be described as *igneous-plutonic-granite-*

monzogranite, or *X Bed* might be *X Group:X Formation:X Bed*. In essence, the path of traversal from the top of the hierarchy to each object is recorded with the object. This method is typically implemented in three modes:

- Within one column of data (see Tables 6.2 and 6.3);
- In separate data columns (see Tables 6.4 and 6.5);
- As one column in a catalogue of terms related to a data table (see Tables 6.6 and 6.7).

Table 6.2. Single column hierarchy encoding of *lithostratigraphic units.*

Location	Unit	Rank	Description	Age
…	*X* Group:*X* Formation: *X* Member:*X* Bed	Bed	…	…
…	*Y* SuperGroup:*Y* Group:*Y* Formation	Formation	…	…

Table 6.3. Single column encoding of *rock types*.

Rock Name	Minerals	Textures
igneous-plutonic -granite-monzogranite	…	…
igneous-volcanic-dacitic-dacite	…	…

Table 6.4. Multiple column hierarchy encoding of *lithostratigraphic units* (Colman-Sadd *et. al.*, 1996).

Location	Supergroup	Group	Formation	Member	Bed	Rank	Description	Age
…		*X* Group	*X* Formation	*X* Member	*X* Bed	Bed	…	…
…	*Y* Supergroup	*Y* Group	*Y* Formation			Formation	…	…

Table 6.5. Multiple column encoding of *rock types*.

Rock Level 1	Rock Level 2	Rock Level 3	Rock Level 4	Minerals	Textures
igneous	plutonic	granite	monzogranite	…	…
igneous	volcanic	dacite		…	…

Table 6.6. Lookup table encoding of *lithostratigraphic units.*

Location	Unit Name
…	*X* Bed
…	*Y* Formation

Unit Name	Code	Rank	Description	Age
X Bed	*X* Group:*X* Formation: *X* Member:*X* Bed	Bed	…	…
Y Formation	*Y* SuperGroup:*Y* Group:*Y* Formation	Formation	…	…

Table 6.7. Lookup table encoding of *rock types.*

Rock Name	Minerals	Textures
monzogranite	…	…
dacite	…	…

Rock Name	Code
monzogranite	igneous-plutonic-granite-monzogranite
dacite	igneous-volcanic-dacitic-dacite

6.3.2 Algorithmic method

The algorithmic method differs from the encoded one in that it requires recursive processing to determine hierarchical structures. Thus the total hierarchy is not embedded in the dataset or lookup table. It is instead inferred from the knowledge of the hierarchical parent of each item. As such the method is procedural and non-deterministic and is not very amenable to processing with standard relational techniques.

The algorithmic technique utilizes a data structure with lookup tables, with the exception that the encoded hierarchy is replaced by a reference to the immediate parent of the item. Thus only the immediate parent of an item is included, instead of the complete hierarchical path. In order to reduce space, each item and its parent are usually identified by a number or short text code (Boisvert and Lauzier, 1996). The hierarchy thus minimally contains a column for the item name, its identifying number and its parent number. In Tables 6.8 and 6.9 the parent name is also included for reasons of clarity in the illustration but is actually redundant and unnecessary.

Table 6.8. Algorithmic organization of *rock types*. The *Parent Name* column is redundant.

Rock ID	Rock Name	Parent ID	Parent Name
1	igneous	0	NULL
2	plutonic	1	igneous
3	granitic	2	plutonic
4	granite	3	granitic
5	monzogranite	4	granite
6	granodiorite	3	granitic
7	tonalite	3	granitic
8	syenitic	2	plutonic
9	syenite	8	syenitic
10	volcanic	1	igneous
11	rhyolitic	10	volcanic
12	rhyolite	11	rhyolitic
13	dacitic	10	volcanic
14	dacite	13	dacitic
15	metamorphic	0	NULL
16	sedimentary	0	NULL

Table 6.9. Algorithmic organization of *lithostratigraphic units*. The *Parent Name* column is redundant.

Unit ID	Unit Name	Rank	Parent ID	Parent Name
1	*X* Group	Group	0	NULL
2	*X* Formation	Formation	1	*X* Group
3	*X* Bed	Bed	2	*X* Formation
4	*X* Member	Member	3	*X* Bed
5	*Y* Supergroup	Supergroup	0	NULL
6	*Y* Group	Group	5	*Y* Supergroup
7	*Y* Formation	Formation	6	*Y* Group

This approach would seem more suited to answering *isa* questions than *hasa* questions, as the expanding recursive nature of the *hasa* query is substantially more complex. Because recursion is not supported by SQL, recursive solutions must be implemented within proprietary database programming environments, are thus not general or transportable.

Some databases have incorporated extensions to the SQL language to facilitate *isa* and *hasa* queries based on the above approach and data structure (Date, 1995; Koch *et al.*,1995; Oracle Corporation, 1992). For instance, the Oracle® system uses the *CONNECT BY* clause to identify the parent column in hierarchical queries

6.3.3 Set-theoretic method

The *set-theoretic* approach has been selected for the implementation of the hierarchical geological database scheme. The database structure illustrated in Figure 6.4 is proposed.

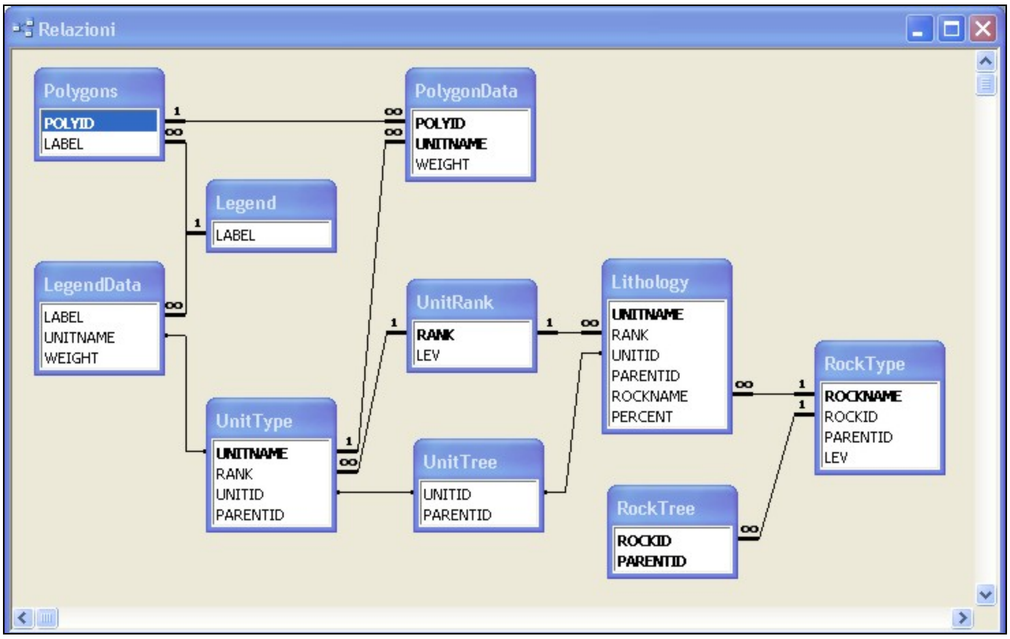


Figure 6.4. The hierarchical geological database scheme.

Conventional solutions to the classic *parts explosion* problem are situated in a middle ground between the encoded and algorithmic methods. Instead of including the entire hierarchy with each hierarchical item, as in the encoded case, or minimally including the parent of an item, as does the algorithmic method, the traditional approach has tended to associate each hierarchic item with its immediate descendants (Date, 1995). This is a top-down philosophy, going from item to descendant, and is in contrast with the item-parent direction of the algorithmic method and the encompassing approach of the encoded method. Because each item may contain several descendants (e.g., a one-to-many relationship) it is impossible to store the list of descendants alongside each item, at least not in a normalized fashion. Therefore an extra table must be created which associates an item to its immediate descendants. Semantically this is quite elegant as it separates the concept from its hierarchical arrangement, its tree structure. Thus it is possible to vary the concept classification simply by modifying the tree table. In essence this permits multiple user profiles (e.g., classification systems) to be employed against a catalogue of terms. In order to reduce the amount of storage space utilized, each term is usually assigned a unique numeric identifier, and it is this identifier that is arranged within the hierarchical tree table instead of the actual terms. Table 6.10 illustrates this design. Note that this structure can be accessed only by the Oracle® software CONNECT BY clause. A standard RDBMS uses two separated tables to identify the parent column in hierarchical queries, as shown in Table 6.11.

Table 6.10. *Rock Type* and *Tree* catalogues. Note that the term *obsidian* (18) occurs twice. It is an example of an instance that possesses multiple parents, e.g., *rhyolitic* (11) and *dacitic* (13).

Rock ID	Rock Name	Parent ID
1	igneous	0
2	plutonic	1
3	granitic	2
4	granite	3
5	monzogranite	4
6	granodiorite	3
7	tonalite	3
8	syenitic	2
9	syenite	8
10	volcanic	1
11	rhyolitic	10
12	rhyolite	11
18	obsidian	11
13	dacitic	10
14	dacite	13
18	obsidian	13
15	metamorphic	0
16	sedimentary	0

Table 6.11. Table shown in figure 6.14 adapted for a standard RDBMS. Two different tables are present.

Rock ID	Rock Name		Rock ID	Parent ID
1	igneous		1	0
2	plutonic		2	1
3	granitic		3	2
4	granite		4	3
5	monzogranite		5	4
6	granodiorite		6	3
7	tonalite		7	3
8	syenitic		8	2
9	syenite		9	8
10	volcanic		10	1
11	rhyolitic		11	10
12	rhyolite		12	11
18	obsidian		18	11
13	dacitic		13	10
14	dacite		14	13
18	obsidian		18	13
15	metamorphic		15	0
16	sedimentary		16	0

An algorithmic solution is still required to implement this approach, as only one level of descendants is known for any item. However, by modifying the technique slightly and taking some liberties with space requirements, a non-recursive solution applicable to geological hierarchies is possible. Consider maintaining a complete list of descendants for each item, instead of a partial list of immediate descendants as illustrated in Tables 6.12 and 6.13, this permits all parents and all descendants to be determined for any item. There is one serious drawback to this approach: if the entire hierarchy originates from a common origin (e.g., the parts of a car) then the method would require a complete list of the descendants of the origin to be archived, in addition to a list of descendants for each item. This replication of items for the origin is untenable and unnecessary: most geological hierarchies are not an assembly of parts originating from a single root item, such as a car, they are a collection of many assemblies with no particular common origin, e.g., a unit table may contain many unrelated unit hierarchies. Thus for geological hierarchies it is feasible to utilize an abstract item as their root. For instance, the root of a unit hierarchy would be an abstract *unit*, for the rock type hierarchy it would be *rock type* and *time scale* for the time scale hierarchy. Because the root is abstract, only its immediate descendants are stored in the hierarchy, however, without straying outside the relational model, a listing of all the descendants of the root (e.g., the complete hierarchy) is impossible to generate. This is largely immaterial as the root is an artificial, abstract object. Because the root is only associated with its immediate descendants, and not with their descendants, those items that exist two or more levels below the root do not recognize the root as a parent (to no adverse effect), thus further reducing potential wasted space.

The example in Tables 6.10 and 6.11 is reformulated in Tables 6.12 and 6.13 according to this new design, which can be applied to any standard RDBMS. The structure may be perceived with equal validity in two ways, as a collection of all descendants for each parent, or a collection of all parents for each descendant.

Table 6.12. *Rock type* catalogue.

Rock ID	Rock Name
0	rock type
1	igneous
2	plutonic
3	granitic
4	granite
5	monzogranite
6	granodiorite
7	tonalite
8	syenitic
9	syenite
10	volcanic
11	rhyolitic
12	rhyolite
18	obsidian
13	dacitic
14	dacite
18	obsidian
15	metamorphic
16	sedimentary

Table 6.13. Modified *Rock type* tree.

Rock ID	Parent ID
1	0
15	0
16	0
2	1
3	1
4	1
5	1
6	1
7	1
8	1
9	1
10	1
11	1
12	1
18	1
13	1
14	1
3	2
4	2
5	2
6	2
7	2
8	2
9	2
4	3
5	3
6	3
7	3
5	4
9	8
11	10
12	10
18	10
13	10
14	10
12	11
18	11
14	13
18	13

An examination of typical geological hierarchies indicates that they seldom have many levels. Perhaps the most relevant hierarchy to examine is the geological unit hierarchy that might contain thousands of items. The depth of the unit hierarchy is formally defined as its rank and is relatively shallow, typically containing about five categories (supergroup, group, formation, member, bed, or supersuite, suite, etc.). It is important to note that hierarchical depth and rank are not equivalent. For instance, a group that is not part of any supergroup (e.g., does not possess parents) exists effectively at the first level of the hierarchy, at the same level as some supergroup, though its rank is nominally lower, as shown in Tables 6.14 and 6.15. Most units will not contain components in each of the rankings, thus further reducing the overall average depth of the tree. Therefore it is conceivable to apply this approach to unit hierarchies, without incurring undue redundancy and wastage. Classification hierarchies such as rock types or time scales may require deeper trees, but generally they contain significantly fewer items, and should be adequately served by the approach.

Table 6.14. Conceptual *Unit* table. Rank varies at first level. This is a diagrammatic portrayal of the table to illustrate *A* and *Y Groups* as synonyms (highlighted in colour), sharing descendants. In practice, *Y Formation* would not be duplicated in this table.

Unit ID	Unit Name	Rank
0	Unit	TOP
1	*X* Group	Group
2	*X* Formation	Formation
3	*X* Member	Bed
4	*X* Bed	Member
5	*Y* Supergroup	Supergroup
8	A Group	Group
7	*Y* Formation	Formation
6	*Y* Group	Group
7	*Y* Formation	Formation

Table 6.15. *Unit tree* table.

Unit ID	Parent ID
1	0
2	1
3	1
3	2
4	1
4	2
4	3
5	0
6	5
7	5
7	6
7	8
8	5

6.3.3.1 Advantages

The advantages to this last approach are its simplicity, its expandability, and its conformity with the relational data model (Codd, 1970; 1980). It is conceptually simple in that the hierarchy associates an item with all its parents, it is structurally simple to implement using an auxiliary tree table containing rows of item and parent column pairs. Its SQL implementation is more involved, but once defined it may be globally applied. Of the three methods discussed this method is uniquely portable, in that all operations are achieved with standard, set-theoretic relational tools such as SQL. Furthermore, there are no restrictions on hierarchical depth that can be expanded or contracted as required simply by adding or removing parents/descendants from the hierarchy. Multiple inheritance is easily supported because there is no restriction on the items possessing parents from any particular hierarchical level.

6.3.3.2 Disadvantages

An apparent disadvantage of the set-theoretic approach (as well as of the algorithmic method) is its lack of item ordering: each parent and descendant of an item is known, but not its hierarchical depth, which prevents the hierarchy from being re-constructed in an appropriate sequence, e.g., for visual display or listing. In essence this conforms to set theory where set elements are inherently unordered. This lack of ordering can be somewhat overcome by introducing a rank table that enumerates the ranks in ascending order (e.g., *top* = 0, *supergroup* = 100, *group* = 200, *formation* = 300, …), as shown in Tables 6.16 and 6.17.

Table 6.16. Rank order sequencing of Table 6.14.

Unit ID	Unit Name	Rank
0	Unit	Top
5	*Y* Supergroup	Supergroup
1	*X* Group	Group
6	*Y* Group	Group
8	*A* Group	Group
2	*X* Formation	Formation
7	*Y* Formation	Formation
3	*X* Bed	Bed
4	*X* Member	Member

Table 6.17. *Rank* table.

Rank	Level
Top	0
Supergroup	100
Group	200
Formation	300
Member	400
Bed	500
Sub-Bed	600

The hierarchy could then be generated based on rank order by joining this rank table to the hierarchy and concept tables. This, however, satisfies only grouping within ranks and does not generate proper sequencing. It would seem that encoded methods must be adopted to obtain proper sequencing. However, assigning a numeric value to each rank should prove beneficial for analytic purposes such as the hierarchical generalization and the reclassification of data.

Oracle® RDBMS, however, overcomes this disadvantage through the CONNECT BY and START WITH clauses. In Oracle® it is in fact possible to generate automatically the hierarchical tree as illustrated in Figures 6.5, 6.6 and 6.7.

```
ROCKID ROCKNAME                                                   PARENTID
------ ---------------------------------------------------- --------
     1 igneous                                                           0
     4       plutonic                                                    1
     6             granitic                                              4
    25                   alkali feldspar granite                         6
    33                         alaskite                                 25
    26                   granite                                         6
    34                         syenogranite                             26
    35                         monzogranite                             26
   146                         alkaline granite                         26
   147                         peralkaline granite                      26
   148                         subalkaline granite                      26
    27                   granodiorite                                    6
    28                   tonalite                                        6
    36                         plagiogranite                            28
     7             syenitic                                              4
    29                   alkali feldspar syenite                         7
    30                   syenite                                         7
    38                         albitite                                 30
    31                   quartz syenite                                  7
    32                   syanogabbro                                     7
    39                         quartz monzonite                         32
    40                         monzonite                                32
    41                         quartz monzodiorite                      32
    42                         monzodiorite                             32
    43                         quartz monzogabbro                       32
    44                         monzogabbro                              32
     8             gabbroic                                              4
    45                   quartz anorthosite                              8
    46                   anorthosite                                     8
    47                   quartz gabbro                                   8
    48                   gabbro                                          8
    49                         norite                                   48
    50                         troctolite                               48
    51                         hornblende gabbro                        48
    52                   quartz diorite                                  8
    53                   diorite                                         8
   162             unsaturated rocks                                     4
   163                   ijolite                                       162
   164                   foyaite                                       162
   165                   carbonatite                                   162
```

Figure 6.5. Part of the Rock tree generated by Oracle® using the CONNECT BY clause.

```
RANK        UNITID UNITNAME                                     PARENTID
----------  ------ -------------------------------------------- --------
supergroup       1 victoria lake group and mid-ordovician shale        0
supergroup       2 hall hill - mansfield cove complex                  0
group           14       mansfield cove complex                        2
group           18       hall hill complex                             2
formation       44       rowsell hill basalt                           2
supergroup       3 betts cove complex                                  0
group            4 wild bight group                                    0
formation       32       sparrow cove formation                        4
formation       37       side harbour formation                        4
formation       41       seal bay brook formation                      4
formation       47       penny's brook formation                       4
formation       49       omega point formation                         4
group            5 western arm group                                   0
formation       25       western head agglomerate                      5
formation       26       welsh cove tuff                               5
formation       36       skeleton pond tuff                            5
formation       71       big hill basalt                               5
group            6 victoria lake group                                 0
formation       29       tally pond volcanic rocks                     6
group            7 twin lakes complex                                  0
group            8 topsails intrusive suite                            0
group            9 springdale group                                    0
group           10 south lake igneous complex                          0
group           11 sops head complex                                   0
formation       39       shale wedge zone                             11
formation       59       fault sliver zone                            11
group           12 roberts arm group                                   0
formation       28       tholeiitic volcanic rocks                    12
formation       33       south brook basalt                           12
formation       56       gullbridge felsic volcanic rocks             12
formation       57       gull hill sedimentary rocks                  12
formation       63       crescent lake formation                      12
formation       64       calc-alkaline volcanic rocks                 12
formation       65       burnt island basalt                          12
formation       72       baker brook basalt                           12
group           13 micmac lake group                                   0
group           16 loon pond - woodfords arm plutons                   0
formation       24       woodfords arm pluton                         16
formation       51       loon pond pluton                             16
group           17 hungry mountain complex                             0
group           19 frozen ocean group                                  0
group           21 catchers pond group                                 0
```

Figure 6.6. Part of the Lithostratigraphic tree generated by Oracle® using the CONNECT BY clause.

LithostratigraphicTree.SQL - Blocco note

File Modifica Formato Visualizza ?

```
COLUMN unitname FORMAT a44
SELECT rank,unitid,lpad(' ',6*(level-1))||unitname unitname, parentid
FROM unittype
START WITH parentid=0
CONNECT BY parentid=PRIOR unitid;
```

Figure 6.7. The Oracle® SQL query with the CONNECT BY clause used to generate the Lithostratigraphic tree of Figure 6.6.

6.3.4 *Pros and cons summary*

The separation of the hierarchy into two tables, conceptual and hierarchical (*tree*), as proposed in the set-theoretic approach, will no doubt cause performance degradation, particularly in those areas where the other methods applied standard relational operators. However, our set-theoretic method should outperform them in those areas where the previous methods required algorithmic solutions (e.g., inserting in the encoded approach and querying in the algorithmic). All in all, the generality of the approach outweighs any performance setbacks. Following is an example of the most common operations performed to managing a hierarchical geological database.

6.3.4.1 *Insertion*

An empty hierarchy minimally contains the root abstract object, thereby providing an item under which any insertion can be placed. Insertions thus first require the identification of a parent item. Then, the following steps are required:

1. The item and its rank are inserted into the conceptual table;
2. The item and parent pair are inserted into the tree table;
3. All the parent's parents are found and added as parents to the item in the tree table;
4. The item is added as a parent to all the parent's descendants in the tree table.

This insertion method places the new item directly below the parent item and above its descendants, thus incrementing the depth level of the tree, as shown in Tables 6.18 and 6.19. When the new item is simply added to some existing level without inheriting any descendants, that is, at the same level as the selected item, then only steps 1 and 3 above are applied, as the inserted item simply inherits the parents of the selected item as shown in Table 6.20. Connecting an existing item in the hierarchy to an additional parent (for multiple parents), implies eliminating step 1 from the process.

Figure 6.8 illustrates a queries used to insert a new item directly below the parent item.

Table 6.18. Original table.

Rock Name
ROCK TYPE
igneous
plutonic
granite
monzogranite
granodiorite
tonalite

Table 6.19. Insertion of granitic under plutonic.

Rock Name
rock type
igneous
plutonic
granitic
granite
monzogranite
granodiorite
tonalite

Table 6.20. Insertion of volcanic beside plutonic.

Rock Name
rock type
igneous
plutonic
granite
monzogranite
granodiorite
tonalite
volcanic

```
InsertChild.txt - Blocco note
File  Modifica  Formato  Visualizza  ?
INSERT INTO rocktree ( rockid, parentid )
SELECT DISTINCT rocktree.rockid AS rockid, rocktype.rockid AS parentid
FROM rocktype, rocktree
WHERE rocktree.rockid=ANY
            (SELECT rocktree.rockid
             FROM rocktype, rocktree, rocktype rd1
             WHERE rocktype.rockname=[Rockname of the ABOVE rock:]
                   AND rocktype.rockid=rocktree.parentid
                   AND rocktree.rockid=rd1.rockid
                   AND rd1.rockid<>
                       (SELECT rocktype.rockid
                        FROM rocktype
                        WHERE rocktype.rockname=[Rockname of the rock to INSERT:]))
       AND rocktype.rockid=
              (SELECT rocktype.rockid
               FROM rocktype
               WHERE rocktype.rockname=[Rockname of the rock to INSERT:]);
```

Figure 6.8. The InsertChild query for inserting a descendant of a parent rock.

6.3.4.2 Deletion

Deletion is simple when cascading foreign key relationships are established between the concept and the tree tables: the parent and descendant identifiers of the tree table reference the item identifier (*primary key*) in the conceptual table. Thus deleting an item in the conceptual table will remove all references to that item in the hierarchy, and the item will no longer exist as a parent for other items, nor itself possess parents. When these relationships are impossible to establish, then all references to the deleted item, as either parent or descendant, must be first removed from the tree table before the item can be deleted from the concept table. Figure 6.9 displays an example of query for the deletion of a whole rock tree hierarchy.

```
DELETE *
FROM rocktree
WHERE rocktree.rockid=ANY
               (SELECT DISTINCTROW rh2.rockid
                FROM rocktype AS rd1, rocktype AS rd2, rocktree AS rh1, rocktree AS rh2
                WHERE rd1.rockname=[Rockname of the rock to MOVE:]
                             AND rd1.rockid=rh1.parentid
                             AND rh1.rockid=rh2.rockid
                             AND rh2.parentid=ANY
                                     (SELECT (rh3.parentid)
                                      FROM rocktype AS rd2, rocktree AS rh3
                                      WHERE rd2.rockname=[Rockname of the rock to MOVE:]
                                                   AND rd2.rockid=rh3.rockid))
       AND rocktree.parentid=ANY
                (SELECT DISTINCTROW rh2.parentid
                 FROM rocktype AS rd1, rocktype AS rd2, rocktree AS rh1, rocktree AS rh2
                 WHERE rd1.rockname=[Rockname of the rock to MOVE:]
                              AND rd1.rockid=rh1.parentid
                              AND rh1.rockid=rh2.rockid
                              AND rh2.parentid=ANY
                                      (SELECT (rh3.parentid)
                                       FROM rocktype AS rd2, rocktree AS rh3
                                       WHERE rd2.rockname=[Rockname of the rock to MOVE:]
                                                    AND rd2.rockid=rh3.rockid));
```

Figure 6.9. An example of SQL query for deleting a whole rock tree.

6.3.4.3 Modification

Modifying an item is performed directly and involves one UPDATE SQL statement.

6.3.4.4 Moving items

Moving one item in the hierarchy to a new position is relatively easy as it involves deleting the item from the tree and inserting it, as a descendant or sibling, into a new location within the hierarchy. This algorithm is problematic only when an item contains multiple parents as they cannot be differentiated, and the item is moved from all parents to its new location. Figure 6.10 illustrates an example of SQL query.

```
DELETE rocktree.*
FROM rocktree
WHERE rocktree.rockid=
                    (SELECT rocktype.rockid
                     FROM rocktype
                     WHERE rocktype.rockname=[Rockname of the rock to MOVE or DELETE:])
             OR rocktree.parentid=
                    (SELECT rocktype.rockid
                     FROM rocktype
                     WHERE rocktype.rockname=[Rockname of the rock to MOVE or DELETE:]);
```

Figure 6.10. The SQL queries used to assign a new position in the hierarchy to an item requires the deletion of the item and its insertion into a new location.

6.3.4.5 *Finding (isa and hasa queries)*

Finding an item can lead to two different cases: finding a descendant of an item (*isa* query or *generalization* query) or finding a parent of an item (*hasa* query or *specialization* query). Figures 6.11, 6.12, 6.13 and 6.14 show an example of Microsoft Access® and Oracle® SQL queries to select the parents and descendants of an item in the rock hierarchy.

```
FindParent.txt - Blocco note
File  Modifica  Formato  Visualizza  ?
SELECT rocktype.rockid, rocktype.rockname AS child, rd2.rockname AS parent, rd2.rockid
FROM rocktype, rocktree, rocktype AS rd2
WHERE rocktype.rockname=[Rockname of rock:]
              AND rocktype.rockid=rocktree.rockid
              AND rocktree.parentid=rd2.rockid
ORDER BY rd2.rockid;
```

Figure 6.11. The Microsoft Access® SQL query to select the parents of an item in the rock hierarchy (*hasa* query).

```
FINDPARENTS.SQL - Blocco note
File  Modifica  Formato  Visualizza  ?
CLEAR BUFFER
CLEAR SCREEN
UNDEFINE rock
PROMPT Enter the ROCKNAME of the rock
ACCEPT rock CHAR PROMPT 'Rock:'
SELECT rocktype.rockid, LPAD(' ',3*(LEVEL-1))||rocktype.rockname rockname, rocktype.parentid
FROM rocktype
START WITH rockid=(SELECT rocktype.rockid
                  FROM rocktype
                  WHERE rocktype.rockname='&rock')
CONNECT BY rockid=PRIOR parentid
          AND rocktype.rockid !=0;
```

Figure 6.12. The Oracle® SQL query to select the parents of an item in the rock hierarchy (*hasa* query).

```
FindChild.txt - Blocco note
File  Modifica  Formato  Visualizza  ?
SELECT rocktype.rockid, rocktype.rockname AS parent, rd2.rockname AS child, rd2.rockid
FROM rocktype, rocktree, rocktype AS rd2
WHERE rocktype.rockname=[Rockname of rock:]
              AND rocktype.rockid=rocktree.parentid
              AND rocktree.rockid=rd2.rockid
ORDER BY rd2.rockname;
```

Figure 6.13. The Microsoft Access® SQL query to select the descendants of an item in the rock hierarchy (*isa* query).

```
FINDCHILDREN.SQL - Blocco note
File  Modifica  Formato  Visualizza  ?
CLEAR BUFFER
CLEAR SCREEN
UNDEFINE rock
PROMPT Enter the ROCKNAME of the rock
ACCEPT rock CHAR PROMPT 'Rock:'
SELECT rocktype.rockid,LPAD(' ',3*(LEVEL-1))||rocktype.rockname rockname,rocktype.parentid
FROM rocktype
START WITH rockid=(SELECT rocktype.rockid
                  FROM rocktype
                  WHERE rocktype.rockname='&rock')
CONNECT BY parentid=PRIOR rockid;
```

Figure 6.14. The Oracle® SQL query to select the descendants of an item in the rock hierarchy (*isa* query).

6.3.4.6 Deleting, Moving and Inserting rocks in the hierarchy

As already mentioned, to update and manage the database often it is necessary to execute more than one query in a row. The queries are grouped by type of operation in Figure 6.15. The system has been structured so as to call automatically the queries without the intervention of the user. Note that often the same query is used in different operations.

<u>INSERTING</u>

INSERT-SIBLING (If only Siblings are present)

- INSERTROCK
- INSERTTOPPARENT
- INSERTPARENT

INSERT-CHILD (Only if Children are present)

- INSERTROCK
- INSERTTOPPARENT
- INSERTPARENT
- INSERTCHILD

<u>DELETING</u>

- DELETEROCKTREE (**MUST** be executed **BEFORE** DeleteRockType!)
- DELETEROCKTYPE (**MUST** be executed **AFTER** DeleteRockTree!)

<u>FINDING</u>

- FINDCHILD
- FINDPARENT

<u>MOVING ONE ROCK</u>

MOVE-SIBLING

- DELETEROCKTREE
- INSERTTOPPARENT
- INSERTPARENT

MOVE-CHILD

- DELETEROCKTREE
- INSERTTOPPARENT
- INSERTPARENT
- INSERTCHILD

<u>**MOVING A TREE**</u>

MOVE-TREE

- DELETETREE
- DELETEOLDPARENT
- INSERTTOPPARENT
- INSERTPARENT
- INSERTCHILDPARENT

Figure 6.15. List of all the queries used in the managing system of the database.

6.3.4.7 Query

Isa and *hasa* queries are easily generated with this approach, as the descendants and parents of an item are well known: the item is found in the concept table and its parents or descendants are then immediately located in the tree table. The only complexity occurs when the tree table consists of numeric identifiers rather than names. In this event, the parent or descendant identifiers are first retrieved from the tree and then their names are retrieved from the concept table. *Isa* or *hasa* queries follow this pattern: *Return each item that isa X* (all descendants of *X*), or *Return each item that hasa X* (all parents of *X*). These are formulated as follows:

- Join concept table to the tree table to find parents or descendants for each concept:
  - Join the concept identifier with tree descendants to find all parents for *isa*;

  or,
  - Join the concept identifier with tree parents to find all descendants for hasa;
- Join the parents or descendants back to the concept table to return their names;
- Locate the *X* item in the resultant parent (*isa*) or descendant (*hasa*) names.

6.3.4.8 Efficiency

Query and deletion performance is superior to the algorithmic method, and to most of the encoded methods: parents or descendants are located with one join operation and deletion only requires the item to be located. Insertions and moves are clearly more complex as several levels of parents and descendants must be managed, instead of the single level of the algorithmic method. The set-theoretic method is clearly less efficient in its space requirements, but it uniquely permits multiple inheritance and is fully SQL compliant. It is the only method that displays adequate functionality in all remaining areas except item sequencing. This comparison is summarized in Tables 6.21 and 6.22. Overall the set-theoretic method seems best equipped to manage geological hierarchies.

Table 6.21. Comparative chart to rank the methods in terms of efficiency (1 = highest, 4 = lowest) and sequencing.

	Isa/Hasa Query	Multiple Inheritance	Insertion	Deletion	Modification	Moving	Storage Requirements	Ordered
Encoded 1, 2	3	-	4	4	4	4	4	2
Encoded 3	1	-	3	1	1	3	2	1
Algorithmic	4	-	1	2	1	1	1	-
Set-theoretic	2	1	2	1	1	2	3	-

Table 6.22. This is a comparative chart to rank the methods in terms of SQL-compliance.

	Isa/Hasa Query	Insertion	Deletion	Modification	Moving
Encoded 1	√				
Encoded 2	√	√	√	√	√
Encoded 3	√		√	√	
Algorithmic		√	√	√	√
Set-theoretic	√	√	√	√	√

6.4 Remarks

We have seen in the previous chapters that many geological data types are commonly organised into hierarchical arrangements. This is particularly common to geological mapping data and can be attributed in part to the fact that geological field observations are made at mesoscopic level, and then grouped and synthesized into macroscopic units. We have also seen that the practice of grouping geological entities into hierarchies is endemic to the geological thought process: stratigraphic units, rock types, and time scales are common geological data types that are frequently organised into a hierarchical scheme.

Many geological questions involve the re-ranking of observed data into successively more general or detailed categories within a hierarchy. For instance, in the course of a compilation exercise a particular stratigraphic unit can evolve from being a member to part of a formation or group, because of scale restrictions. It is therefore important that computer-based techniques are capable of effectively manipulating hierarchies to aid the mapping process.

The proposed generalization system is a valuable tool in the generalization operation from a large geological scale, at which the geology has been sketched and recorded in the field (in Italy usually 1:25,000), to the smaller scale chosen for the printed product (usually 1:50,000). The system helps the geologist in the decisional hierarchical process of directly extracting the information to be displayed in the printed map from the database, e.g., the geological database is generalized according to the rules that have been set during the encoding of the geological information. Geological information can therefore be archived at a higher level of resolution and can be at any moment extracted at the chosen scale of representation through a rule-based expert system based on standard SQL queries. This leads also to a reduction of the volume of the archived data and avoid the presence of redundant information.

The system manages multiple representations and creates different versions of the archived information. However, it has to be noticed that reality is abstracted and represented on maps by the geologist-cartographer in a subjective way. The same reality may be abstracted diversely in different maps from different geologist-cartographers, besides original data are part of the same geological database.

6.5 *The Newfoundland case study*

The proposed generalization system has successfully been tested on original data provided by the Geological Survey of Canada (GSC). Six geological sheets represent the Region of Newfoundland, Canada, as shown in Figure 6.16. Figure 6.17 shows the full lithostratigraphic legend.

Figure 6.16. The geological map of Newfoundland. Six geological sheets have been mosaicked. Faults are shown as red lines (Courtesy of the Geological Survey of Canada).

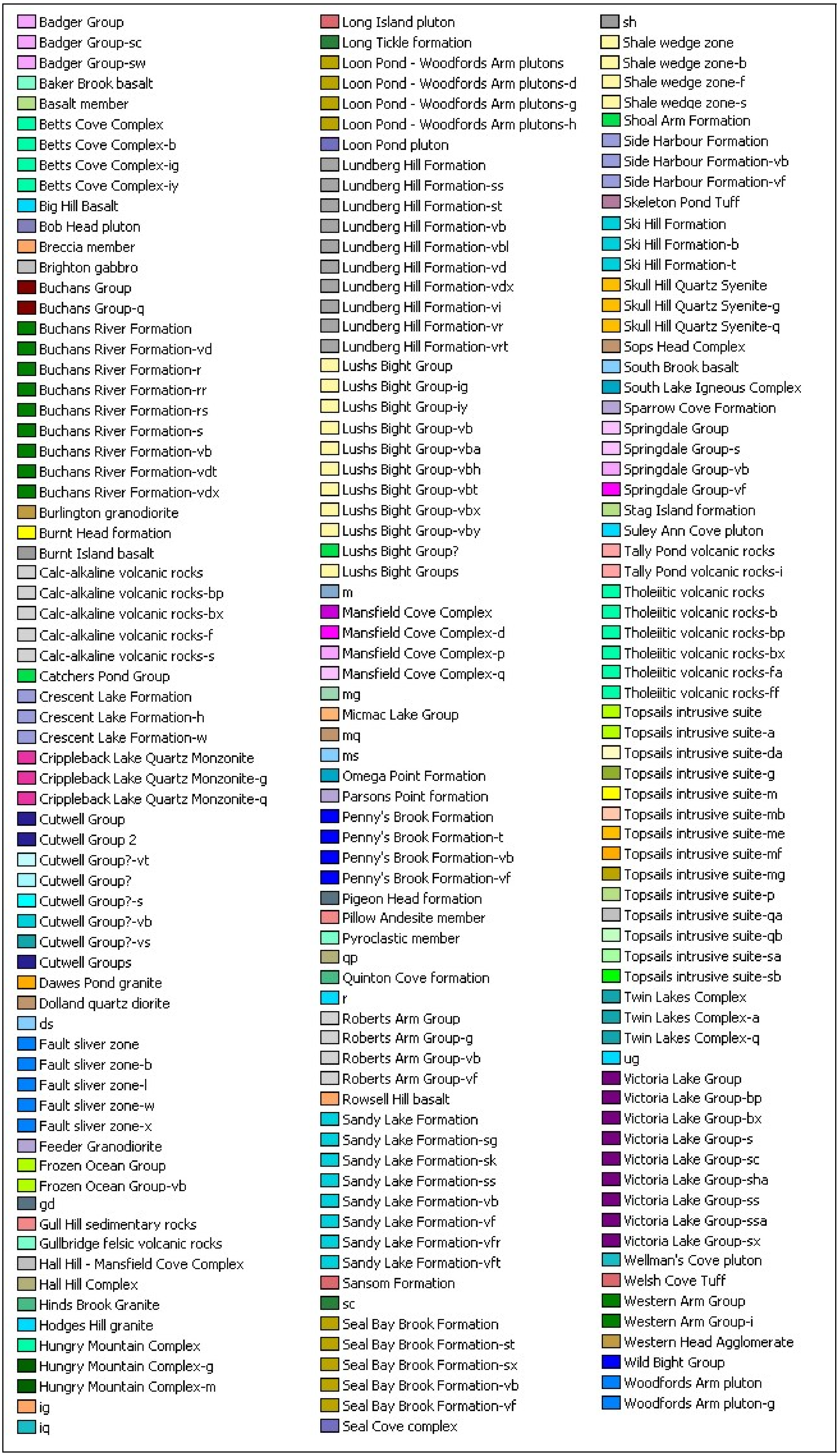


Figure 6.17. The lithostratigraphic legend of the Newfoundland map.

6.5.1 *Geological outline*

Newfoundland represents the north easternmost extension of the Appalachian mountain system in North America. It formed from parts of three areas of the world brought together about 400 million years ago by continental drift. Central Newfoundland is the remains of an ocean floor that lay between North America and Africa about 500 million years ago. The island's west coast is part of the ancient margin of North America. The east coast was once part of south western Europe or North Africa. When the continental plates again separated (which led to the formation of the Atlantic Ocean basin) the split occurred east of where they had collided and this left a piece of the eastern plate attached to North America.

The last 200 million years of Earth history in Newfoundland have been dominated by erosion that led to the development of extensive plains, the remnants of which are the upland surfaces of the province.

For the last 2 million years, during the Ice Age, great ice sheets advanced and retreated across Newfoundland many times. At the last glacial maximum, 18,000 years ago, the Laurentide Ice Sheet covered most of Canada including Newfoundland. The tip of the Northern Peninsula was the only part of Newfoundland overrun by the Laurentide Ice Sheet; the rest of the island was covered by its own independent ice cap that originated on uplands and spread out towards the coast. Glaciers had an enormous effect on the landscape, smoothing and polishing wide areas, eroding lake basins, and carving deep valleys through mountains. Along the coast, these valleys were later flooded by the sea, creating deep fjords.

As the climate warmed, the ice retreated inland, leaving behind a more subdued landscape, in places covered by till or gravel washed out of the melting glaciers. The sea level around the coast of Newfoundland changed considerably as a result of the last glaciation. Ice sheets of great weight pushed land areas downward, and squeezed them outwards beyond the ice margin. Evidence of this process can be seen in most areas of the province. Beaches, deltas, and the remains of marine fauna can be found tens to hundreds of metres above the present level.

The bedrock that underlies Newfoundland is not dominated by either one of the three fundamental rock types (igneous, metamorphic and sedimentary). Rather the underlying geology draws its character from among them.

The oldest rocks in Newfoundland are those that make up parts of the highest mountains in the area. These are ophiolitic rocks, pieces of the ancient ocean floor, which were pushed up during mountain building processes, and which are roughly 500 million years old (Upper Cambrian). These pieces of ancient ocean floor rock were embedded within the mountains, which for the most part are made of granite and roughly 380 million years old (Late Devonian).

The rocks in the immediate vicinity of the ocean are mainly metamorphic rocks such as gneiss, schist and amphibolite. Granite is also common in some areas. Minerals such as garnet, staurolite and kyanite are common in these rocks.

The rocks that underlie the main plains are the youngest in the area. They are Carboniferous in age, or roughly 325 million years old. For the most part, these rocks are sandstones, siltstones and shales. Small seams of coal can be found in some areas and there is even a small area where the concentration of uranium is high. Limestone is also quite common in some areas.

There are 2 major geological faults in Newfoundland. The Cape Ray Fault is about 1 km wide and extends for about 100kms. The largest and most important fault in the area is the Long Range Fault (Cabot Fault). This fault also runs through Nova Scotia and New Brunswick. The Long Range Fault once marked the boundary between North America and Europe before the two continents separated about 200 million years ago. Neither one of these faults is active.

Many of the oldest rocks in south western Newfoundland have elevated gold levels. Hence, they are good source rocks for gold deposits and gold is found in above average crustal abundances in many parts of the region. Galena deposits, large and small, are particularly rich in gold.

6.5.2 The generalization system

We have seen in Section 6.2 that lithostratigraphic (also lithologic) units may have many levels of components: units are composed of other units, which in turn may be composed of units, e.g., a group may consist of several formations, each of which may comprise one or more members. Lithostratigraphic hierarchies are traditionally ranked, in descending order of generality, according to the *supergroup*, *group*, *formation*, *member* and *bed* levels. These rank concepts possess a semantic value that is geological and not simply hierarchical, e.g., items at the same tree level may not be identically ranked, as already shown in Table 6.1. For instance, a hierarchical arrangement of units might find the highest rank for a related collection of units to be *group*, and for another to be *formation*. When the two unrelated collections reside within a single hierarchy, then from a purely hierarchical point of view their topmost units exist at the same level of the hierarchy, despite the semantic difference. Furthermore, we have also seen that it is not unusual to find an object in a hierarchy (e.g., a unit) may contain synonyms, e.g., more than one name for the same unit.

The generalization rule-based model proposed in Sub-section 6.3.3 has been built on these assumptions.

Generalization operations have been performed using a set of nested SQL queries to generalize the original lithostratigraphic map of Newfoundland to the rank of *member*, *formation*, *group*, and *supergroup* or to identify the subordinates or superordinate of a lithostratigraphic unit.

Figure 6.18 shows an enlargement of the northeast area of the lithostratigraphic map. In this area the generalization process that will be performed in the next sections through the rule-based expert system proposed in Sub-section 6.3.3 is more evident.

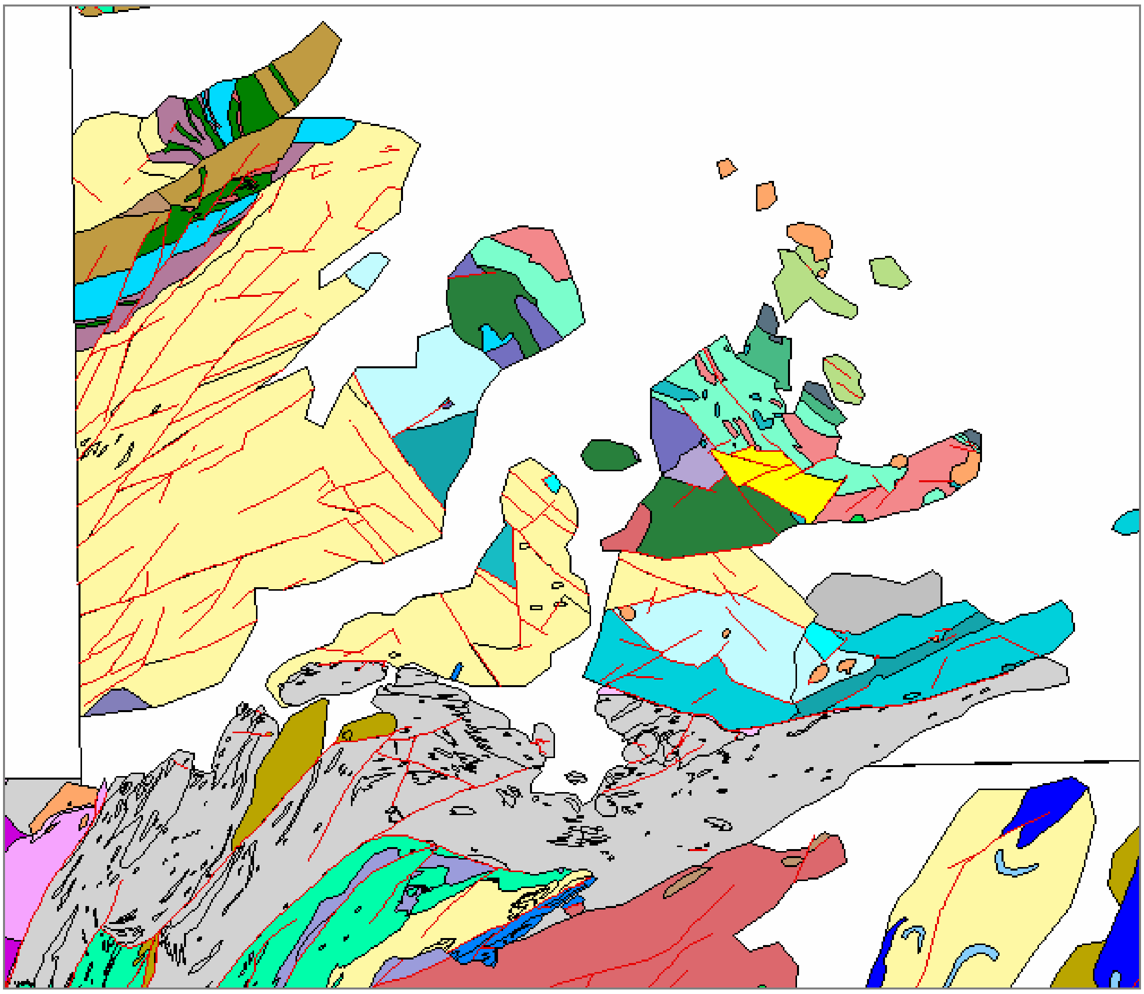


Figure 6.18. An enlargement of the northeast corner of the lithostratigraphic map of Newfoundland.

The database scheme is relatively simple and allows the execution of hierarchical standard SQL queries.

Ten tables are presented as shown in Figure 6.19. Their relationships are shown in Figure 6.4. *Polygons* table relates the geological feature class *Geology* attribute table of the

ArcGIS® system to the tabular information archived in the database. *PolygonData* contains the sum of the weights of generalized lithostratigraphic unit, when present in the LegendData table. *Legend* contains for each polygon the lithostratigraphic label used as annotation for the display or printing of the map. *LegendData* contains the full lithostratigraphic information for any geological feature and, if present, its weight to be considered during the generalization process. *Lithology* contains the full lithologic information, including the name of the lithostratigraphic unit, the name of the main rock component and its percentage. *RockType* and *RockTree* contain the rock dictionary and the hierarchical rock classification tree as well as *UnitType* and *UnitTree* containing the lithostratigraphic dictionary and the hierarchical lithostratigraphic classification.

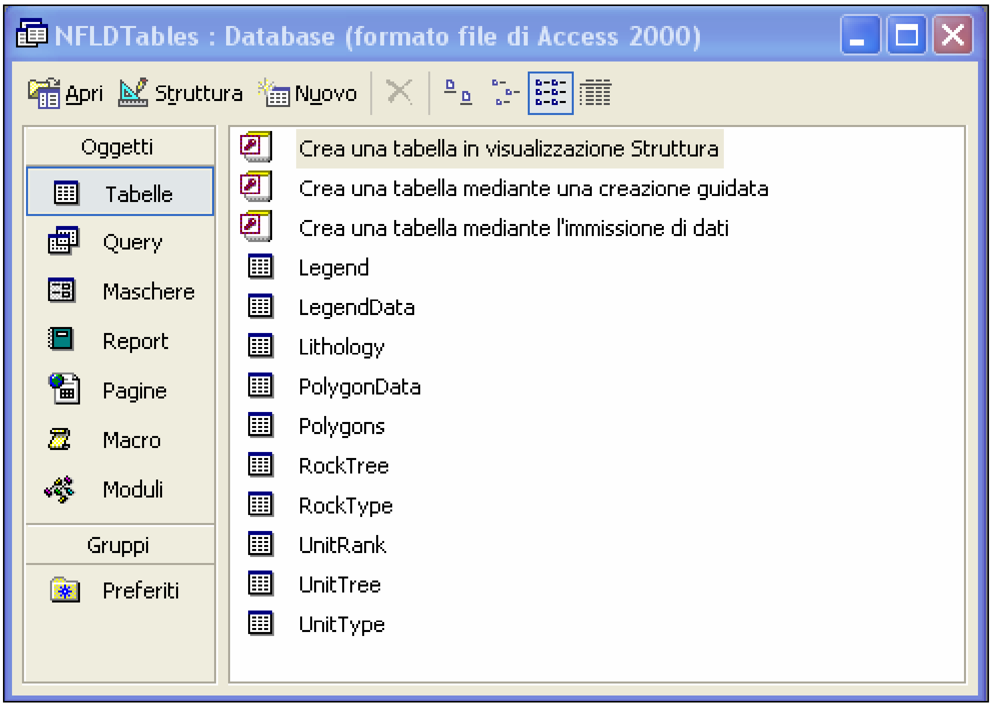


Figure 6.19. The tables present in the lithostratigraphic database of Newfoundland. Relationships between the tables are shown in Figure 6.4.

Figure 6.20 shows part of the lithostratigraphic table *Lithology*, Figure 6.21 shows the *RockType* table and the hierarchical information archived in RockTree table for the *Plutonic* rock type, and Figure 6.22 shows part of the *LegendData* table, used to store the lithostratigraphic labelling information.

Lithology : Tabella

UNITNAME	RANK	UNITID	ROCKNAME	PERCENT
Roberts Arm Group-g	sub-bed	108	Plutonic mafic	40
Roberts Arm Group-vb	sub-bed	109	Volcanic mafic marine	10
Roberts Arm Group-vf	sub-bed	110	Volcanic felsic marine	20
Sandy Lake Formation-sg	sub-bed	171	Siliciclastic marine sandstone	10
Sandy Lake Formation-sk	sub-bed	172	Siliciclastic marine	20
Sandy Lake Formation-ss	sub-bed	173	Siliciclastic marine	10
Sandy Lake Formation-vb	sub-bed	174	Volcanic mafic marine	20
Sandy Lake Formation-vf	sub-bed	175	Volcanic felsic marine	30
Sandy Lake Formation-vfr	sub-bed	176	Volcanic felsic marine	40
Sandy Lake Formation-vft	sub-bed	177	Volcanic felsic marine	5
sc	sub-bed	208	Siliciclastic non-marine conglomer	10
Seal Bay Brook Formation-st	sub-bed	178	Siliciclastic marine	15
Seal Bay Brook Formation-sx	sub-bed	179	Volcanic marine	5
Seal Bay Brook Formation-vb	sub-bed	180	Volcanic mafic marine	10
Seal Bay Brook Formation-vf	sub-bed	181	Volcanic felsic marine	15
sh	sub-bed	209	Siliciclastic black shale	5
Shale wedge zone-b	sub-bed	182	melange	10
Shale wedge zone-f	sub-bed	183	melange	15
Shale wedge zone-s	sub-bed	184	melange	10
Side Harbour Formation-vb	sub-bed	185	Volcanic mafic marine	20
Side Harbour Formation-vf	sub-bed	186	Volcanic felsic marine	30
Ski Hill Formation-b	sub-bed	187	Volcanic mafic marine	5
Ski Hill Formation-t	sub-bed	188	Volcanic marine	10
Skull Hill Quartz Syenite-g	sub-bed	189	Plutonic mafic	15
Skull Hill Quartz Syenite-q	sub-bed	190	Plutonic felsic	5
Springdale Group-s	sub-bed	111	Siliciclastic non-marine	10
Springdale Group-vb	sub-bed	112	Volcanic mafic non-marine	15
Springdale Group-vf	sub-bed	113	Volcanic felsic non-marine	5
Tally Pond volcanic rocks-i	sub-bed	191	Volcanic intermediate marine	5

Record: 1 di 130

Figure 6.20. Part of the lithostratigraphic table of the Newfoundland database. For each lithostratigraphic unit (*UnitName*) the information on the lithostratigraphic rank is given.

RockType : Tabella

ROCKNAME	ROCKID	LEV
Igneous	1	1
melange	34	1
Metamorphic	3	1
Sedimentary	2	1
chert	22	2
Hypabyssal	5	2
Metasedimentary	32	2
Plutonic	4	2
PARENTID: 1		
* 0		
Siliciclastic	23	2
Thermal Metamorphic	31	2
Volcanic	6	2
amphibolite	33	3
Hypabyssal felsic	10	3
Hypabyssal intermediate	11	3
Hypabyssal mafic	12	3
mixtite	35	3
Plutonic felsic	7	3
Plutonic intermediate	8	3
Plutonic mafic	9	3
Siliciclastic black shale	24	3
Siliciclastic marine	25	3
Siliciclastic marine conglomerate	27	3
Siliciclastic marine sandstone	29	3
Siliciclastic non-marine	26	3
Siliciclastic non-marine conglomerate	28	3
Siliciclastic non-marine sandstone	30	3

Record: 1 di 35

Figure 6.21. Part of the lithology table of the Newfoundland database. The *RockType* table is related to the *RockTree* table containing the information on the lithologic hierarchical tree.

LegendData : Tabella

LABEL	UNITNAME	WEIGHT
ORGF	Gullbridge felsic volcanic rocks	
ORGH	Gull Hill sedimentary rocks	
ORS	Crescent Lake Formation	
ORSB	South Brook basalt	
ORSh	Crescent Lake Formation-h	
ORSw	Crescent Lake Formation-w	
ORTb	Tholeiitic volcanic rocks-b	
ORTbp	Tholeiitic volcanic rocks-bp	
ORTbx	Tholeiitic volcanic rocks-bx	
ORTfa	Tholeiitic volcanic rocks-fa	
ORTff	Tholeiitic volcanic rocks-ff	
ORvb	Roberts Arm Group-vb	
ORvb, ORvf	Roberts Arm Group-vb	
ORvf	Roberts Arm Group-vf	
OS	Shoal Arm Formation	
OSBS	Sansom Formation	
OSBsc	Badger Group-sc	
OSBsw	Badger Group-sw	
OSds	ds	
Osh	sh	
OSLd	Loon Pond - Woodfords Arm plutons-d	
OSLg	Loon Pond - Woodfords Arm plutons-g	
OSLh	Loon Pond - Woodfords Arm plutons-h	
OSLL	Loon Pond pluton	
OSLWg	Woodfords Arm pluton-g	
OSM	Sops Head Complex	
OSMFb	Fault sliver zone-b	
OSMFl	Fault sliver zone-l	
OSMFw	Fault sliver zone-w	

Record: 1 di 194

Figure 6.22. Part of the label information table of the Newfoundland database. The information is used for labelling the lithostratigraphic unit.

The generalization system is managed through the execution of twelve standard SQL queries. The queries are nested and they retrieve from the geological database the geological information at the specified level of generalization. Figure 6.23 shows the SQL queries implemented for the system. The Generalize union query is shown in Figure 6.24.

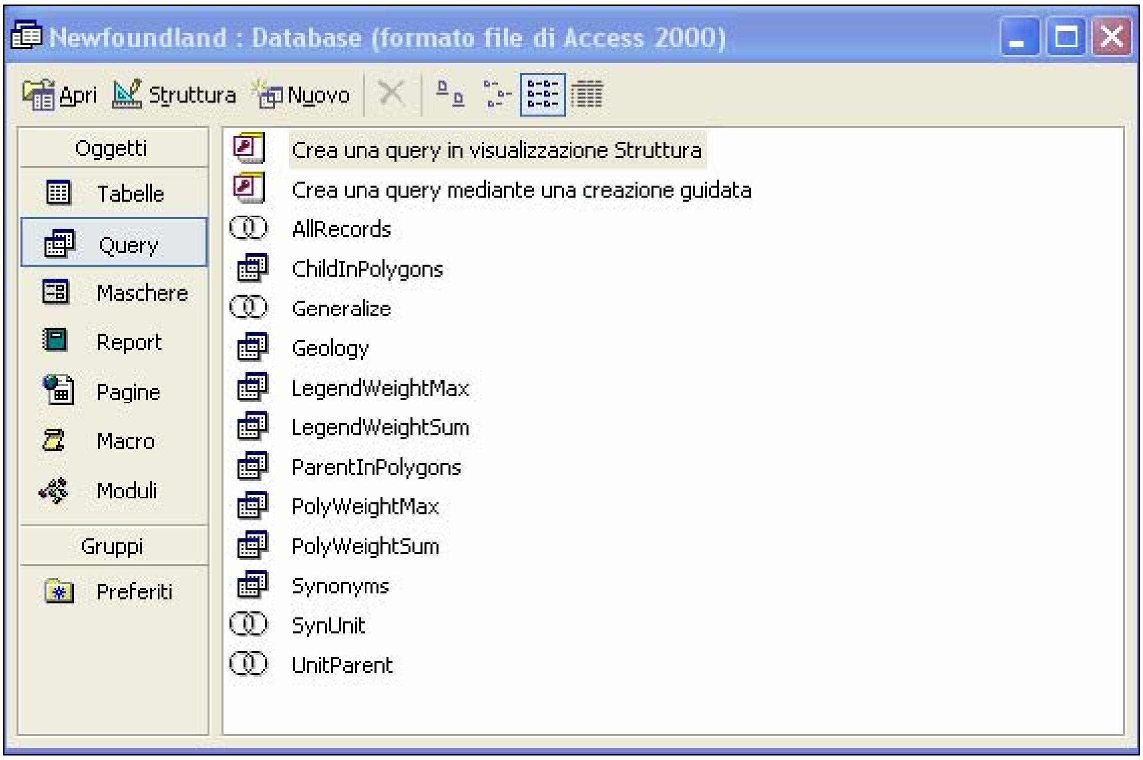


Figure 6.23. The queries used to generalize the Newfoundland lithostratigraphic database and to search through the lithologic and lithostratigraphic hierarchical trees.

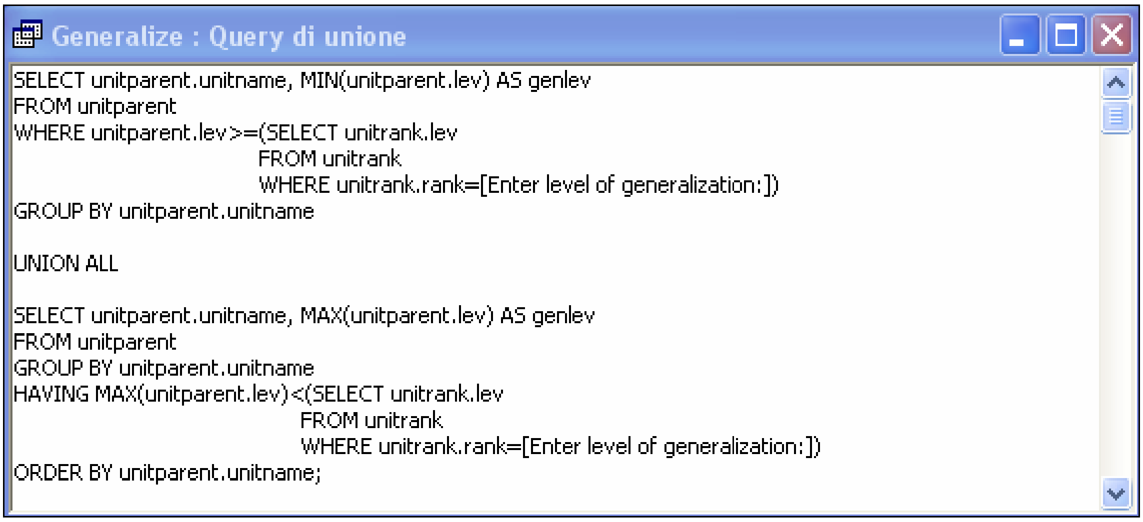


Figure 6.24. The *Generalize* query for the generalization at the rank of *member*, *formation*, *group*, and *supergroup* of the lithostratigraphic database of Newfoundland.

Figures from 6.25 to 6.28 show an example of generalization at a different level of lithostratigraphic detail. Geological information is merged according to the lithostratigraphic tree shown in Figure 6.6. The legend is shown in Figure 6.17. Note that boundaries among polygons with the same lithostratigraphic code have not been dissolved using the specific GIS software function, in order to highlight which units have been re-coded.

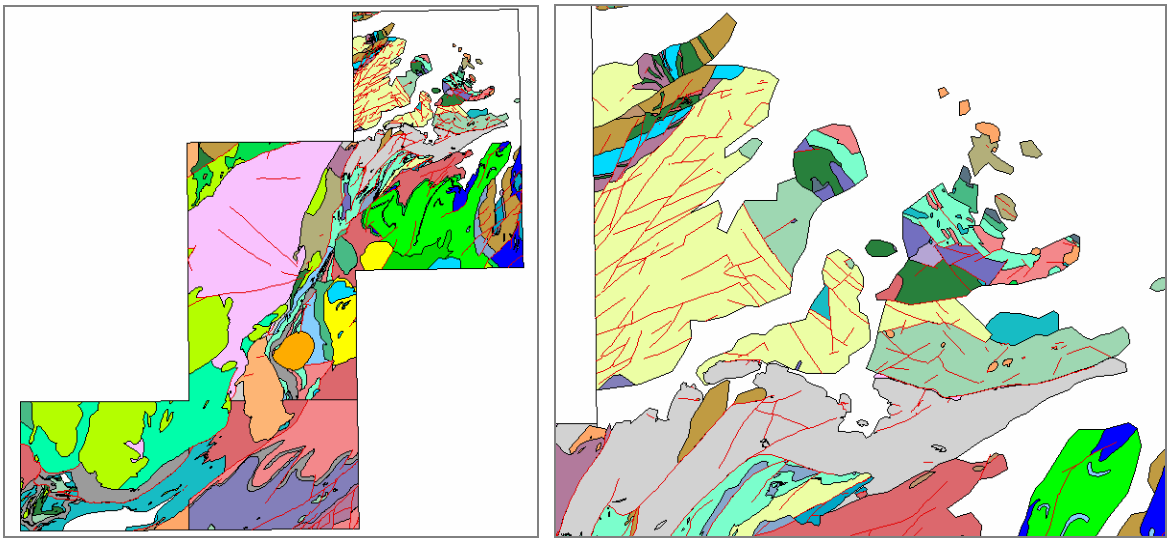


Figure 6.25. Generalization at the level of *member*. Left: the whole lithostratigraphic map of Newfoundland. Right: an enlargement of the northeast corner of the map. Legend shown in Figure 6.17.

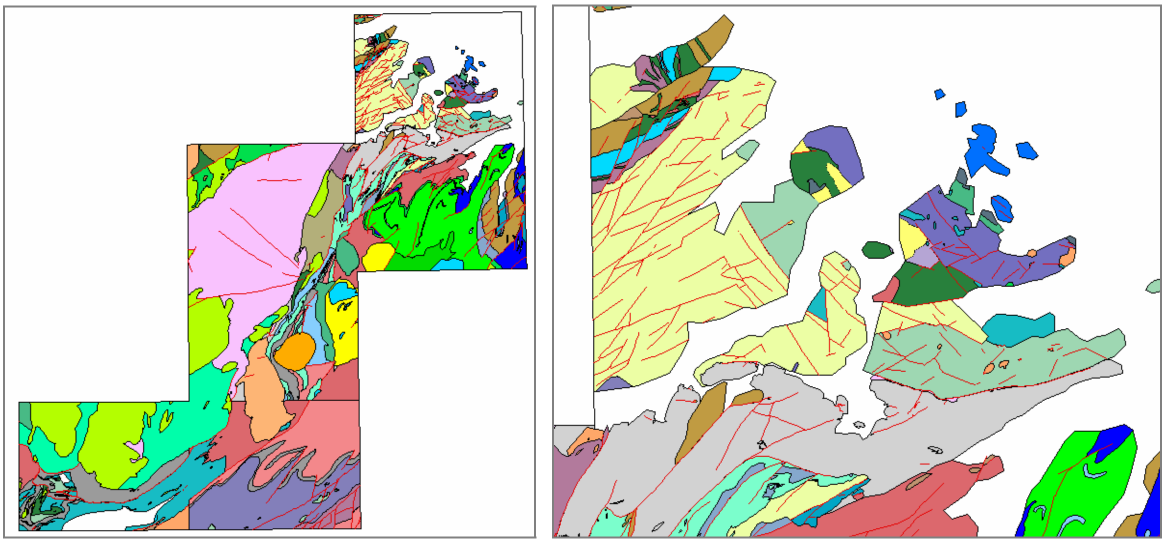


Figure 6.26. Generalization at the level of *formation*. Left: the whole lithostratigraphic map of Newfoundland. Right: an enlargement of the northeast corner of the map. Legend shown in Figure 6.17.

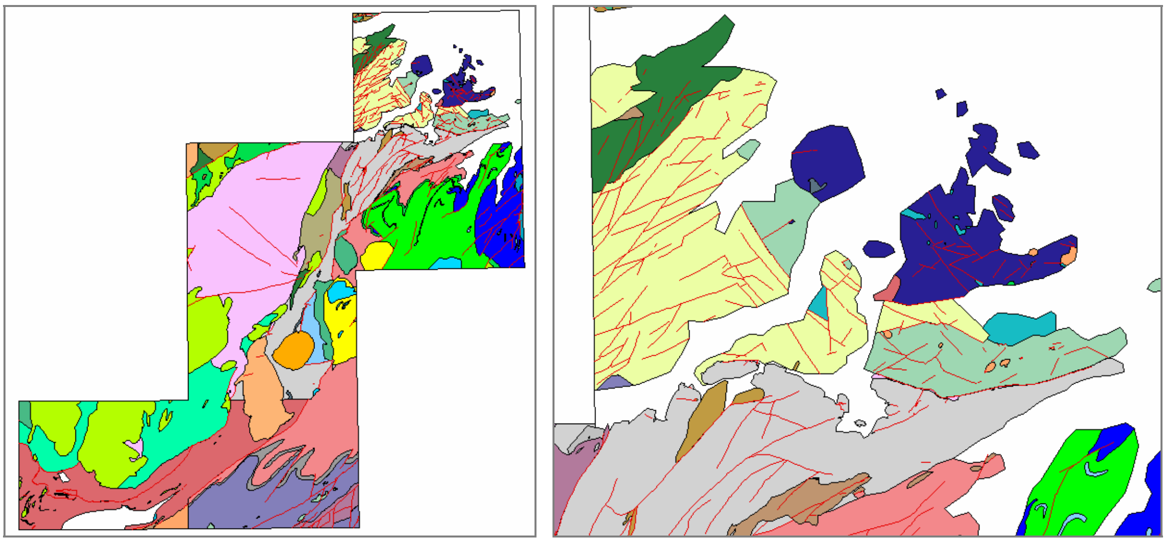


Figure 6.27. Generalization at the level of *group*. Left: the whole lithostratigraphic map of Newfoundland. Right: an enlargement of the northeast corner of the map. Legend shown in Figure 6.17.

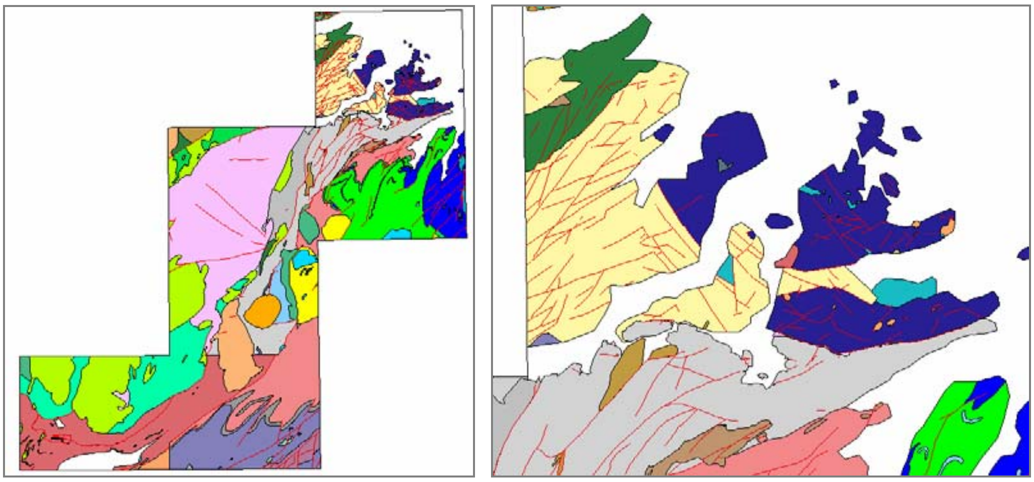
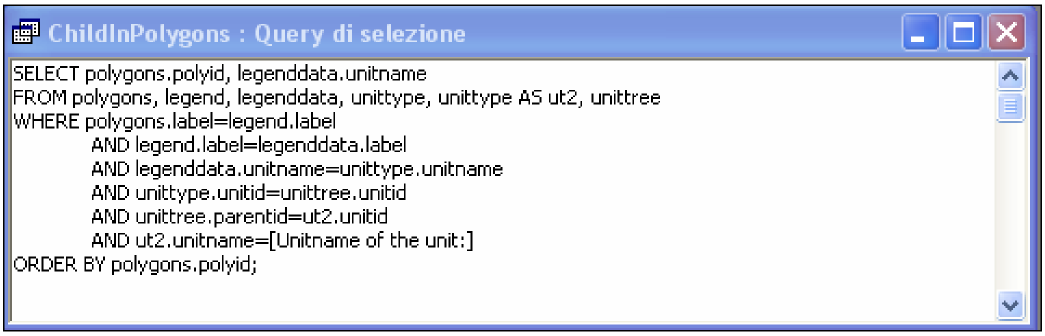


Figure 6.28. Generalization at the level of *supergroup*. Left: the whole lithostratigraphic map of Newfoundland. Right: an enlargement of the northeast corner of the map. Legend shown in Figure 6.17.

The database scheme allows also the selection of *subordinates* (children) or *superordinates* (parents) of a lithostratigraphic unit though SQL queries. In Figures from 6.29 to 6.31 an example of selection of the subordinates of the *Robert Arm Group* is shown. The lithostratigraphic hierarchical tree is shown in Figure 6.6. Figures from 6.32 to 6.34 show an example of selection of the superordinate of the *Pillow andesite member*.



ChildInPolygons : Query di selezione

```
SELECT polygons.polyid, legenddata.unitname
FROM polygons, legend, legenddata, unittype, unittype AS ut2, unittree
WHERE polygons.label=legend.label
        AND legend.label=legenddata.label
        AND legenddata.unitname=unittype.unitname
        AND unittype.unitid=unittree.unitid
        AND unittree.parentid=ut2.unitid
        AND ut2.unitname=[Unitname of the unit:]
ORDER BY polygons.polyid;
```

Figure 6.29. The SQL query used for the selection of the subordinates of a lithostratigraphic unit.

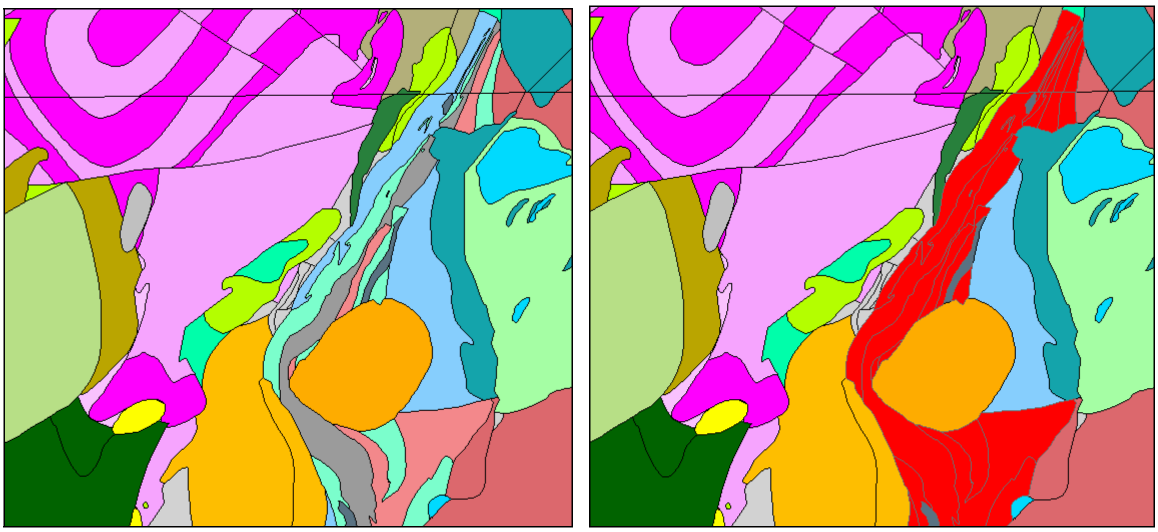


Figure 6.30. An enlargement of the lithostratigraphic map of Newfoundland. Left: lithostratigraphic unit. Right: the subordinates of the *Robert Arm Group* are shown in red.

Attributes of ChildrenRobertArmGroup

OBJECTID*	Shape*	AREA	POLYID	LABEL	UNITNAME
1	Polygon	2268194	84	ORGH	Gull Hill sedimentary rocks
2	Polygon	1100681	91	ORS	Crescent Lake Formation
3	Polygon	3739406	95	ORGF	Gullbridge felsic volcanic rocks
4	Polygon	1130498	98	ORSB	South Brook basalt
5	Polygon	28613220	101	ORGH	Gull Hill sedimentary rocks
6	Polygon	6023572	102	ORBB	Baker Brook basalt
7	Polygon	34049840	277	ORBI	Burnt Island basalt
8	Polygon	361638.5	442	ORS	Crescent Lake Formation
9	Polygon	2188062	725	ORBB	Baker Brook basalt
10	Polygon	1749022	726	ORBB	Baker Brook basalt
11	Polygon	3445469	747	ORBB	Baker Brook basalt
12	Polygon	2385345	748	ORGH	Gull Hill sedimentary rocks
13	Polygon	16479560	764	ORSB	South Brook basalt
14	Polygon	17335220	766	ORGF	Gullbridge felsic volcanic rocks
15	Polygon	6015545	775	ORSB	South Brook basalt
16	Polygon	1361201	776	ORBI	Burnt Island basalt
17	Polygon	33219	782	ORGF	Gullbridge felsic volcanic rocks
18	Polygon	600759	783	ORGF	Gullbridge felsic volcanic rocks
19	Polygon	265646.5	784	ORGF	Gullbridge felsic volcanic rocks
20	Polygon	27963	785	ORSB	South Brook basalt
21	Polygon	1251990	786	ORBI	Burnt Island basalt
22	Polygon	675559.5	787	ORGF	Gullbridge felsic volcanic rocks
23	Polygon	6099726	790	ORBB	Baker Brook basalt
24	Polygon	111475.5	791	ORGF	Gullbridge felsic volcanic rocks
25	Polygon	86481.5	792	ORGF	Gullbridge felsic volcanic rocks
26	Polygon	19428	793	ORGF	Gullbridge felsic volcanic rocks
27	Polygon	154472	806	ORS	Crescent Lake Formation
28	Polygon	396594	1142	ORS	Crescent Lake Formation
29	Polygon	612042.5	1143	ORBB	Baker Brook basalt
30	Polygon	444953	1144	ORGH	Gull Hill sedimentary rocks
31	Polygon	3438897	1145	ORGH	Gull Hill sedimentary rocks
32	Polygon	1610188	1147	ORBB	Baker Brook basalt

Record: 1 Show: All Selected Records (0 out of 32 Selected.) Options

Figure 6.31. The attributes of the selected lithostratigraphic units.

ParentInPolygons : Query di selezione

```
SELECT polygons.polyid, ut2.unitname
FROM polygons, legend, legenddata, unittype, unittype AS ut2, unittree
WHERE unittype.unitname=[Unitname of the unit:]
        AND unittype.unitid=unittree.unitid
        AND unittree.parentid=ut2.unitid
        AND ut2.unitname= legenddata.unitname
        AND legenddata.label=legend.label
        AND legend.label=polygons.label
ORDER BY polygons.polyid;
```

Figure 6.32. The SQL query used for the selection of the superordinate of a lithostratigraphic unit.

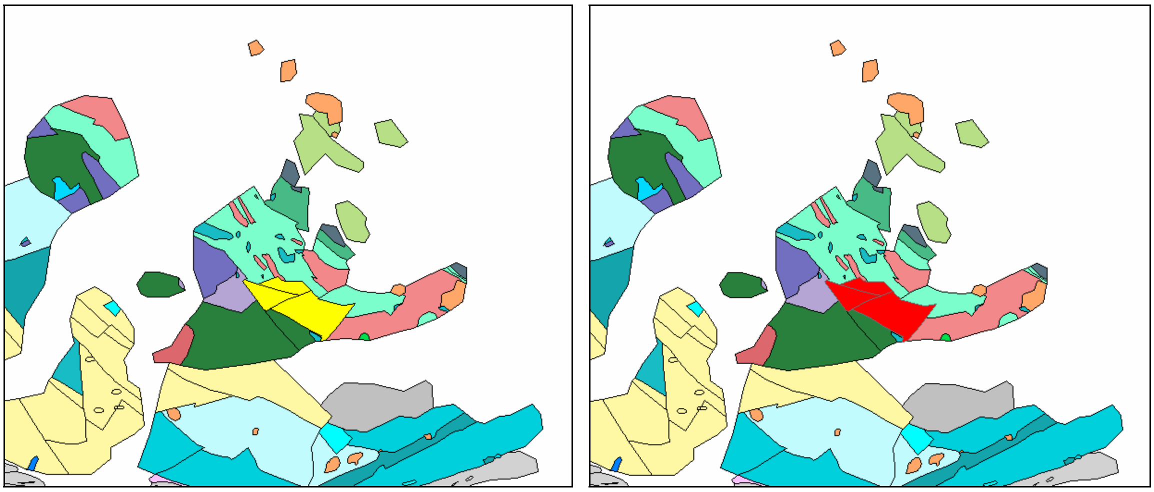


Figure 6.33. An enlargement of the lithostratigraphic map of Newfoundland. Left: lithostratigraphic unit. Right: the subordinate of the *Pillow andesite member* are shown in red.

Attributes of ParentsPillowAndesiteMember

OBJECTID*	Shape*	AREA	POLYID	LABEL	UNITNAME
1	Polygon	1172530	121	OCB	Burnt Head formation
2	Polygon	821864	189	OCB	Burnt Head formation
3	Polygon	3218616	202	OCB	Burnt Head formation

Record: 1 Show: All Selected Records (0 out of 3 Selected.) Options

Figure 6.34. The attributes of the selected lithostratigraphic units.

Generalization operations can also be performed using a set of nested SQL queries to generalize the original Newfoundland database according to the lithologic information associated to each lithostratigraphic unit (see Table 6.10 and Figure 6.21).

To test the universal validity of the proposed model with different GIS software, the system has also been tested using ArcView GIS® 3.2 software of ESRI and a Microsoft® ODBC (Open Database Connectivity) connection to access to an external database, the Newfoundland database. The results of the lithologic generalization at the top hierarchical level and at an intermediate level of the hierarchical tree are shown in Figure 6.35 and Figure 6.36.

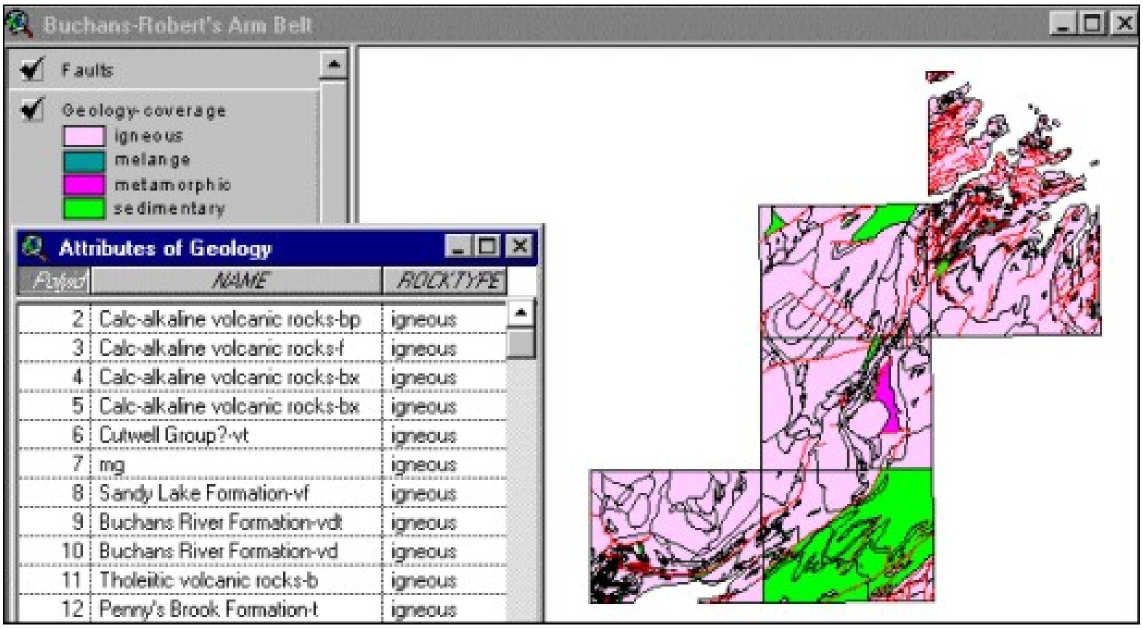


Figure 6.35. Lithologic generalization of the lithostratigraphic unit of the Newfoundland map at the upper level of the hierarchical tree (see Table 6.10). Units have been assigned to the *igneous*, *metamorphic*, *sedimentary*, or *melange* domain.

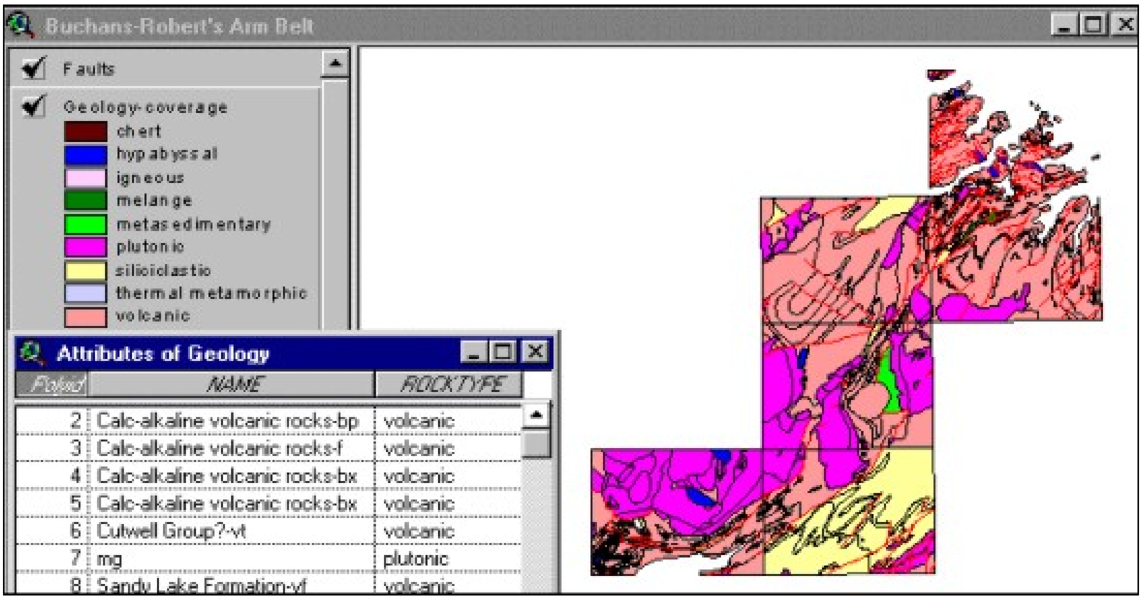


Figure 6.36. Lithologic generalization of the lithostratigraphic unit of the Newfoundland map at an intermediate level of the hierarchical tree (see Table 6.10). Units have been assigned to the proper domain according to the information archived in the database.

6.6 Conclusions

The design of a Geographic Information System for the management of Earth Sciences data has to deal with the very nature of geology, which is historical in character, so that it differs substantially from other fields of geographic applications. Geology is basically concerned with the analysis, classification, and description of complex structures whose presence and extension are affected by uncertainty and by gaps. Many geological data types such as lithostratigraphic units, rock types, and time scales are commonly categorised and organized into hierarchical arrangements. Computer-based techniques must be capable of effectively manipulating such hierarchies. Furthermore, geological information is often gathered in the field at a scale larger than the final representation scale. This implies a generalization process to maintain readability and to avoid symbol overcrowding.

It has been proposed a hierarchical expert system for the generalization of the geological database, for both the multiple thematic and the multi-scale representations of the information generated and archived. The set-theoretic method has been proved to conform to the relational data model and is advantageous in managing geological hierarchies. The method has been applied to several case studies, using standard SQL queries, where the methodology and the geological object model proposed in this research have been successfully validated.

The system has proved to be an effective means of organizing and storing hierarchical geological, lithostratigraphic, and lithologic information, facilitating the generalization at a defined hierarchical level.

In the next chapter the proposed system for the generalization of overcrowded symbology will be presented and discussed.

Chapter Seven

7 Symbol generalization

In Chapter 6 an object-oriented model was described that creates a view of a geological database at multiple scales. The system based on the object-oriented model is designed to automatically generalize geological data between different scales. In this chapter the issue of symbol generalization will be addressed and the resolution of cluttered symbology for enhancing legibility will be discussed.

Geological maps are extremely complex interpretative documents. The primary objective of a geological map is to portray the reconstructed geological evolution of an area. A geologist understands the geometries of the rock bodies, their deformation and their lateral and vertical relationships from the symbols and the geological elements represented on the map.

On a geological map many different types of information are displayed. Additional complexity is introduced by the lack of consistency at different levels of representation, starting from the original scale of surveying where information is observed with a higher level of detail to the design of the GIS database and to the scale of the printed product derived from them. Furthermore, fields geologists tend to map geological features (e.g., to filter or select the features that will eventually appear on the map) depending upon the scale of surveying. What is definite at a smaller scale may be only inferred at a larger scale. The cartographer only applies graphical simplification if at all necessary, generalizing from a large scale (higher level of detail) to a small scale (lower level of detail), e.g., from 1:25,000 to 1:50,000 as in our case study.

7.1 Generalization operations

Digital generalization, rooted on conventional cartography, has become an increasing concern in both the Geographic Information Systems (GIS) and the digital cartography fields.

Generalization is an essential component in mapmaking. The process of generalization extracts and reduces information from reality (or *source* map) and portrays it to represent a specific theme and/or at a smaller scale (or *target* map), while meeting cartographic specifications, aesthetic qualities, and maintaining the representative integrity of the mapped area.

Manual generalization, as the traditional means, is extremely subjective and time consuming. Cartographers, who often are also geologists or have a geological background, draw a reduced map by hand. They eliminate unimportant point features, simplify lines and boundaries, combine area features, and resolve conflicts as they draw. The result depends on the knowledge, habits and ability of the cartographer.

As geographic databases are constantly built, there is a stringent need for automation of the generalization capabilities for multi-purpose output. The field of generalization has extended to include GIS applications. Noticeable efforts have been made by researchers and some GIS and mapping software vendors to define digital generalization problems and to develop solutions. However, none of the existing systems has provided a set of tools that fully satisfies the digital generalization needs, especially in the field of geology and of the geosciences at large.

Although principles and guidelines of generalization can be found in cartographic literature and among mapping organizations, a set of universal rules that explicitly defines how generalization should be performed has not been defined as yet. Manual generalization depends mainly on the experience and the habits of the operator and therefore often produces inconsistent results.

The lack of a full understanding of this process that is often very subjective and the scarcity of technical means that mimic human analysis, decision-making, and consequent actions make the automation of the generalization of geological maps an arduous task. However, the evolution of digital generalization technology in general has gone on for decades. Major efforts and achievements in this field can be summarized as follows. In the 1960s and 1970s, isolated research attempted to develop simple techniques that reduce data complexity. Examples of a few known algorithms are Douglas-Peucker’s (Douglas and Peucker, 1973) and Lang’s (Lang, 1969) line simplification algorithms; and Brophy’s (Brophy, 1972) and Chaiken’s (Chaiken, 1974) line smoothing routines.

Evaluations of existing algorithms have taken place since the early 1980s (Visvalingam and Whyatt, 1990; Beard, 1991). More comprehensive techniques for automated generalization have been explored for a long time; modelling and rule-based generalization has became of increasing interest in the late 1980s (e.g., by Nickerson and Freeman, 1986; McMaster and Shea, 1988). Significant progress in digital generalization has been made worldwide in the 1990s.

A number of international organizations have been established to coordinate digital generalization research projects and special meetings. The main focus is to formalize digital generalization in theory and practise it in reality. The availability of more comprehensive generalization systems has provided cartographers with experimental environments.

In order to stimulate and formalize the research activities on digital generalization, the following organizations and working groups have been established. The Working Group on Map Generalization under the International Cartographic Association (http://ncl.sbs.ohio-state.edu/95_ica.html), as part of the Commission on Advanced Technology, was formed at the fifteenth International Cartographic Conference (ICC) in Bournemouth, United Kingdom, in 1991. It has played an important role in providing a forum for exchanging ideas, supporting a network communication among people and institutions in map generalization, and coordinating activities with other research groups. One of the most significant activities was the three-day workshop on Progress in Automated Map Generalization held prior to the seventeenth ICC in Barcelona, Spain, in 1995. More than 30 active researchers and users presented their work and discussed the short- and long-term research directions and focuses.

The Working Group on Automatic Generalization under the *Organisation Europeenne des Etudes en Photogrammétriques Experimentale* (OEEPE) is largely connected to national mapping agencies. Their research focus is to find solutions for practical problems. The initial project of this group concentrates on developing criteria for the evaluation of the quality of generalization results and on evaluation of commercial generalization software.

The EC GI & GIS portal provides information on European GI & GIS Activities including information on GI & GIS Activities within the European Commission (http://www.ec-gis.org/).

The European Science Foundation (http://www.esf.org) has organized a research program called GISDATA. Part of the GISDATA activities is the creation of various task forces that are responsible for the organization of specialist meetings on various issues related to GIS. One of the task forces is on the topic of generalization. A specialist meeting was held in Compiegne, France, in December 1993. As a result of this meeting, a book (Müller, *et al.*, 1995) was published as a collection of articles that represent and describe the state of the art of digital map generalization. The U.S. National Center for Geographic Information Analysis (NCGIA) held the Symposium on Map Generalization at Syracuse University in mid-April 1990, funded jointly by Syracuse University. One of NCGIA's research initiatives is *Formalizing Cartographic Knowledge*. A specialist meeting was held in October 1993, addressing generalization and other digital cartographic issues.

Nevertheless, there is a very limited published research specifically concerned with the generalization of geological data. A valuable and unfortunately isolated example is the research of Downs and Mackaness (2002) that deals with the generalization of geological maps, taking into account structural and lithologic features.

Geological symbology may occur with such a rich diversity and complexity that it is difficult to establish a fixed set of procedures to generalize and simplify it. The placement of geological symbols on maps has proved remarkably resistant to computerization. Positioning geological symbols requires that the geological phenomenon be clearly described and represented, that overlaps be avoided, that cartographic conventions and standards be obeyed and that a high level of aesthetic quality be achieved.

For the performance of an automatic symbol placement system to be considered satisfactory, it must come close to matching the quality of manual symbol placement and generalization.

Differently from other countries where digital geological maps and geological databases are freely distributed and are replacing the traditional printed geological product, like the US Geological Survey, in Italy there is still a very strong resistance from the geological community to distribute digital geological data and the geological database. The responsible person for the survey and the production of the a geological sheet and the surveyors own the copyright of the geological data collected, while the SGN owns only the copyright of the printed geological map; e.g., THE SGN can distribute only the geological sheet (or at the most a digital image of the geological map) but cannot distribute the original geological data and the geological database. Therefore, the traditional printed geological map has still a relevant importance and map generalization is still a major issue. In the other countries, where digital geological maps are shared and distributed often over the Internet, GIS tools can be used to dynamically adapt symbology and labels according to the display scale of the computer screen or to show more details and information collected by the geologist in the field than in a printed geological product.

7.1.1 Generalization operators

Cartographic generalization is the process of selecting and simplifying the representation of detail of a source map appropriate to the scale and the purpose of a target map. This graphic process corresponds to the fundamental human activity of abstracting and reducing complexity and involves a great deal of analysis of the geographic data and decisions on what to generalize, how to generalize and the averaging, and how to resolve symbol conflicts.

It would be very difficult to fully automate this process due to its subjective nature and the present lack of well-defined rules to guide the decision making. A good alternative would be to automate the computational work as much as possible and leave the decision making to the users, e.g., the computer-assisted solution, especially in the generalization of a geological map.

In order to develop the computer-assisted solution, it is necessary to understand what exactly happens when a cartographer generalizes a map, and to make the operations explicitly defined for digital implementation. A complex generalization process can be decomposed into the operation categories listed below (ESRI, 1996), which are described in digital generalization terminology. Most operators are only vaguely defined, so that any cartographer may use different definitions for the same term or use different terms for the same definition. In this research the terminology proposed by ESRI and used in ArcGIS® software will be used.

7.1.1.1 Selection

This involves selecting certain feature classes from a master database for the inclusion in the final map. What to be selected depends on the target map scale and purpose. The preselected features will participate further in generalization operations.

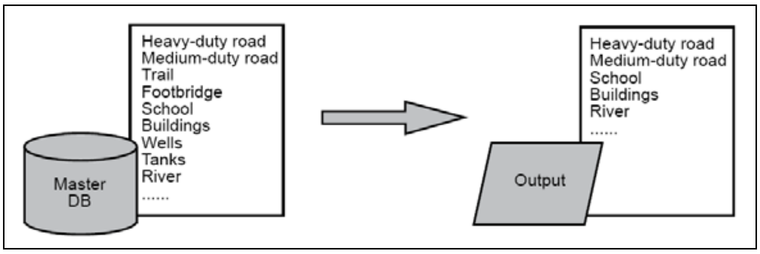


Figure 7.1. Selection.

7.1.1.2 Elimination

This is for selectively eliminating features that are too small, too short, and too insignificant to be presented in the final map; for instance, small islands, short roads, little villages, and so on.

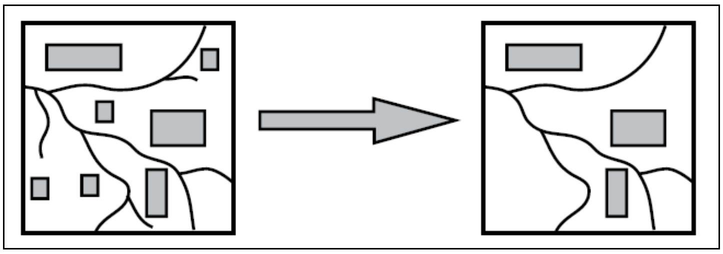


Figure 7.2. Elimination.

7.1.1.3 Simplification

This is for removing unnecessary detail, such as extraneous bends and fluctuations, from a line or an area boundary without destroying its essential shape.

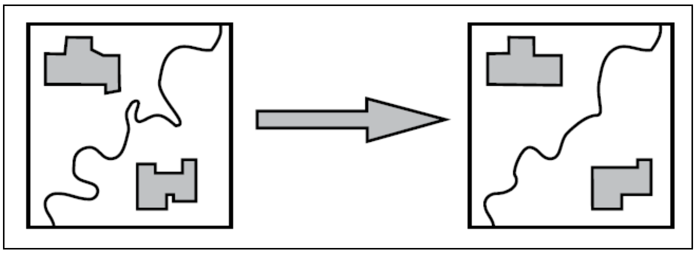


Figure 7.3. Simplification.

7.1.1.4 Aggregation

This involves combining features in close proximity or adjacent features into a new area feature; for instance, forming a built-up area from a cluster of buildings or joining patches of crop fields into a large agricultural area.

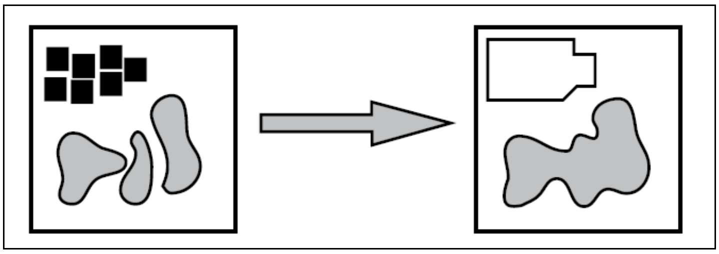


Figure 7.4. Aggregation.

7.1.1.5 Collapse

This involves reducing a feature dimension or the representation of its spatial extent; for instance, changing an area feature to a linear or point feature, changing a multiple-line feature to a single-line feature, and so on.

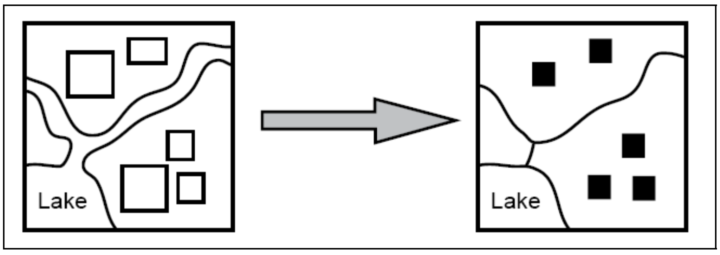


Figure 7.5. Collapse.

7.1.1.6 Typification

This involves reducing feature density and the level of detail while maintaining the representative distribution pattern and visual impression of the original feature group; for instance, reducing the amount of detail in a drainage network without losing the impression of its structure.

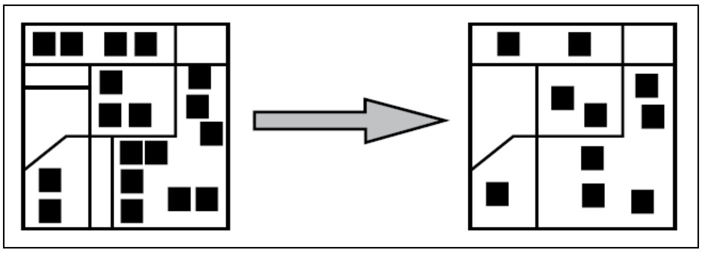


Figure 7.6. Typification.

7.1.1.7 Exaggeration

This involves increasing the spatial extent of a feature representation for the purpose of emphasis and legibility; for instance, enlarging the size of an island, which is otherwise small enough to be removed, to include it for its significance as a navigational point of reference.

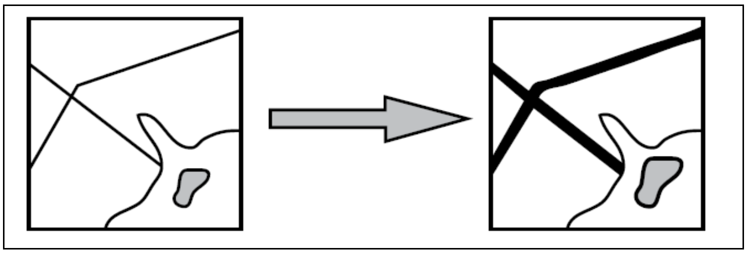


Figure 7.7. Exaggeration.

7.1.1.8 Classification and symbolization (amalgamation, merge)

This involves grouping features sharing similar geographic attributes into a new, higher-level feature class and representing it with a new symbol.

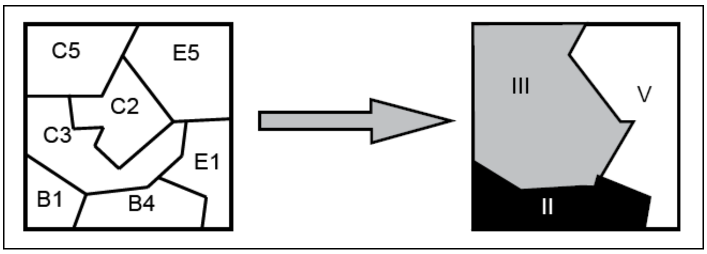


Figure 7.8. Classification and symbolization.

7.1.1.9 Conflict resolution (displacement)

This is for detecting feature conflicts and then repositioning the less important conflicting features or adjusting feature extents to satisfy the threshold of separation and other cartographic specifications.

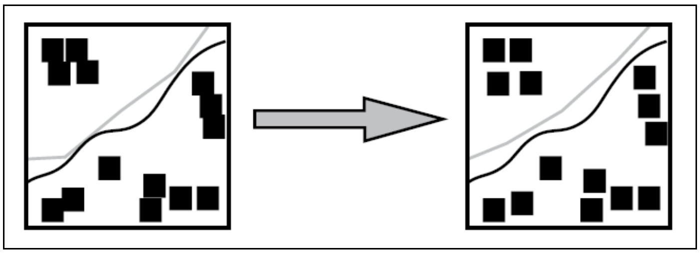


Figure 7.9. Conflict resolution (displacement).

7.1.1.10 Refinement

This involves altering and adjusting a feature's geometry or appearance to improve its aesthetic (visual) impression and to ensure its agreement with reality. Some examples are smoothing a line, squaring a corner, changing the orientation and alignment of a point symbol, correcting the intersecting angles of a contour and a river, and so on.

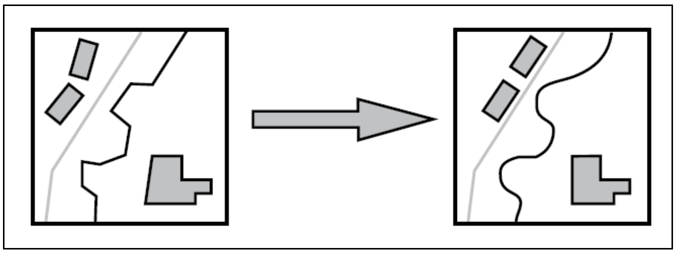


Figure 7.10. Refinement.

7.2 The generalization approach

Based on the above definitions, a set of generalization operators has been selected to automatically perform these operations and produce the desired results for this research.

The proposed generalization system is a mix of the *Selection* and *Aggregation* operators, together with statistical methodologies. Bedding symbols are *selected* according to specific rules, and their strike and dip values are *aggregated*, *averaged* and assigned to one of the points of the initial selected set. No displacement operations are performed on the point features and no elimination operations are carried out on the attribute tables contained in the geographic database in order to maintain both the original information collected by the geologist during the field mapping and the original data archived in the geological database.

The symbols to be shown on the geological map at the scale of 1:50,000 are selected from the map database and then positioned according to their original coordinates, rotated according to their strike attribute, and labelled according the dip value. The system generalizes and averages only the information contained in the geological geodatabase without performing any operation of elimination or displacement. Original information is maintained and no symbol is deleted.

The *strike* is the line formed by the intersection of an imaginary horizontal plane with the inclined surface and its direction measured from the north has a value ranging from 0° to 360°. The *dip* is the inclination of the inclined surface measured perpendicular to the strike line and has a value of the angle ranging form 0° to 90°. Figure 7.11 shows how the strike and dip angles are measured on a tilted surface.

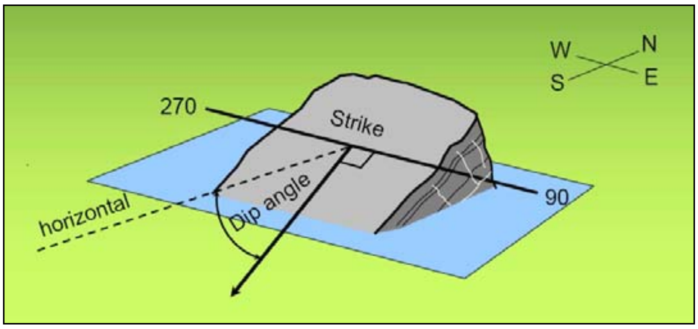


Figure 7.11. Measuring the strike and dip angles on an inclined surface. (Source: Boyce, 2006).

A compass is used to measure the strike angle, while the dip is measured using an inclinometer, as shown in Figure 7.12 and Figure 7.13.

Figure 7.12. Strike is measured by placing the compass parallel with the outcrop face. (Source: Boyce, 2006).

Figure 7.13. Dip angle measured by placing the long axis of the compass parallel with the dip direction. (Source: Boyce, 2006).

Strike and dip are usually measured where layered rocks (which can be originated from magmatic, metamorphic, tectonic or sedimentary processes) outcrop. Layered rocks are usually recognizable through the presence of distinct layers formed during the period of deposition. These layers can be termed *strata*, or simply *beds*. The planes of separation between layers are stratification planes, or bedding planes. Bedding planes in their original condition are nearly horizontal, but they may have become steeply tilted, overturned or otherwise distorted into wavelike folds by subsequent movements of the earth crust.

Geologists typically work from available surface outcrops of rock formation to reconstruct subsurface structures. Strike and dip values are used for the orientation of a surface in the space and to reconstruct a geological cross-section (or structural section) of an area from a printed geological map. Strike and dip angles are vital information in a geological map. Figure 7.14 and Figure 7.15 show how strike and dip values are measured on dipping strata.

Bedding symbology has been used to test the generalization procedure proposed in the next section.

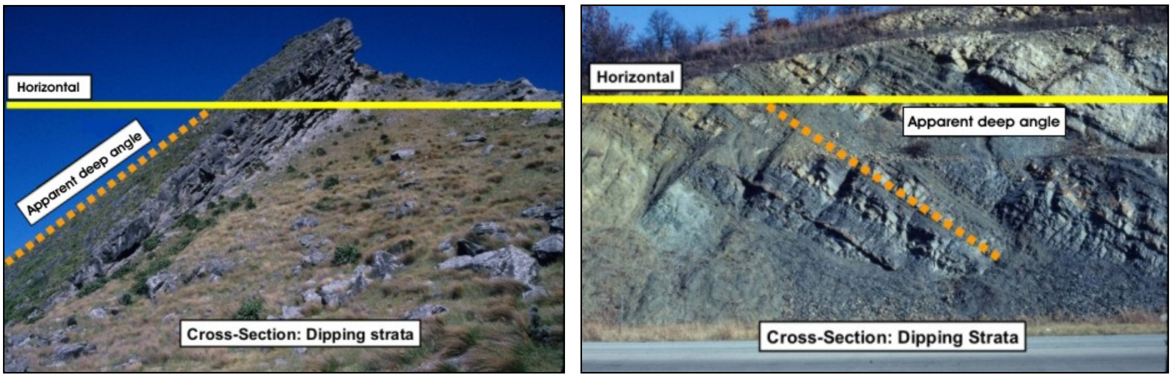


Figure 7.14. Two examples of how strike and dip are measured on dipping strata. (Source: McBride, 2006).

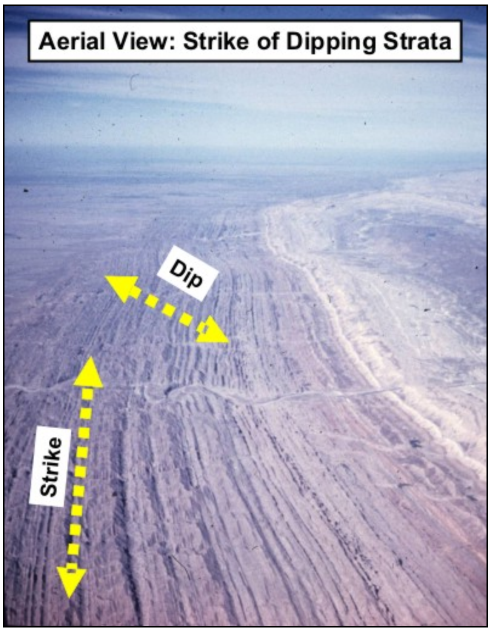


Figure 7.15. An aerial view of dipping strata. (Source: McBride, 2006).

7.3 The Sestri Levante case study

When reducing the scale of a geological map it is necessary to emphasize essential geological information while repressing the redundant data. Generalization of a geological map is acknowledged to be subjective, but nevertheless must continue to maintain the logical and unambiguous relationships between geological objects, showing the salient symbols while removing unnecessary detail. Reducing the scale of a geological map without some form of generalization would result in a cluttered map, with overlapping symbols, and extremely complex to interpret. The document would be unintelligible, unable to communicate effectively with the users and therefore it would be of diminished value (Downs and Mackaness, 2002). The difficulty of symbol placement depends on the density of the information and the relevance of their relationships. On sparse maps, or maps at a larger scale, as for instance the 1:25,000 topographic base map used to collect geological data in the field in Italy, there is more empty space between symbols than at 1:50,000, the scale for the printed product, where the information is definitely denser and more cluttered.

Experience has shown that manual generalization of a digital geological map can be a very time consuming and difficult operation. The ability to easily and quickly generalize such datasets would be highly advantageous, particularly in the context of current digital frameworks, like the Italian CARG Project described in Sub-section 5.5.2.

This research aims to derive a 1:50,000 (the *target* scale) geological map from a 1:25,000 (the *source* scale) geological database constructed according to the CARG database scheme described in detail in Sub-section 5.5.3.

The test area is located in the Liguria region, selecting a portion of the 1:25,000 *Sestri Levante* geological map (see Section 5.5). The Sestri Levante geological sheet provides a suitable source scale dataset. The test area has been selected for two reasons: (i) the range of symbology available, and (ii) the high density of symbology at the source scale. However, only a sub-set of symbols were used for the generalization test. The bedding symbology containing the strike and dip attribute values was selected and used to test the proposed system. By piecing together such information, the geologist can generally establish the stratigraphic succession and discover the variations in thickness of beds. More structural symbology is plotted on a geological map. Lineations, foliation, schistosity, gneissosity, for instance, are represented using vector symbology showing the trend and the plunge as shown in Figures 7.16, 7.17 and 7.18. Both these symbols are often collected densely on a rock outcrop, but cannot be all represented on a geological map. Geological maps demand rigorous selection of data. They emphasize some features at the expense of others. The cartographer or the geologist (in a subjective and aesthetic way) calculates and assigns separately the average values of the strike angle and the dip angle to the most representative symbol of the cluster of symbols. The methodology used to generalize bedding symbology showing strike and dip values or the other structural symbology showing a direction and an inclination is the same. The generalization system proposed in the following sections may be therefore applied with the same efficiency to any geological or structural symbols plotted on a geological map.

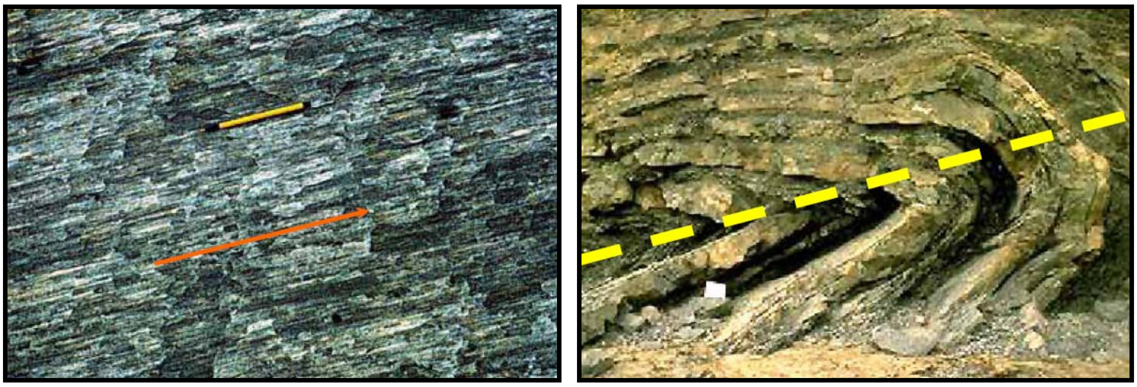


Figure 7.16. Geological feature showing trend and plunge. Left: Lineation in gneiss. Right: Fold axial trace. (Source: Boyce, 2006).

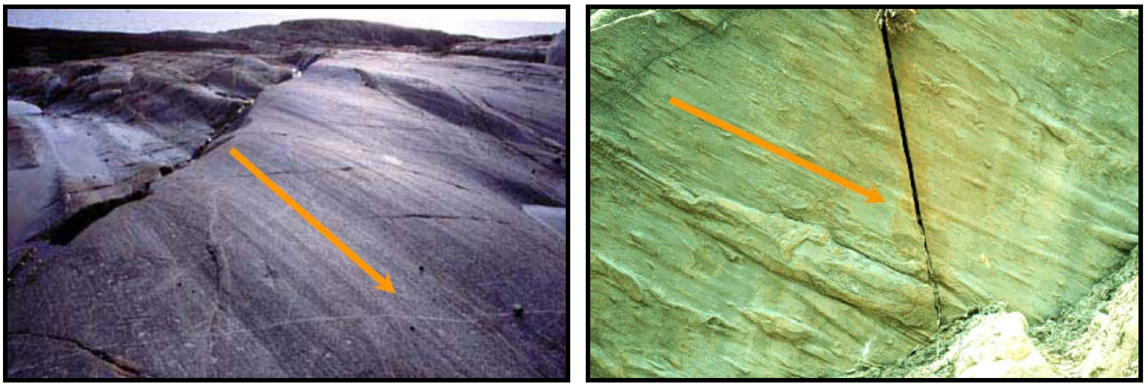


Figure 7.17. Geological feature showing trend. Left: Glacial striations on bedrock. Right: Sole marks. (Source: Boyce, 2006).

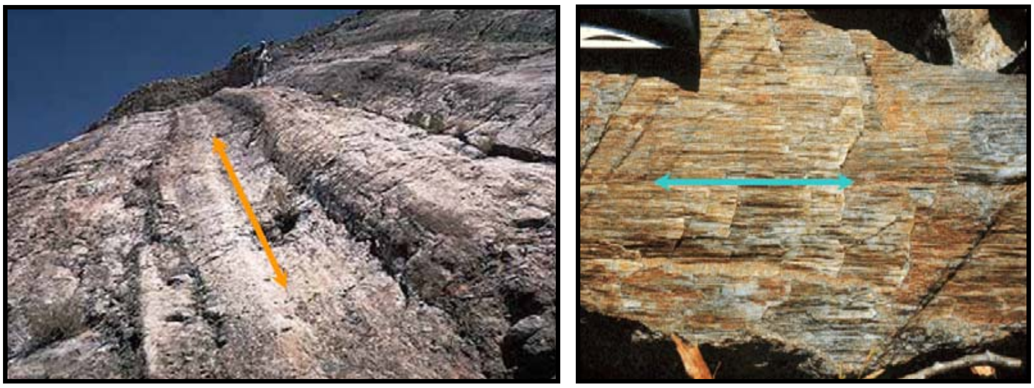


Figure 7.18. Geological feature showing trend and plunge. Left: Groves on exposed fault plane. Right: Slickenlines. (Source: Boyce, 2006).

Throughout this research effort, modelling, evaluation and tuning of the generalization process were obtained through empirical observations in close consultation with field geologists and cartographers at the University of Rome *La Sapienza*, Department of Earth Sciences, and at the Geological Survey of Italy. This process of visual inspection and comparison of source and target scale maps enabled the identification of the principal clusters of geological symbols requiring generalization.

Besides this research concentrated on bedding symbology, it is readily acknowledged that generalization should also include the whole set of geological symbology and geological features and the relationships and overlapping conflict between the different type of symbols shown in a geological map. The present work is just a first attempt to implement a generalization system using only the standard commands, tools, and functions of commercial GIS software, generalizing the information contained in the geological database without modifying, altering or deleting the original source data. However, it is sufficient to bring up general problems and identify possible solutions. In future research work, systematic procedures of generalization of different objects or symbols will be developed in order to obtain a complete and general solution for the generalization of the geological information contained in a geological map.

It has been preferred to use some kind of rule-based approach to control the generalization operations. This was because it can be easily implemented on general-purpose GIS software. The routine was constructed using standard tools of the ArcGIS® software, so that when a condition was satisfied a generalization operation was initiated by the system. Distance calculation when bedding symbols needed to be selected and aggregated was established by evaluating manually-produced geological maps at the same scale and by consulting a cartographer. A distance of 0.5 cm on the geological map was initially suggested as the most appropriate for the target scale. To work in map units, e.g., metres on the ground, the equivalent acceptable distance to avoid symbol cluttering on a 1:50,000 geological map was set at 250 m. This distance, however, can be easily modified because it is an input parameter of the generalization routine.

The final geological map at the target scale, 1:50,000, has been evaluated visually by geologists and cartographers who have determined how successfully the process and the operations had been in satisfying the research objectives.

7.3.1 The Radical Law

To determine how many bedding symbols should be retained at the target scale has been the first question that has been posed. The *Radical Law* of Topfer and Pillewizer (1966) provides a means for determining the number of source scale objects belonging to a particular theme that should be retained on a map undergoing scale reduction, based on the number of objects in the source map, the source scale and the target scale.

The radical law is an empirical formula that allows computation of the number of objects of the source map that should be maintained in the target map:

$$nt = ns \times \sqrt{\frac{ss}{st}} \qquad \textbf{(7.1)}$$

nt is the number of objects at the target scale, *ns* is the number of object at the source scale, *ss* is the source scale, and *st* is the target scale.

The radical law only expresses the number of objects to maintain, but provides no information about the choice of objects. However, if linked with the attributes of a feature class, it can provide guidance also for the selection of individual symbols.

The radical law was applied to determine the number of bedding symbols that should have been retained at the target scale. When a map is reduced, the available area on paper is reduced accordingly. In the original source scale map (1:25,000) 250 bedding symbols were selected in the test area. According to the radical law, after the generalization process only 175 symbols should have been maintained on the geological map at the target scale, 1:50,000, as shown below:

$$nt = 250 \times \sqrt{\frac{25000}{50000}} = 250 \times \sqrt{\frac{1}{2}} = 250 \times 0.7 = 175$$

7.3.2 Circular statistics

Circular or directional statistics is the sub-discipline of statistics that deals with circular or directional data, like the compass directions of the strike measurements. The fact that 0° and 360° are identical angles, so that for example 190° is not the mean of 40° and 340°, provides one illustration that special statistical methods are required for the analysis of circular data. The fundamental insight is that such data are often best handled not as numbers, but as unit vectors, as shown in Figure 7.19.

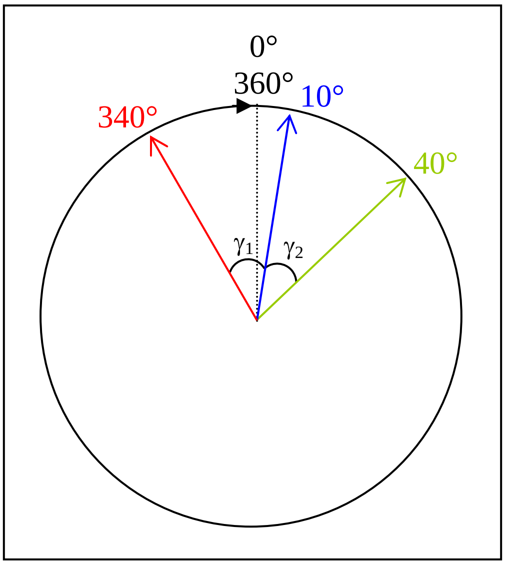


Figure 7.19. A characteristic of directional data is that the mean of 40° (green vector) and 340° (red vector) is not 190° but 10° (blue vector). Note that γ_1 is equal to γ_2.

7.3.2.1 Difference of angles

Classic algebra and statistics are in general not appropriate to analyze angle values and circular data. The generalization system proposed in Section 7.4 selects clusters of bedding symbols and verifies whether their values of strike and dip angles are in a range of $\pm 15°$ the value of the centroid of the cluster of symbols (see Figures 7.20 and 7.21 and Section 7.4 for a full explanation of the generalization system).

Dip angles range from 0° (horizontal layers) to 90° (vertical layers) while strike directions range from 0° to 360° (actually, because we are dealing with round angles, 0° and 360° are identical angles as shown in Figure 7.19 and the value of 360° is never used).

Therefore, while it is possible to use classical algebra, e.g. the algebraic difference operation, to control whether the value of dip is within or outside the range of +/- 15°, this is not possible with the strike angle. For instance, if we have a set of angle values of 10°, 20° 35° and 355° and we want to verify which values are within the range of +/- 15° of the centroid that has a value of 5°, with the classic algebra we would select just the value of 10° and 20°, missing the value of 355°. This problem arises only when in the same set of selected symbols are included symbols with an angle value $\leq$ 15° or $\geq$ 345°. In this case, a procedure is needed to select correctly the bedding symbols. The algorithm can be easily implemented in a scripting language, such as Python® in ArcGIS®, or in a routine using *IF … THEN* conditions.

Say θ is the value of the angle we want to add or subtract to the strike angle value of the centroid, α_c is the angle value of the strike direction of the centroid of the cluster of symbols, α_n are the angle value of the strike directions of the other bedding symbols and dSTRIKE is an attribute table item where a temporary value of strike is archived for the difference calculation, then the following algorithm can be applied:

$$\begin{aligned} &IF\ (\alpha_n \leq \theta\ AND\ \alpha_n \geq (360-\theta))\ AND\ (\alpha_c \leq \theta\ OR\ \alpha_c \geq (360-\theta)) \\ &THEN\ \ SELECT\ \alpha_n \geq (360-2\theta) \\ &\qquad\quad SET\ dSTRIKE = \alpha_n - 360 \end{aligned} \qquad \textbf{(7.2)}$$

The selection operation can then be performed on the values stored in the dSTRIKE attribute. For instance, using the set of angle values listed above, 10°, 20°, 35° and 355°, with the centroid having an angle value of 5°, we have to apply the Algorithm 7.2. The angle value of 355° is then calculated as:

$$\alpha_n - 360 = 355 - 360 = -5$$

It is therefore this value that is used correctly when we want to control if a symbol has a angle value of strike in the range of +/- 15° the angle value of the centroid.

When the average operation is performed on the selected symbols, the average value of the strike angle to be assigned to the centroid needs to be calculated using the Equations 7.3 to 7.8.

7.3.2.2 Average of angles[2]

Much geological data involve not only directions in the plane but spatial directions as well. Strike and dip angle values can be expressed as a unit normal vector to the plane, so that their endpoints all lie on the surface of a sphere with unit radius. We need to use a 3D Cartesian coordinate system to describe the unit vectors as shown in Figure 7.20. Thus, any vector *V* is uniquely determined by the triplet (*x*,*y*,*z*).

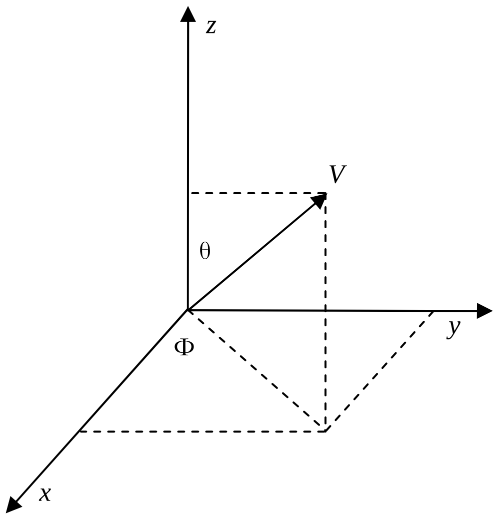


Figure 7.20. The relation between the Cartesian and spherical coordinate systems. (Redrawn after Wolfe, 2001).

We could also use spherical angles θ (colatitude) and ϕ (longitude) to specify the vector direction. We can relate the Cartesian coordinates and the spherical angles as follows:

$$\begin{aligned} x &= \sin\theta\cos\phi \\ y &= \sin\theta\sin\phi \\ z &= \cos\theta \end{aligned} \qquad \textbf{(7.3)}$$

However, geological measurements like strike and dip angles follow their own convention. We define a new local coordinate system in which *x* points toward north, *y* points east, and *z* points vertically down (in order to maintain a right-handed coordinate system). For the plane in Figure 7.21 we find that the angle *A* is the azimuth of the strike of the plane, and *D* is the dip, measured positive down. The vector *OP* is then given by its components:

[2] This Sub-section has been extracted and adapted after the work of Wolfe (2001).

$$x = -\sin(A)\cos(D)$$
$$y = \cos(A)\cos(D) \quad \textbf{(7.4)}$$
$$z = \sin(D)$$

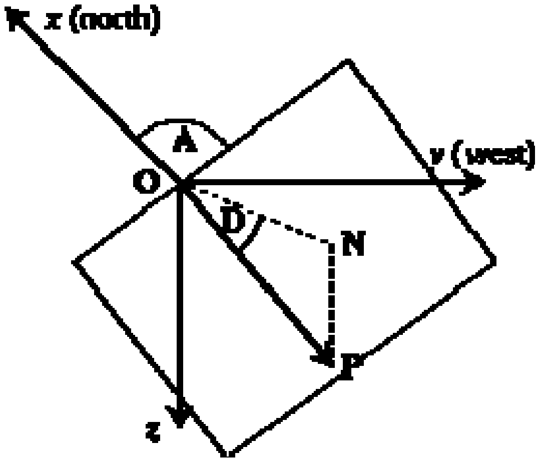


Figure 7.21. Local, right-handed coordinate system shows the convention used in structural geology. *A* is the strike of the dipping plane, and *D* is its dip. (Source: Wolfe, 2001).

Once we have converted our (*A*, *D*) data to (*x*,*y*,*z*) we can compute such quantities as mean direction. The length of the resultant vector is simply:

$$R = \sqrt{\left(\sum x_i\right)^2 + \left(\sum y_i\right)^2 + \left(\sum z_i\right)^2} \quad \textbf{(7.5)}$$

Equation 7.5 is usually normalized as:

$$\bar{R} = \frac{R}{n} \quad \textbf{(7.6)}$$

The coordinates $\bar{x}, \bar{y}$ and $\bar{z}$ of the mean vector are then:

$$\bar{x} = \sum \frac{x_i}{R}$$
$$\bar{y} = \sum \frac{y_i}{R} \quad \textbf{(7.7)}$$
$$\bar{z} = \sum \frac{z_i}{R}$$

The mean strike and dip angles are then given by:

$$\overline{D} = \arcsin(\overline{z})$$
$$\overline{A} = \arctan\left(\frac{-\overline{x}}{\overline{y}}\right) \qquad \textbf{(7.8)}$$

Where $\overline{D}$ is the average dip angle value and $\overline{A}$ is the average strike angle value.

These equations can be easily implemented in a scripting language, such as Python® in ArcGIS® software application.

7.4 The rule-based system and the generalization process

The rule-based system and the routine used for the generalization operations are described in a schematic view in Figure 7.22. Table 7.1 summarizes the main operations carried out by the generalization process of the bedding symbols that will be fully described in detail later in this Section.

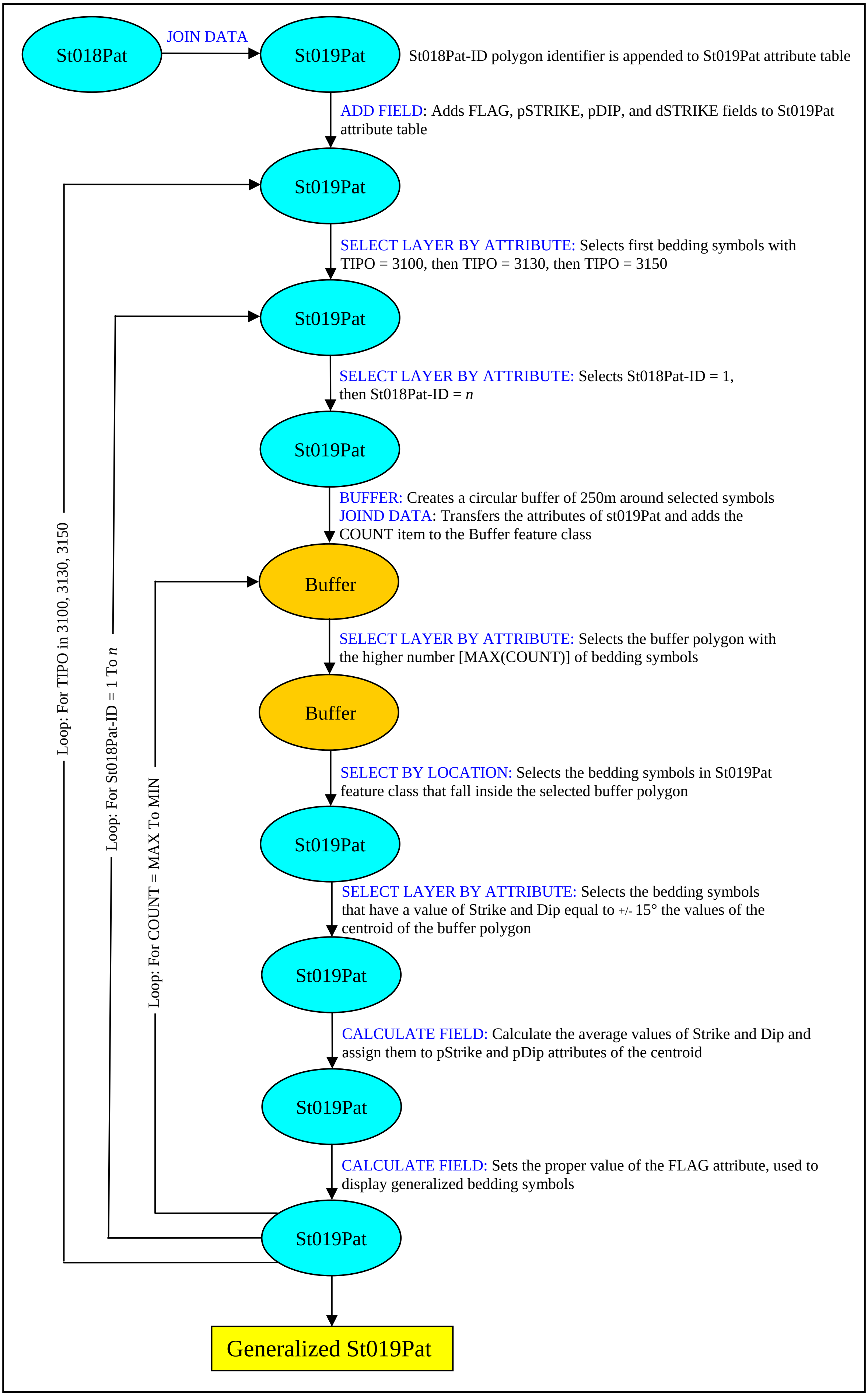


Figure 7.22. A schematic view of the generalization process of the bedding symbology. For the full explanation see Table 7.1. In blue, ArcGIS commands.

Table 7.1. Simplified summary of the main operations carried out by the generalization process of the bedding symbology.

ArcGIS® COMMAND	EFFECT	NOTE
Join Data	Appends St018Pat-ID polygon identifier to St019Pat attribute table	Any bedding symbols are assigned the unique identifier (ID) value of the St018Pat polygon (geological and stratigraphic information) that contains them. In this way, any symbol can be selected according to the polygon, e.g., le geological formation, that contains it, and aggregated according the unique value of St018Pat-ID.
Add Field	Adds 4 fields to St019Pat attribute table	Fields FLAG, pSTRIKE, pDIP, and dSTRIKE are added to St019Pat attribute table for the generalization process. See Table 7.4 for the full description of the fields.
Select Layer by Attribute	Selects TIPO = 3100 or TIPO = 3130 or TIPO = 3150 in St019Pat	Select only bedding symbols in St019Pat feature class. The generalization procedure generalizes routinely at first bedding symbols with TIPO = 3100, then bedding symbols with TIPO = 3130, and at the end bedding symbols with TIPO = 3150. See Table 7.3 for further information.
Select Layer by Attribute	Selects St018Pat-ID = 1	The routine starts selecting in St019Pat feature class the symbols that are contained in the polygon with ID = 1 of St018Pat. In the next iterations, the points contained inside any other polygon are selected. On a geological map, bedding measurements are related to the bedrock outcrops or the geological formations where the structural stations are established. Symbols inside the generalization distance but belonging to a different formation, e.g., belonging to different digital polygons in a GIS system, must not be selected and aggregated, because strike and dip values are referred to different geological objects.
Buffer	Creates a circular buffer of 250 m around any selected bedding symbol of St019Pat	A new buffer feature classes is created for any selected group of bedding symbols. The attributes of St019Pat are transferred to the buffer feature class.
Join Data	Transfers the attributes of St019Pat and adds the item COUNT to the buffer feature class.	The number of points that are completely within any buffer polygon are quantified. The COUNT attribute contains the number of bedding symbols inside any buffer circle.
Select Layer by Attribute	Selects COUNT > 1 in the buffer feature class	Buffer polygons with COUNT = 1 are excluded because they contain just one point, e.g., the bedding symbol around which the buffer polygon has been generated.
Select Layer by Attribute	Selects MAX(COUNT) in the buffer feature class	The buffer polygon with the higher value of COUNT is selected. If more polygons are selected, the first one in the attribute table is chosen. A higher value of COUNT indicates a higher probability of symbol overcrowding.
Select by Location	Selects the points of St019Pat that are inside the selected buffer polygon	All the bedding symbols of St019Pat that are inside the selected polygon of the buffer feature class are selected. These points will be used in the generalization operations.
Select Layer by Attribute	Selects the point with St018Pat-ID equal to the buffer polygon identifier	The system selects in St019Pat feature class the centroid of the selected buffer polygon. The centroid has the St019Pat-ID identifier equal to the buffer polygon identifier. The average values of strike and dip will be assigned only to the centroids of the buffer polygons.
Select Layer by Attribute	Selects the points of St019Pat where FLAG attribute is null	Any bedding symbol that has been previously used in an average (generalization) operation is excluded from any further selection.
Select Layer by Attribute	Selects the points of St019Pat where the values of strike and dip = ± 15° the values of the centroid of the buffer polygon	The bedding symbols that have the values of strike and dip equal to ± 15° the values of the centroid of the buffer polygon, e.g., the point at the centre of the buffer polygon, are selected. These symbols will be used to calculate the average values that will be assigned separately to the pSTRIKE and pDIP attributes of the centroid.
Calculate Field	Assigns the average values of strike and dip to pSTRIKE and pDIP.	The average strike and deep values are calculated using Equations 7.3 to 7.8 shown in Sub-section 7.3.2.2. The angle values are assigned to the pSTRIKE and pDIP attributes of St019Pat. Both pSTRIKE and pDIP values will be used to plot the bedding symbols.
Calculate Field	Sets the proper value of FLAG.	The proper value of the FLAG attribute is set. See Table 7.4 for further detailed information.
Select Layer by Attribute	Selects the points of St019Pat with FLAG=1 or FLAG=2	Only bedding symbols with FLAG value equal to 1 or 2 are plotted on the geological map, rotated according the value of pSTRIKE and labelled with the value of pDIP. Points with FLAG = 0 are excluded from the visual representation, besides they are maintained in the database.

Loop: For TIPO in 3100, 3130, 3150

Loop: For St018Pat-ID = 1 To *n*

Loop: For COUNT = MAX To MIN

St018Pat is the geological feature class containing the geological and stratigraphic information, while St019Pat contains the Geological Observation points. The St019Pat attribute table is shown in Table 7.2.

Only points with attribute TIPO = 3100 OR 3130 OR 3150 have been selected and extracted to test the generalization system as shown in Figure 7.23. Each set of symbols is processed separately by the generalization system, for it represents different geological objects undergoing different geological processes.

Table 7.2. The scheme of the Geological Observation Stations attribute table. Geometry: Points. In red, the translation in English.

CAMPO (FIELD)	LUNG. (LENGTH)	TIPO (TYPE)	N.DEC (DECIMALS)	NOTE (NOTES)
NUM_OSS	5	I		Codice identificativo univoco e non nullo dell'elemento grafico **(Identifier)**
TIPO	6	I		999 = affioramento s.l. 1000 = affioramento geologico o elemento geomorfologico di particolare interesse 1100 = affioramento di interesse stratigrafico 1110 = località fossilifera 1111 = località fossilifera a vertebrati 1112 = località fossilifera ad invertebrati 1113 = località fossilifera a vegetali 1114 = resti o impronte di tronchi fluitati 1200 = affioramento di interesse sedimentologico 1220 = *slumping* intraformazionale non cartografabile 1300 = affioramento di interesse strutturale 1310 = stazione strutturale (numerata) 1400 = affioramento/località di interesse mineralogico petrografico **3100 = superficie di origine primaria (Normal younging direction)** 3110 = stratificazione orizzontale 3120 = stratificazione verticale **3130 = stratificazione rovesciata (Overturned bedding)** 3131 = stratificazione rovesciata orizzontale 3140 = stratificazione contorta con valori medi di immersione e inclinazione **3150 = stratificazione a polarità sconosciuta (Unknown younging direction)** 3151 = stratificazione verticale a polarità sconosciuta 3152 = stratificazione orizzontale a polarità sconosciuta 3160 = direzione di *younging* 3210 = superficie di clivaggio o scistosità inclinata 3220 = superficie di clivaggio o scistosità orizzontale 3230 = superficie di clivaggio o scistosità verticale 3300 = elementi lineari primari e lineazioni 3310 = elemento lineare primario (struttura sedimentaria, direzione di flusso in rocce ignee) 3311 = elemento lineare primario con direzione e verso (struttura sedimentaria, direzione di flusso in rocce ignee) 3312 = elemento lineare primario verticale 3313 = elemento lineare primario orizzontale 3320 = lineazione (orientazione preferenziale di forma) 3321 = lineazione minerale 3322 = lineazione d'intersezione 3330 = specchio di faglia inclinato 3331 = specchio di faglia visibile verticale 3410 = asse di piega simmetrica 3411 = asse di piega simmetrica (vergenza neutra) orizzontale 3412 = asse di piega simmetrica (vergenza neutra) verticale

				3420 = asse di piega asimmetrica 3421 = asse di piega asimmetrica orizzontale 3430 = inclinazione del piano assiale riferita alla traccia della superficie assiale
TIPOLOGIA	1	I		Informazione facoltativa. 0 = dato mancante 1 = certo 2 = dedotto 3 = incerto 4 = sepolto 9 = non applicabile/non classificabile
STRATO	3	I		Nel caso di correlazione dell'indagine con un oggetto presente in un altro ST è l'identificativo dello ST a cui appartiene l'oggetto correlato.
ID_CORR	5	I		Chiave esterna alla tabella specifica di STRATO. Corrisponde all'ID dell'oggetto a cui è correlata l'indagine, contenuto nello strato informativo identificato in STRATO.
IMMERSIO	3	I		Misura in gradi da 0 a 360 della direzione di immersione della superficie. Si applica alla famiglia di TIPO > 3000.
DIREZIO **(STRIKE)**	3	I		Misura in gradi da 0 a 360 direzione della superficie (per inclina = 90). Si applica alla famiglia di TIPO > 3000. **(Measure in degree ranging from 0 to 360 of the direction of the surface)**
INCLINA **(DIP)**	2	I		Misura in gradi da 0 a 90 dell'inclinazione della superficie. Porre 99 quando non applicabile/non classificabile. Si applica alla famiglia di TIPO > 3000. **(Measure in degree ranging from 0 to 90 of the dip of the surface)**
QUOTA	12	F	3	Quota in metri. Numero con 3 cifre decimali
METODO	64	C		Nota relativa alla tecnica di misura della quota quando questa non è ricavata dalla carta topografica

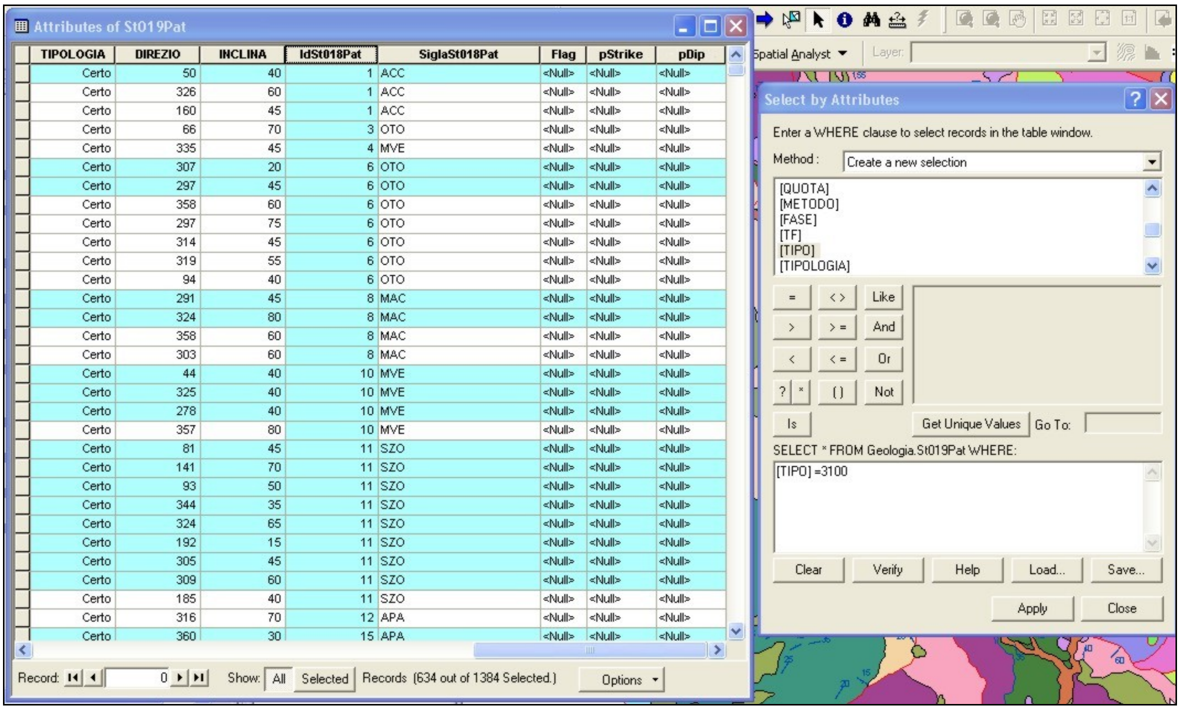


Figure 7.23. The Select by Attribute windows in ArcGIS®. Selected records for TIPO = 3100 are highlighted in cyan.

The symbology used for the bedding measurements is shown in Table 7.3. It complies with the standards of the Geological Survey of Italy (Servizio Geologico d'Italia, 1996) for the CARG Project (see Section 5.5.2).

Table 7.3. The bedding symbology selected to test the proposed system (See also Table 7.2 for a detailed description of the symbology).

Symbol	Colour	TIPO	Description
	Blue	3100	Normal younging direction
	Black	3130	Overturned bedding
	Red	3150	Unknown younging direction

The source scale geological map with the official bedding symbology is shown in Figure 7.24. The projection that has been used is the Universal Transverse of Mercator, European Datum 1950, Zone 33.

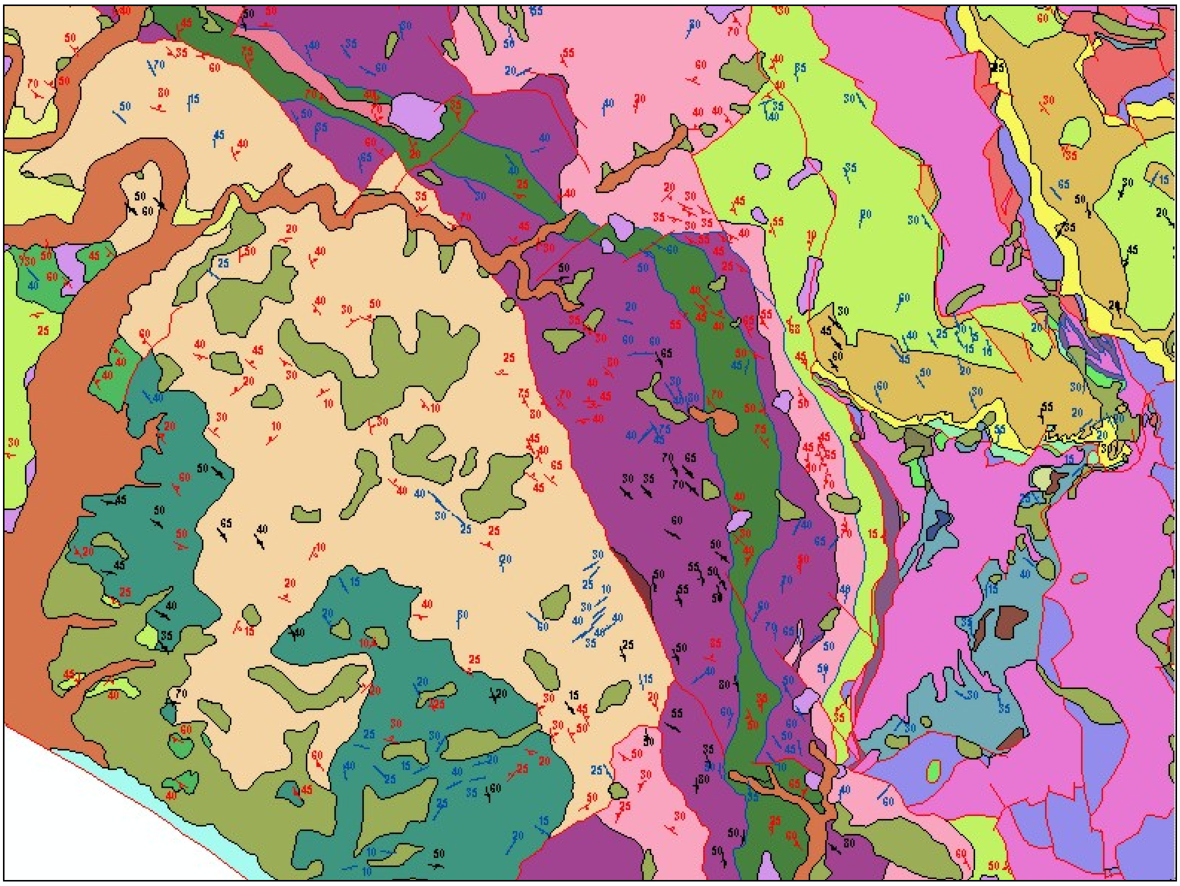


Figure 7.24. The original geological sheet of Sestri Levante before the generalization process. Projection Universal Transverse of Mercator, European Datum 1950, Zone 33, *XY* coordinates domain has *x*-min: 527360, *y*-min: 4904888, *x*-max: 537732, *y*-max: 4912586.

Figures 7.25 shows separately the bedding symbology classified by the TIPO (Type) attribute. The bedding symbology is rotated according to the value of strike recorded in the DIREZIO (Strike) attribute. The value labelled close to each symbol shows the dip value archived in the INCLINA (Dip) attribute.

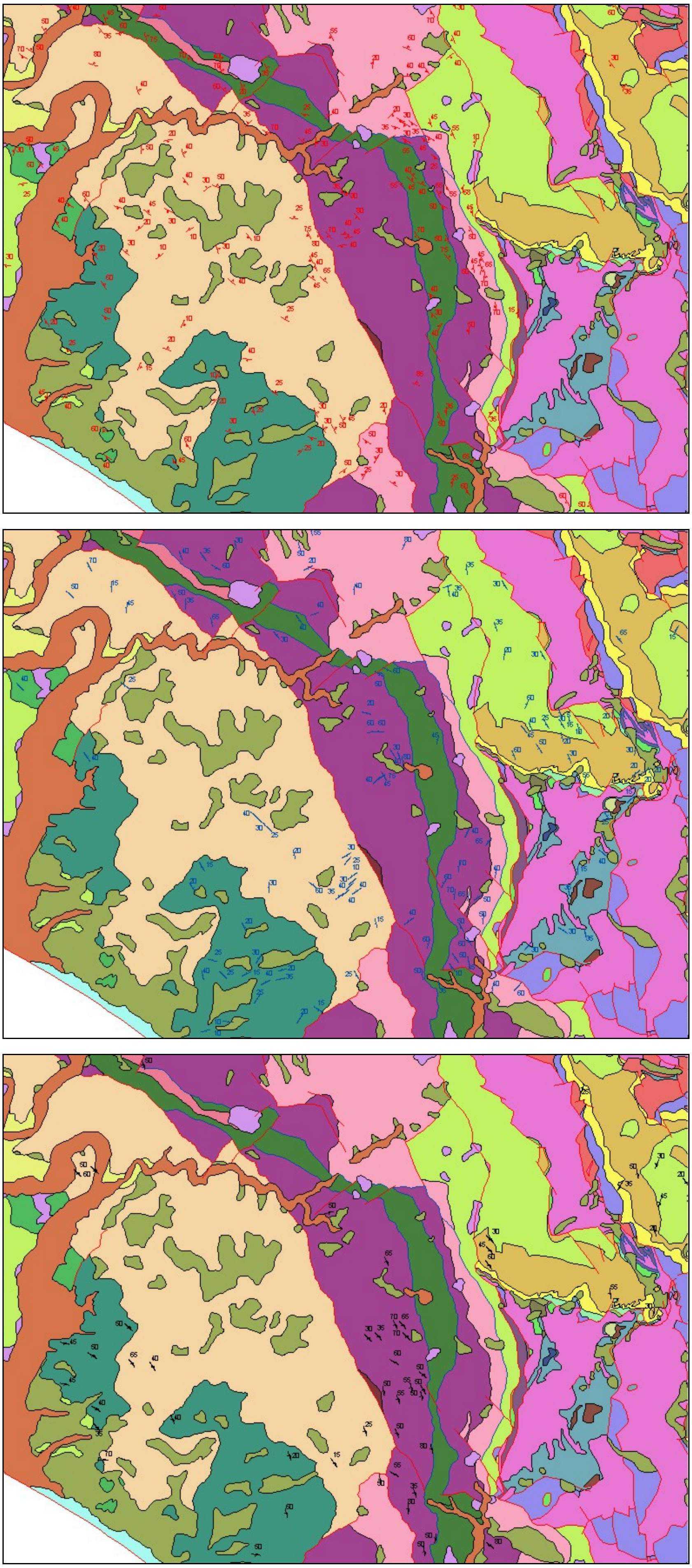


Figure 7.25. Top: TIPO = 3100 (Normal younging direction), Centre: TIPO = 3130 (Overturned bedding), Bottom: TIPO = 3150 (Unknown younging direction).

ArcGIS® places labels (e.g., the value of the dip angle) automatically according to an internal engine in the most suitable position around the bedding symbol in order to avoid labels overlapping. Therefore, this problem has not been dealt in the present work. Moreover, Italian geological maps do not comply with the international convention to place the dip value along the dip direction line of the bedding symbol. Labels can be placed in any position along an imaginary circle of specified radius built around the centroid of the symbol, avoiding overlapping with the symbol itself.

Figure 7.26 shows an example of automatic label placements around bedding symbology. Overlapping between the labels and the bedding symbols themselves can be avoided specifying an offset distance.

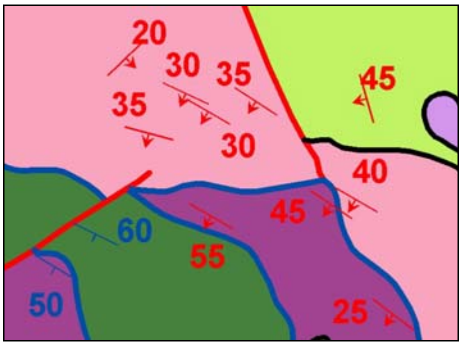


Figure 7.26. Automatic labels (dip angles) placement around bedding symbology using the ArcGIS internal engine to avoid labels overlapping.

In a geological map, structural information is not uniformly placed. Geological observation stations are usually set where the bedrock outcrops or where a particular geological phenomenon has been observed. In these areas more measurements are gathered, and this explains while the symbology may be very dense in some areas while appears quite sparse in most of the others.

On a geological map, bedding measurements are related to the bedrock outcrops or the geological formations where the structural stations are established. Symbols inside the generalization distance but belonging to a different formation (see Chapter 6 for an exhaustive description of the term *formation*), e.g., belonging to different digital polygons in a GIS system, must not be selected and aggregated, because strike and dip values are referred to different geological objects. This is the case where symbols may be close to the boundary between two distinct formations. Furthermore, if a same formation is traversed by a fault, e.g., it is split in two or more different polygons, we can select and aggregate symbols contained only inside any distinct polygon, because the fault could have tilted or displaced the different blocks, therefore creating different geological objects. Also in this case, strike and dip symbols should be neither generalized nor averaged.

In order to overcome this problem, to any bedding symbol it has been assigned the unique identifier (ID) value of the polygon that contained it. St019Pat feature class has therefore been merged with St018Pat feature class, which contains the geological and stratigraphic information. From the attribute table of St018Pat, St018Pat-ID item has then been transferred to St019Pat. In this way, any symbol can be selected according to the polygon that completely contains it, and aggregated according to the unique value of St018Pat-ID.

An assumption of the rule-based system is that the original information in the database must not be altered, eliminated or modified. In order to generalize the values of the DIREZIO (Strike) and INCLINA (Dip) attributes, the generalized values must be recorded in new items. Six new items were added to the scheme of the original attribute table of St019Pat feature class as shown in Table 7.4.

Table 7.4. Added items to St019Pat attribute table.

CAMPO	LUNG.	TIPO	N.DEC	NOTE
FLAG	1	I		0 Point used in an averaging operation 1 Centroid of the buffer area selected for the average operation. Average strike and dip values of the selected symbols that are within the buffer area are assigned to its pSTRIKE and pDIP attributes 2 Point that has not been used in any average operation
pSTRIKE	3	I		Average measure in degrees of the horizontal direction of the surface, clockwise in the range from 0 to 360 when FLAG = 1. Original measure in degrees of the direction of the surface in the range from 0 to 360 when FLAG = 2. Null value when FLAG = 0.
pDIP	3	I		Average measure in degrees of the dip of the surface in the range from 0 to 90 when FLAG = 1. Original measure in degrees of the dip of the surface in the range from 0 to 90 when FLAG = 2. Null value when FLAG = 0.
dSTRIKE	3	I		Item storing the temporary values used to calculate if the selected bedding symbols have the value of strike equal to ± 15° the value of the centroid of the buffer polygon. See Equations 7.2 and Sub-sections 7.3.2 and 7.3.2.1 for a full explanation.

The ArcGIS® buffer command has been used to create a buffer polygon (in this case a circle) at the specified distance of 250 m around any selected group of bedding symbols contained inside any polygon of St018Pat. The command creates a new feature class that will be used in the next operations, to which all the attributes of St019Pat are also transferred. The operation has been performed routinely for any class of bedding symbols defined by the unique value of St018Pat-ID and the value of TIPO = 3100, 3130, and 3150. Figure 7.27 shows the Buffer wizard in ArcGIS®.

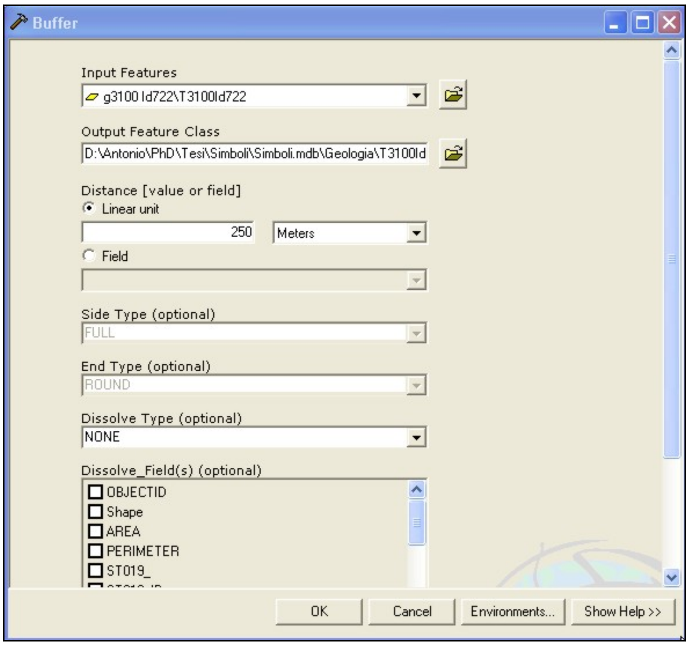


Figure 7.27. The Buffer wizard used to create a new feature class containing the buffer polygons with a radius of 250 m around the selected points with TIPO = 3100 and St018Pat-ID = 722.

The next step is to quantify the number of points that are completely within any buffer polygon with a radius of 250 m and that are contained inside any single St018Pat polygon. This has been obtained using the JOIN DATA function that transfers the attributes of St019Pat and add the item COUNT to the buffer feature class. COUNT contains the number of features, e.g., points, inside any buffer circle. Polygons with a COUNT > 1 are then selected for the generalization process. Any buffer polygons with COUNT=1 are excluded, because they contain just one point, e.g., the bedding symbol around which the buffer circle has been generated, and no other point in a radius of 250 m. The central points around which the buffer polygons have been generated are the centroids of the polygons. Figure 7.28 shows the Join Data wizard, while Figure 7.29 shows the result of the operation.

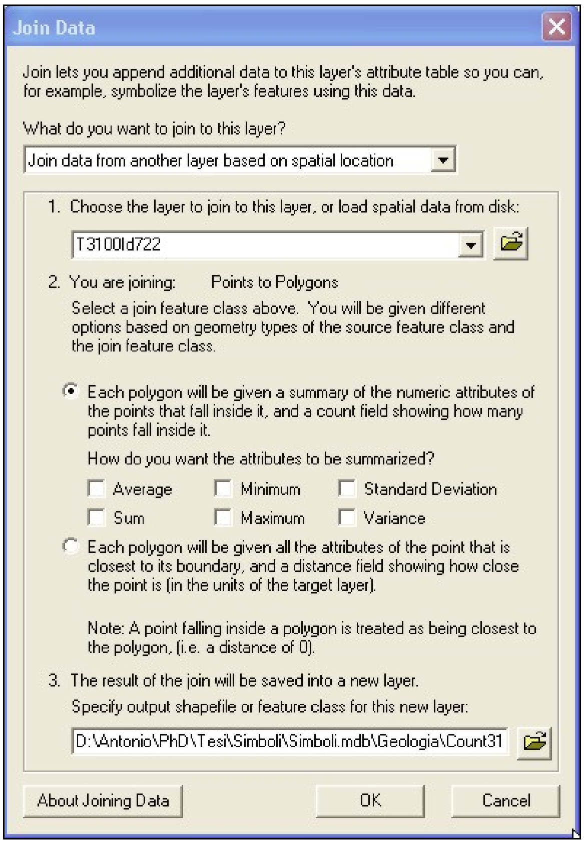
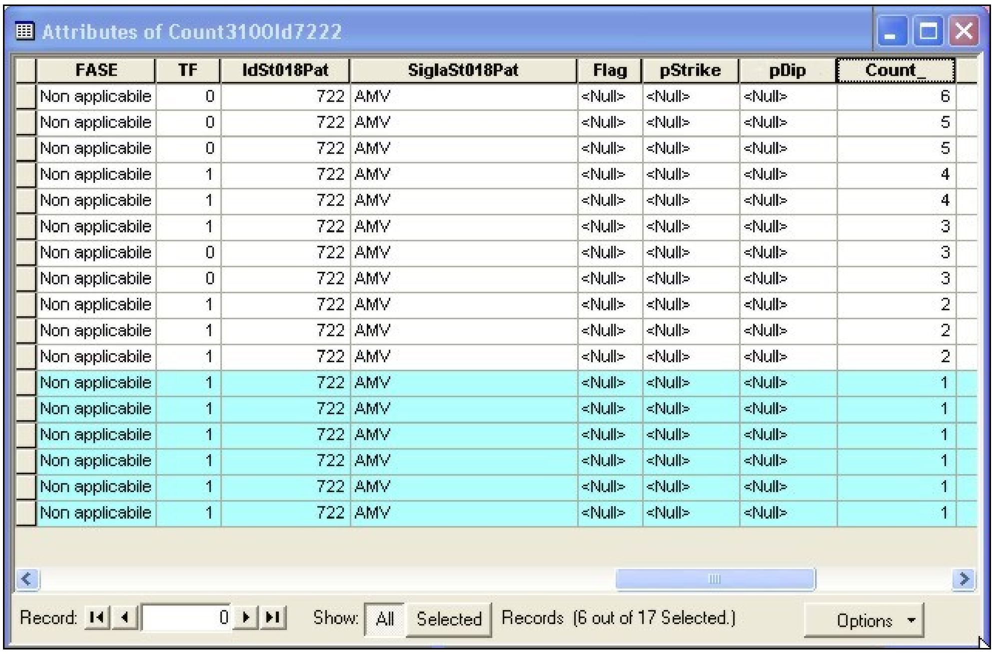


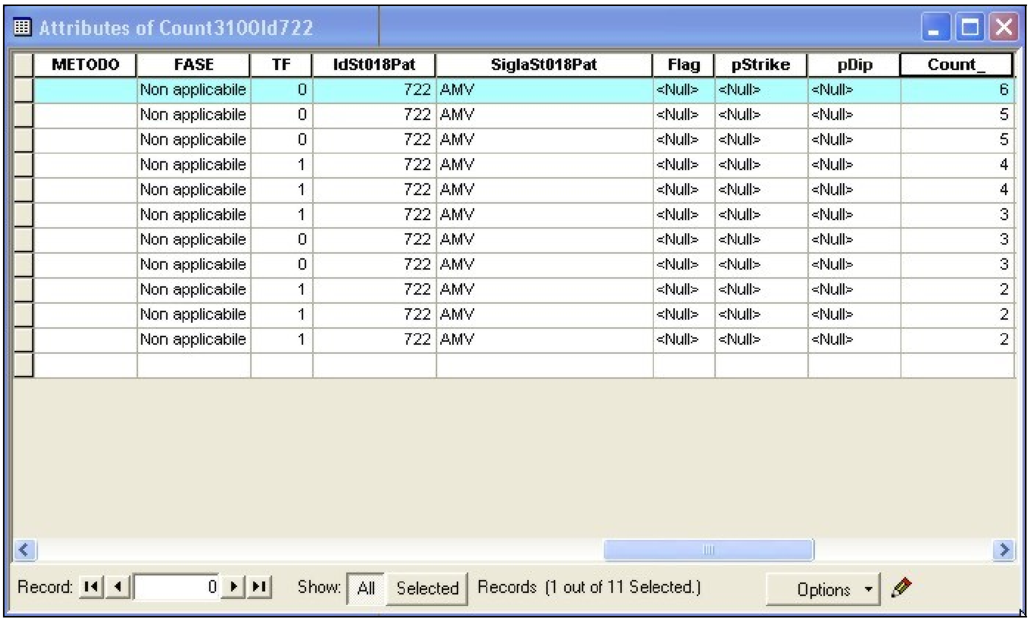
Figure 7.28. The Join Data command used to give to the buffer feature class a summary of the numeric attributes of the points that fall inside each buffer polygon.



FASE	TF	IdSt018Pat	SiglaSt018Pat	Flag	pStrike	pDip	Count_
Non applicabile	0	722	AMV	<Null>	<Null>	<Null>	6
Non applicabile	0	722	AMV	<Null>	<Null>	<Null>	5
Non applicabile	0	722	AMV	<Null>	<Null>	<Null>	5
Non applicabile	1	722	AMV	<Null>	<Null>	<Null>	4
Non applicabile	1	722	AMV	<Null>	<Null>	<Null>	4
Non applicabile	1	722	AMV	<Null>	<Null>	<Null>	3
Non applicabile	0	722	AMV	<Null>	<Null>	<Null>	3
Non applicabile	0	722	AMV	<Null>	<Null>	<Null>	3
Non applicabile	1	722	AMV	<Null>	<Null>	<Null>	2
Non applicabile	1	722	AMV	<Null>	<Null>	<Null>	2
Non applicabile	1	722	AMV	<Null>	<Null>	<Null>	2
Non applicabile	1	722	AMV	<Null>	<Null>	<Null>	1
Non applicabile	1	722	AMV	<Null>	<Null>	<Null>	1
Non applicabile	1	722	AMV	<Null>	<Null>	<Null>	1
Non applicabile	1	722	AMV	<Null>	<Null>	<Null>	1
Non applicabile	1	722	AMV	<Null>	<Null>	<Null>	1
Non applicabile	1	722	AMV	<Null>	<Null>	<Null>	1

Figure 7.29. The attribute table of the buffer feature class with the attributes transferred from St019Pat and the COUNT item. Records with COUNT = 1 (highlighted in cyan) must be unselected.

The system now selects the buffer polygon with the higher value of COUNT. A higher value of COUNT indicates a possible symbol overcrowding. If more than one record is selected, the first one in the attribute table is chosen. In the example of Figure 7.30, the first selected polygon has a value of COUNT = 6.



Attributes of Count3100Id722

METODO	FASE	TF	IdSt018Pat	SiglaSt018Pat	Flag	pStrike	pDip	Count_
	Non applicabile	0	722	AMV	<Null>	<Null>	<Null>	6
	Non applicabile	0	722	AMV	<Null>	<Null>	<Null>	5
	Non applicabile	0	722	AMV	<Null>	<Null>	<Null>	5
	Non applicabile	1	722	AMV	<Null>	<Null>	<Null>	4
	Non applicabile	1	722	AMV	<Null>	<Null>	<Null>	4
	Non applicabile	1	722	AMV	<Null>	<Null>	<Null>	3
	Non applicabile	0	722	AMV	<Null>	<Null>	<Null>	3
	Non applicabile	0	722	AMV	<Null>	<Null>	<Null>	3
	Non applicabile	1	722	AMV	<Null>	<Null>	<Null>	2
	Non applicabile	1	722	AMV	<Null>	<Null>	<Null>	2
	Non applicabile	1	722	AMV	<Null>	<Null>	<Null>	2

Record: 0 Show: All Selected Records (1 out of 11 Selected.) Options

Figure 7.30. The system selects the first polygon with the higher value of COUNT.

In the following step of the procedure, all the points of St019Pat that *are completely within* the selected polygon of the buffer feature class are selected using the *Select By Location* wizard of ArcGIS®, as shown in Figure 7.31.

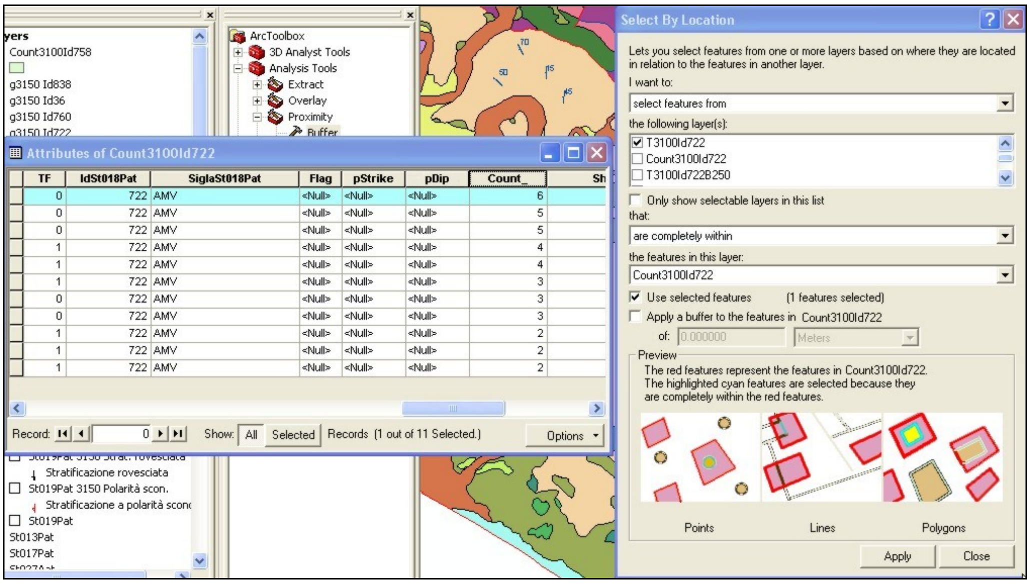


Figure 7.31. The Select By Location command and the attribute table of a buffer polygon feature class.

The resulting selected points will be used for the generalization operation that is performed in one of the following steps. The system then selects the centroid of the buffer polygon, e.g., the point around which the circle with the radius of 250 m has been generated, which has the ID equal to the ID of the buffer polygon. The average values of the strike and dip attributes are indeed assigned by the system only to the centroid of the buffer polygon.

According to the panel of experts mentioned in Section 7.5, in the broader case, the correct methodology to generalize a set of cluttered bedding symbols is to select the symbols that have the values of strike and dip equal to $\pm 15°$ the values of the more representative symbol in the cluster, e.g., usually the central point, chosen in a subjective and aesthetic way by the cartographer. Because we are dealing with an automatic system, the concept of *more representative symbol* is very vague, and it cannot be easily translated into a set of rules. It has been therefore decided to consider the centroid of the buffer polygon in which the symbols are contained as a more representative symbol of a cluster of symbols in which the symbols are contained. The compromise has been accepted by the experts, as well as the selection of the buffer polygon with the higher number of COUNT as first polygon for the generalization process, e.g., the one where symbols are more cluttered.

The value of 15°, used commonly by the SGN during the manual generalization of bedding symbology, represents the measure error corresponding to about the 5% of a round angle (360°) and has been estimated as adequate for the generalization process by the panel of experts. Anyway, any value can be used in the system for it is an input parameter of the generalization routine.

However, because we are dealing with directional data, e.g., the angle value of the bedding measurements, classic algebra and statistics are in general not appropriate to analyze such values, because this type of data are best handled not as numbers, but as unit vectors.

To this end, in Sub-section 7.3.2.1 the Algorithm 7.2 was introduced to explain how to select the bedding symbols that have the value of strike equal to $\pm 15°$ the value of the centroid of the buffer polygon. The calculated *ad hoc* values are stored as temporary values in the dSTRIKE item of St019Pat attribute table and are used in the comparison routine.

Also the average angle value of the strike measurements cannot be calculated using classical algebra and statistics. For this purpose, the set of Equations 7.3 to 7.8 of Sub-section 7.3.2.2 have been introduced to calculate the average strike and dip angle values of the symbols selected through the Algorithm 7.2. Both average angle values are then assigned to the centroid of the buffer polygon, while the others symbols are removed from any further selection and then from the representation.

Figure 7.32 shows the selected points of St019Pat that are completely within the buffer polygon with COUNT = 6.

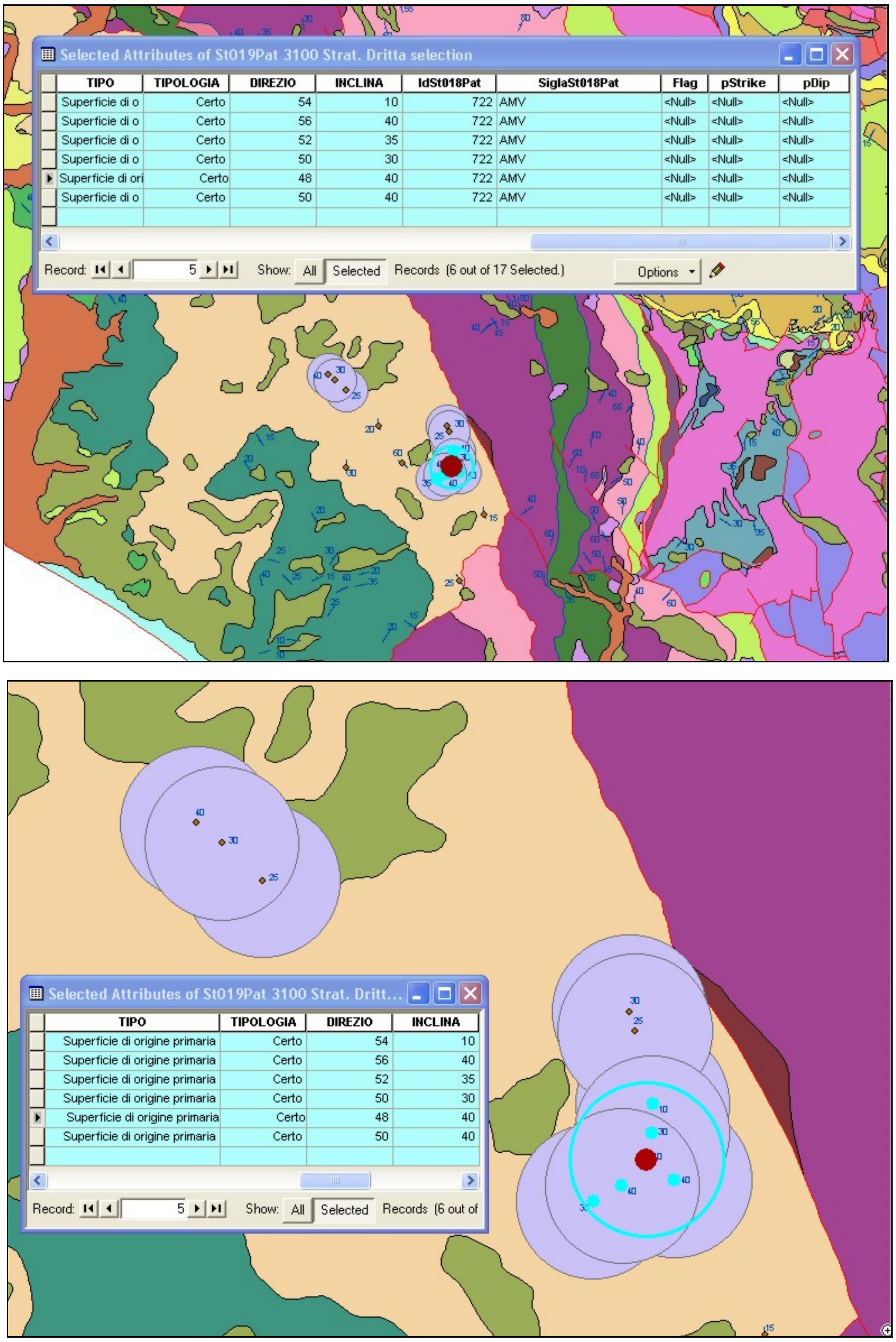


Figure 7.32. Top: Bedding features of St019Pat completely within the buffer polygon with COUNT = 6. Bottom: An enlargement of the area is shown on left. The point in brown represents the centroid of the selected buffer polygon highlighted in cyan. In the attribute table, the attributes of the centroid are highlighted by the right arrow shown in the first column of the table.

According to our selection, aggregation, and generalization criteria, a point that has been used in an average operation is excluded from any other selection. The system therefore checks at first if any FLAG value has been set during a generalization process. Points where FLAG *is not null* are removed from the selection. Because this is the first iteration of the routine, the FLAG value has not been set for any point. Nevertheless, among the selected 6 points shown in Figure 7.32, only the first one in the attribute table does not meet the generalization criteria. It is then removed from the selection as shown in

Figure 7.33 (top) and the average operations are then performed on the remaining five features. The average DIREZIO (strike) and INCLINA (dip) values, calculated using the equations discussed in Sub-section 7.3.2.2, are assigned separately to the pSTRIKE and pDIP attributes of the centroid (the last record in the attribute table). The value of 1 is assigned to the FLAG attribute of the centroid, while 0 is assigned to the other points that have been used to calculate the average value, as shown in Figure 7.33 (bottom).

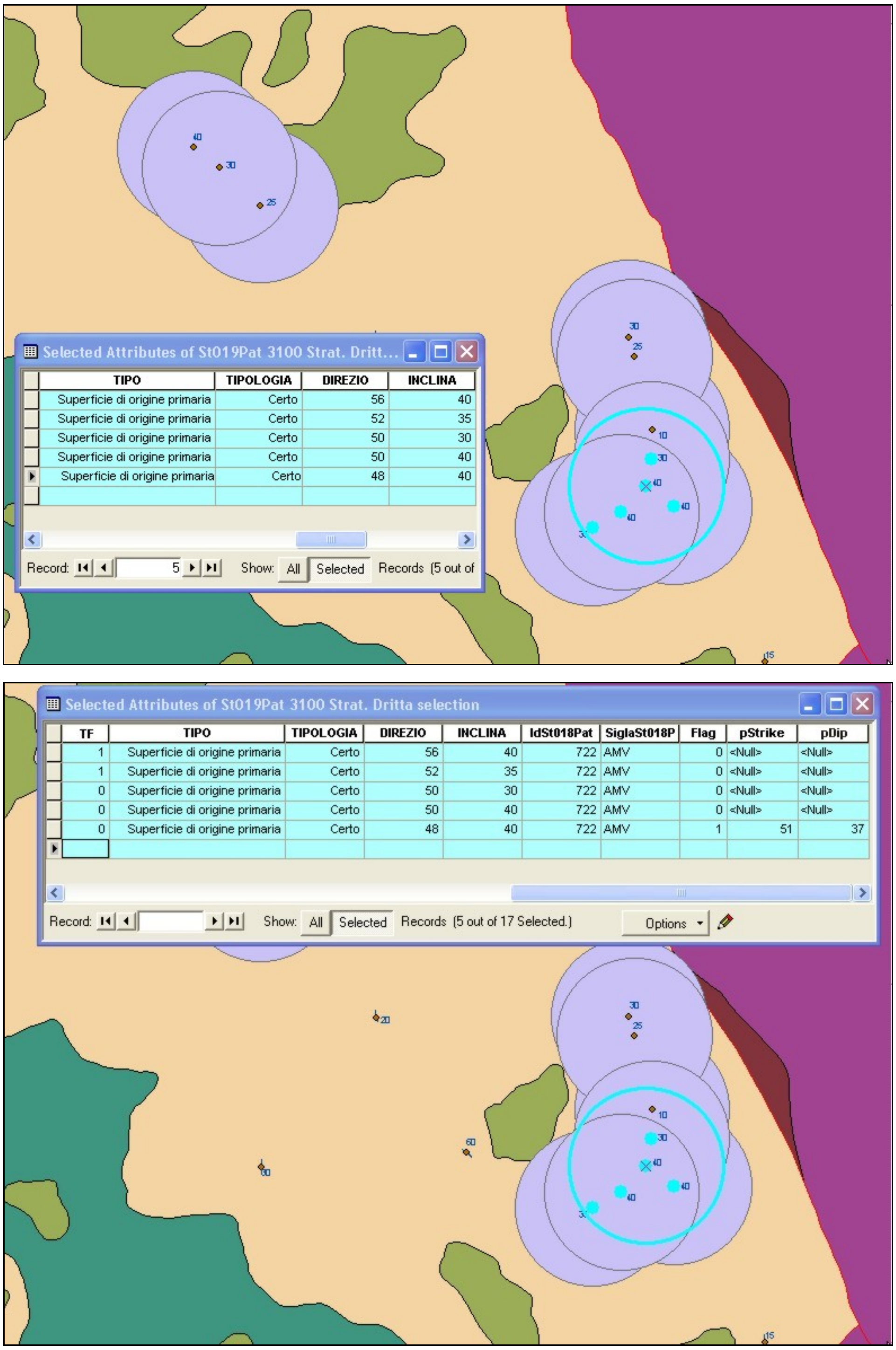


Figure 7.33. Top: The five points that meet the generalization criteria. Bottom: pSTRIKE and pDIP are calculated for the centroid. The FLAG value is set for all the five features.

The next step is the selection of the second record of the attribute table of the buffer polygon feature class with COUNT value equal to 5. The system finds that four out of five points have been already used in an average operation (they have FLAG = 0 or FLAG = 1). Because only one point is available, the system skips the selection and proceeds further. The same happens for the third record of the attribute table, which has again COUNT = 5. All these points have already been included in the first generalization step, when the polygon with COUNT = 6 was selected.

The fourth passage selects the polygon with COUNT equal to 4. In this case two points are available for the average process and meet the generalization criteria. Figure 7.34 shows the second and forth passages of the generalization routine.

Figure 7.34. Top: Second passage of the routine with the selection of the point contained by the buffer polygon with COUNT = 5. No operations are performed. Bottom: Fourth passage of the routine where the buffer polygon with COUNT = 4 is selected. The generalization operation is performed on two points and the average values are assigned to the centroid of the buffer polygon.

The routine continues selecting the records of the buffer polygon feature class according to the values of COUNT ordered in descending order. At the seventh passage, 3 points are completely within the buffer polygon with COUNT equal to 3. None of them meet the generalization criteria. At the eighth passage the system selects 3 points that meet the generalization criteria. The average values are assigned to the centroid. Figure 7.35 shows the seventh and eight iterations of the generalization routine.

No further points are selected during the last three iterations of the routine. The resulting attribute table of the buffer polygon feature class is shown in Figure 7.36.

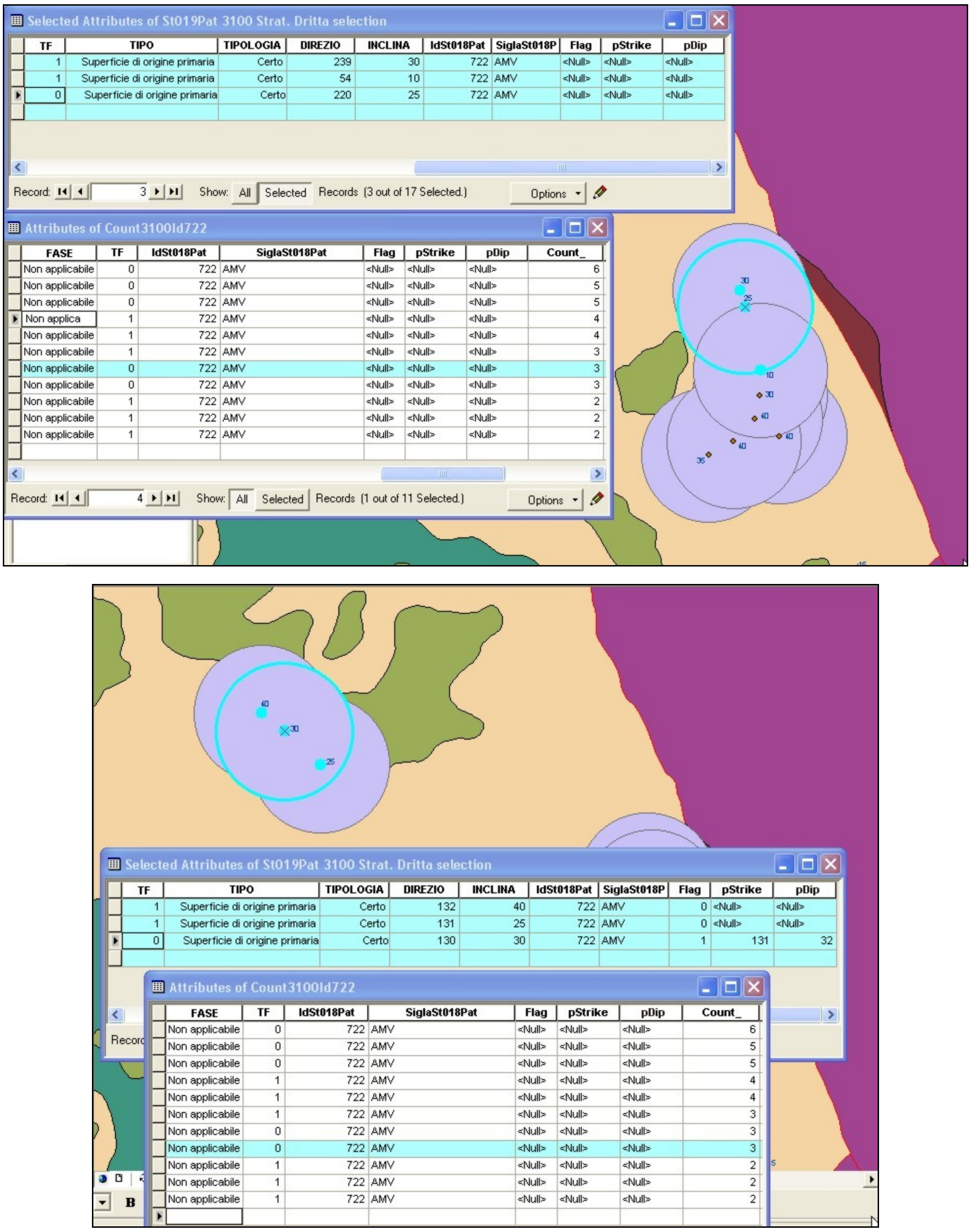


Figure 7.35. Top: Seventh passage of the routine. No point meets the generalization criteria. Bottom: Eight passage: 3 points are selected and averaged. The average values are assigned to the centroid.

Attributes of St019Pat 3100 Strat. Dritta selection

FASE	TF	TIPO	TIPOLOGIA	DIREZIO	INCLINA	IdSt018Pat	SiglaSt018Pat	Flag	pStrike	pDip
Non applicabile	1	Superficie di origine primaria	Certo	306	25	722	AMV	<Null>	<Null>	<Null>
Non applicabile	1	Superficie di origine primaria	Certo	344	15	722	AMV	<Null>	<Null>	<Null>
Non applicabile	1	Superficie di origine primaria	Certo	1	30	722	AMV	<Null>	<Null>	<Null>
Non applicabile	1	Superficie di origine primaria	Certo	330	25	722	AMV	<Null>	<Null>	<Null>
Non applicabile	1	Superficie di origine primaria	Certo	239	30	722	AMV	<Null>	<Null>	<Null>
Non applicabile	1	Superficie di origine primaria	Certo	344	20	722	AMV	<Null>	<Null>	<Null>
Non applicabile	1	Superficie di origine primaria	Certo	128	60	722	AMV	<Null>	<Null>	<Null>
Non applicabile	1	Superficie di origine primaria	Certo	54	10	722	AMV	<Null>	<Null>	<Null>
Non applicabile	0	Superficie di origine primaria	Certo	220	25	722	AMV	<Null>	<Null>	<Null>
Non applicabile	0	Superficie di origine primaria	Certo	48	40	722	AMV	1	51	37
Non applicabile	0	Superficie di origine primaria	Certo	50	40	722	AMV	0	<Null>	<Null>
Non applicabile	0	Superficie di origine primaria	Certo	50	30	722	AMV	0	<Null>	<Null>
Non applicabile	1	Superficie di origine primaria	Certo	52	35	722	AMV	0	<Null>	<Null>
Non applicabile	1	Superficie di origine primaria	Certo	56	40	722	AMV	0	<Null>	<Null>
Non applicabile	0	Superficie di origine primaria	Certo	130	30	722	AMV	1	131	32
Non applicabile	1	Superficie di origine primaria	Certo	132	40	722	AMV	0	<Null>	<Null>
Non applicabile	1	Superficie di origine primaria	Certo	131	25	722	AMV	0	<Null>	<Null>

Record: 1 Show: All Selected Records (0 out of 17 Selected.) Options

Figure 7.36. The attribute table of the buffer polygon feature class after the generalization process.

In order to simplify the plotting of the bedding symbols and their dip value label, the values of DIREZIO and INCLINA for all the points that have not been used in the generalization process are copied into the pSTRIKE and pDIP items. FLAG is set equal to 2 for these records. Points with FLAG = 0 are excluded from the visual representation, besides they are not eliminated from the database.

During the generalization process, the original values of strike and dip of all symbols are maintained in the database. Most geological surveys, in their generalized geological map, do not use averaged bedding measurements but maintain the original values collected by the geologist in the field, just removing the other symbols from the representation. This capability has been provided for the proposed generalization system. The original information is maintained in the DIREZIO (strike) and INCLINA (dip) items and can be used to plot the symbols with FLAG = 1 or FLAG = 2 with their original strike and dip values.

Figure 7.37 shows the final attribute table of the buffer polygon feature class used for the bedding symbols representation.

Attributes of St019Pat 3100 Strat. Dritta selection

FASE	TF	TIPO	TIPOLOGIA	DIREZIO	INCLINA	IdSt018Pat	SiglaSt018Pat	Flag	pStrike	pDip
Non applicabile	1	Superficie di origine primaria	Certo	306	25	722	AMV	2	306	25
Non applicabile	1	Superficie di origine primaria	Certo	344	15	722	AMV	2	344	15
Non applicabile	1	Superficie di origine primaria	Certo	1	30	722	AMV	2	1	30
Non applicabile	1	Superficie di origine primaria	Certo	330	25	722	AMV	2	330	25
Non applicabile	1	Superficie di origine primaria	Certo	239	30	722	AMV	2	239	30
Non applicabile	1	Superficie di origine primaria	Certo	344	20	722	AMV	2	344	20
Non applicabile	1	Superficie di origine primaria	Certo	128	60	722	AMV	2	128	60
Non applicabile	1	Superficie di origine primaria	Certo	54	10	722	AMV	2	54	10
Non applicabile	0	Superficie di origine primaria	Certo	220	25	722	AMV	2	220	25
Non applicabile	0	Superficie di origine primaria	Certo	48	40	722	AMV	1	51	37
Non applicabile	0	Superficie di origine primaria	Certo	50	40	722	AMV	0	<Null>	<Null>
Non applicabile	0	Superficie di origine primaria	Certo	50	30	722	AMV	0	<Null>	<Null>
Non applicabile	1	Superficie di origine primaria	Certo	52	35	722	AMV	0	<Null>	<Null>
Non applicabile	1	Superficie di origine primaria	Certo	56	40	722	AMV	0	<Null>	<Null>
Non applicabile	0	Superficie di origine primaria	Certo	130	30	722	AMV	1	131	32
Non applicabile	1	Superficie di origine primaria	Certo	132	40	722	AMV	0	<Null>	<Null>
Non applicabile	1	Superficie di origine primaria	Certo	131	25	722	AMV	0	<Null>	<Null>

Record: Show: All Selected Records (9 out of 17 Selected.) Options

Figure 7.37. Final attribute table of the buffer polygon feature class used for the bedding symbols representation.

Figure 7.38 shows the result of the generalization process. Red points have been eliminated by the routine, while yellow points are those maintained by the system, either with the original strike and dip values or with the calculated average values.

The final generalized version of the Sestri Levante geological map is presented in Figure 7.39. Bedding symbols are rotated according to the attribute values contained in the added item pSTRIKE, while the pDIP attribute values are used to label the features.

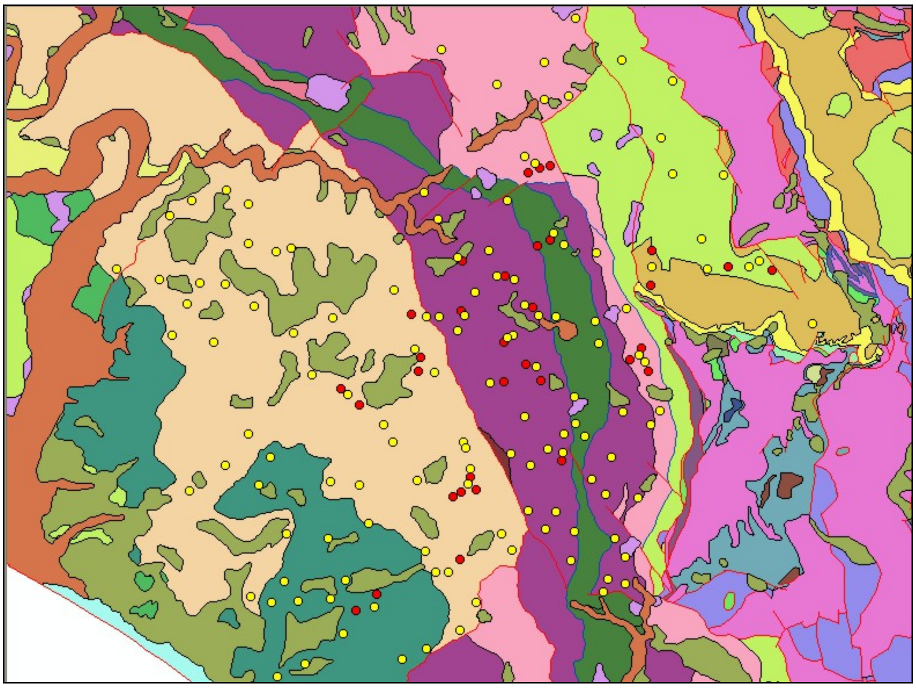


Figure 7.38. Points in red have been eliminated. Points in yellow are those with the average or original strike and dip values.

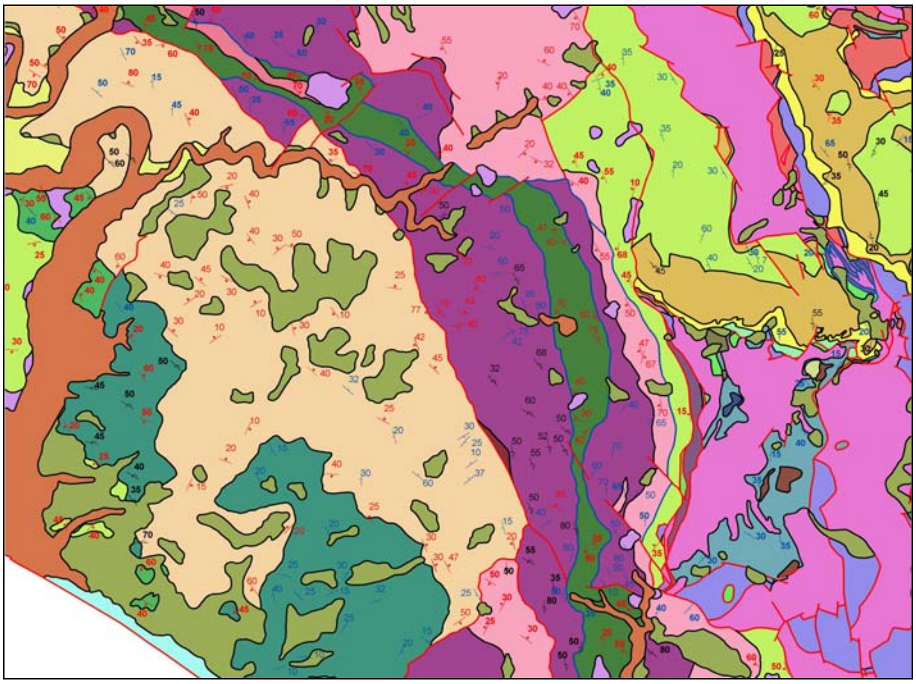


Figure 7.39. The generalized version of the Sestri Levante geological sheet after the application of the generalization procedure.

Figure 7.40 shows three enlargements of the geological map with the bedding symbology before and after the generalization process.

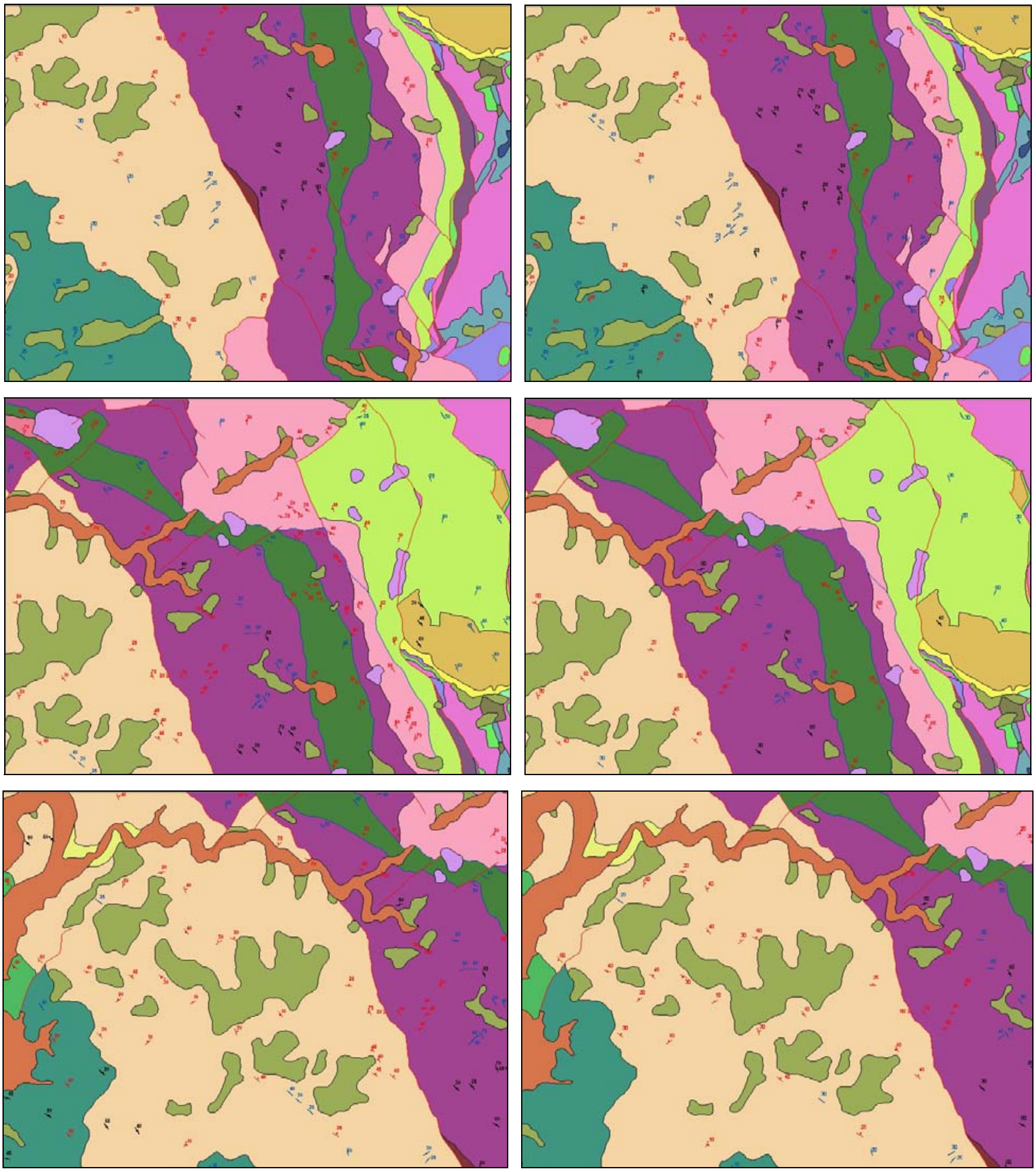


Figure 7.40. Three enlargement of the of the geological map with the bedding symbology before (left column) and after (right column) the generalization process. Bedding symbols are rotated according to the attribute values contained in the added item pSTRIKE, while the pDIP attribute values are used to label the features. Note how the information is less dense in the enlargements shown on right in comparison of the original ungeneralized map shown on left.

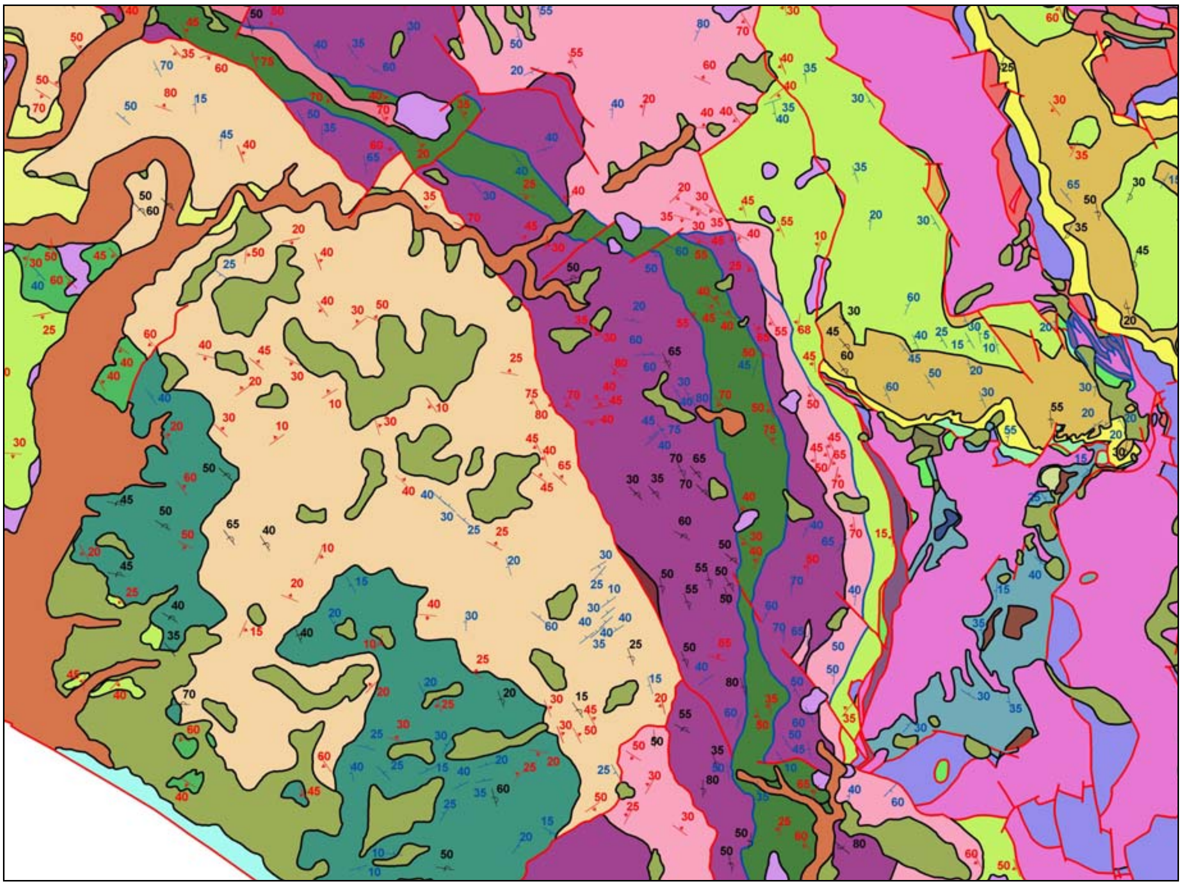
7.5 *Evaluation of the results*

The evaluation of generalization operations and final cartographic results was performed in a subjective manner by a group of geologists and cartographers at the University of Rome *La Sapienza*, Department of Earth Sciences, and at the Geological Survey of Italy, Department of Cartography. The group of experts, which covered the disciplines of geology, stratigraphy, cartography and information sciences, included the professor of Structural stratigraphy at the University of Rome, for the evaluation of the geological information (bedding symbols) before and after the generalization process, the cartographer of the Institute of Environmental Geology and Geoengineering c/o the University of Rome, the architect responsible of the Department of Cartography of the Geological Survey of Italy and his assistant, a computer-oriented geologist. This form of evaluation was considered highly appropriate because of the intrinsic nature of a geological map, which documents the experience, the interpretation and inference capabilities of a skilled professional: the geologist.

The group of experts was first briefed on the procedure that has been followed to generalize the geological map of Sestri Levante. The experts were then shown the illustrations included in Section 7.4, e.g., describing the entire generalization process (from Figure 7.22 to Figure 7.40). Their focus was mainly concentrated on the direct visual comparison of Figure 7.24 with Figure 7.39, shown in Figure 7.41, which include the whole case study area, before and after the generalization process.

The general comments of the experts suggest that an appropriate and significant result was obtained with respect to the case study dataset. According to the professor of Structural stratigraphy, after the generalization, the geological information was still maintained, e.g., it was possible to interpret the geological structures and the stratigraphy of the area using the information of the remaining and generalized bedding symbols. According to the cartographers, the symbology was neither overcrowded nor illegible, and in general the map was uncluttered.

The generalization routine has therefore proved to be successful, removing also the apparent subjectivity that cartographers apply to generalization. This suggests that the application of this tool across different geological maps can guarantee that a standardized, traceable procedure for generalization has been used. This is advantageous because it will ensure consistent generalizations from one map to another.



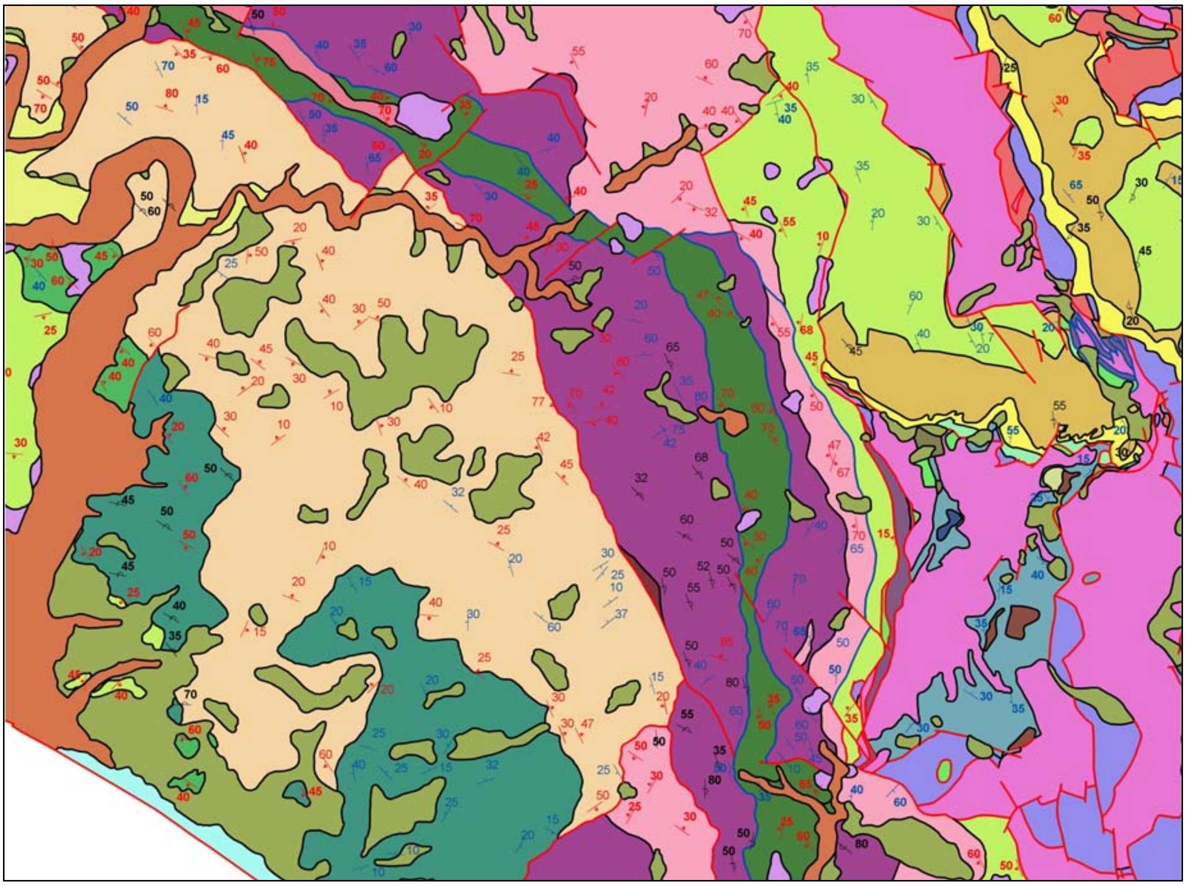


Figure 7.41. A direct visual comparison of the ungeneralized geological map of Sestri Levante (top) and the result of the generalization procedure (bottom).

The resulting number of bedding symbols maintained is 145. The value is very close to the result expected applying the radical law (175). A better match would have been achieved by choosing a smaller distance among symbols to avoid cluttering, e.g., 0.4 cm on the map, equivalent to 200 m on the ground.

7.6 Drawbacks of the system

This research concentrated only on bedding symbology. It is acknowledged that generalization should also include the whole set of geological symbology and geological features, but the present work has been just a first attempt to implement a generalization system using the standard commands, tools, and functions of ArcGIS® software version 9.1. Much more can be done in future research using the future expanded capabilities of the new version 9.2 of ArcGIS® presented by ESRI in December 2006.

During the application of the generalization systems some problems that need to be further investigated have been highlighted. It has been decided to consider the more representative symbol of a cluster of symbols the centroid of the buffer polygon in which the symbols are contained. The compromise has been accepted by the experts, but the choice has shown some drawbacks. Figure 7.42 shows an example where the average values for the strike and dip attributes are assigned to the centroid, while the more representative symbol would have been one of the others. Three points out of four have been selected by the generalization system, e.g., the first three records in the table. The centroid is the first record of the table (it is highlighted by the vertical arrow in the first column of the table) and the average values for strike and dip of the three selected point is assigned to it. However, the mean values are closer to the values of the middle point positioned south-west of the centroid and therefore, according to the *more representative symbol* rules of Section 7.4, they should have been assigned to it. This is a drawback of the choice to select as first polygon for the generalization process the buffer polygon with the higher number of COUNT or, when more than one record are selected, the first record encountered in the attribute table. It seems there is no evident way to bypass this problem other than assigning a weight reflecting some property of the symbols or reflecting the importance of the symbol according to the cartographer or the geologist.

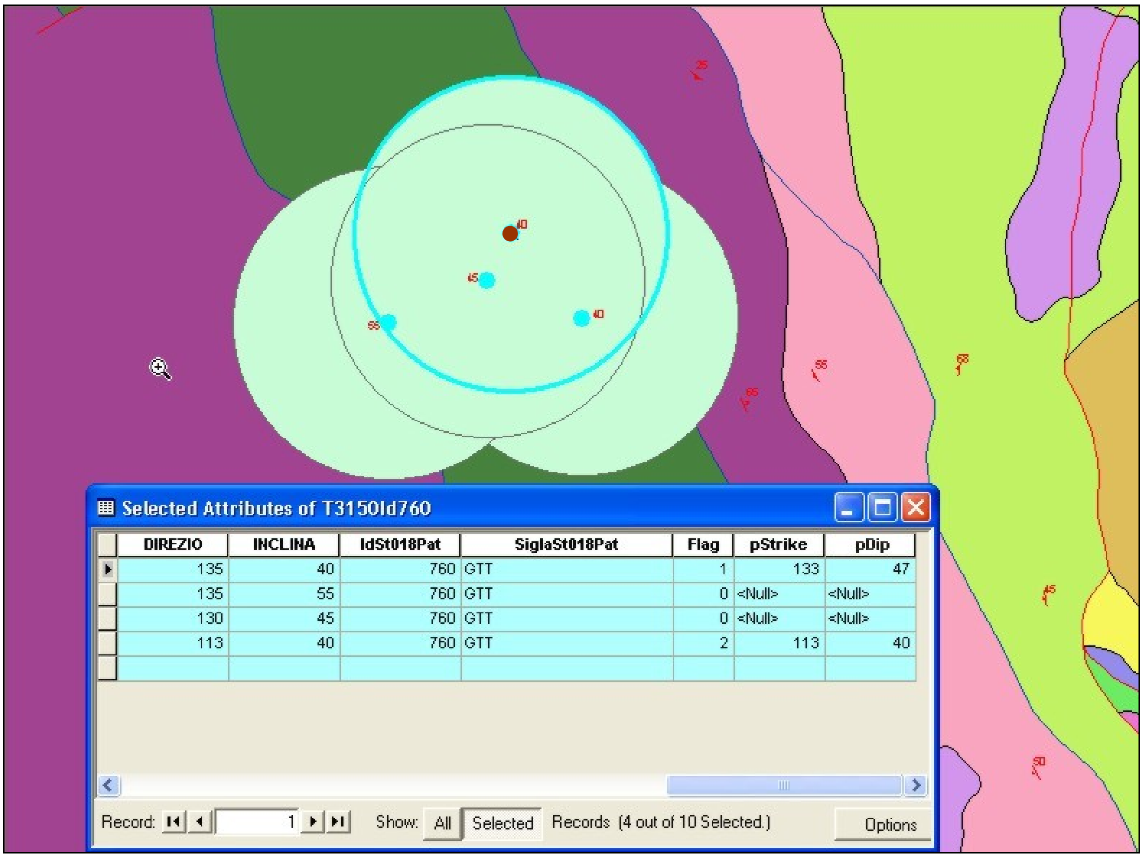


Figure 7.42. A drawback of the generalization process. The centroid is highlighted with a cross.

The choice of the centroid as the more representative point in a cluster of points, anyway, often is not as much of a problem as it may appear. Figure 7.43 shows an example where no symbols match the generalization criteria defined in the system. The centroid, the last record in the table, has DIREZIO (strike) and INCLINA (dip) values that cannot be averaged with the values of the other symbols. However, the second and third selected symbols (represented by the second and third record in the attribute table) could have been averaged and then generalized. This is not a problem for the proposed procedure. Any non-centroid symbol is in turn the centroid of another buffer polygon generated around itself. Therefore, with the second iteration of the routine, the second and third symbol of Figure 7.43 (top) are also included in the buffer polygon shown in Figure 7.43 (bottom), where the second symbol is now the centroid of the polygon. Again, symbols that have the values of strike and dip equal to $\pm 15°$ from the values of the centroid of the polygon are selected. The values of strike and dip are then averaged and assigned to the centroid of the polygon.

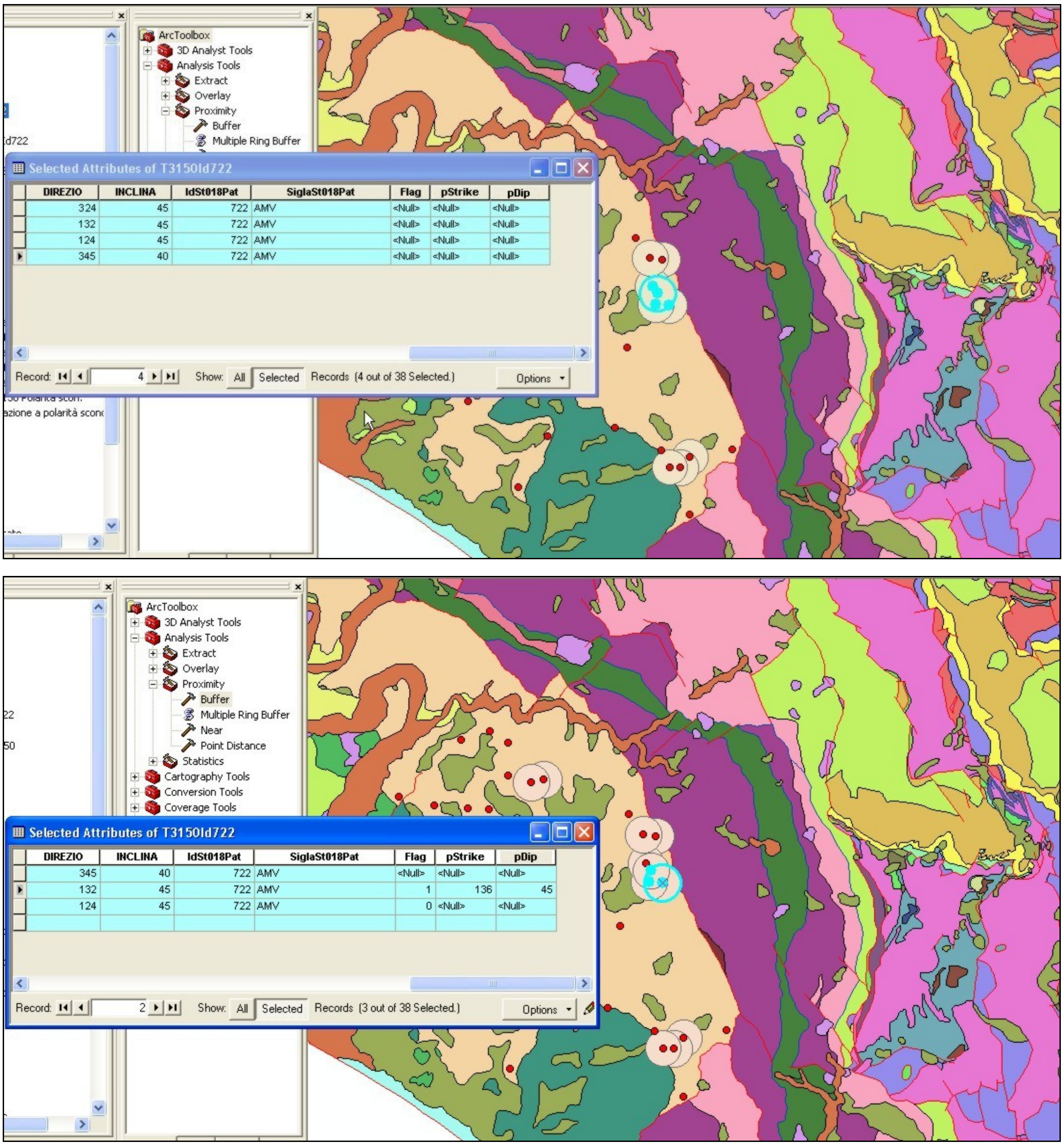


Figure 7.43. Two iterations of the generalization process.

Folds are the most common structures in mountain chains. They range from microscopic crinkles through folds 1-2 km across, to great arches and troughs 70 or more km across. Upfolds or arches in rocks are called *anticlines*, while downfolds or troughs are *synclines*. They are represented on a geological map through specific symbology and alignment of symbols. For instance, bedding symbols describing a anticline or syncline closure are generally aligned along an arc, and because they describe a specific geological structure, their values cannot be generalized and all symbols must be maintained after the generalization process. Should these symbols be closer than the buffer radius and have to match the generalization criteria, they would be generalized automatically by the system. This problem may be overcome introducing in the system the angle and distance values generated by the NEAR command of ArcGIS®, which determines the distance and measure the azimuthal angle from each point in a feature class to the nearest point or line within a specified search radius as shown in Figure 7.44. Using these values it would be possible to identify whether a trend in the angle values of close strike measurements exists or there is an alignment of bedding symbols or symbols are aligned along an arc, such as the axis of a syncline or anticline.

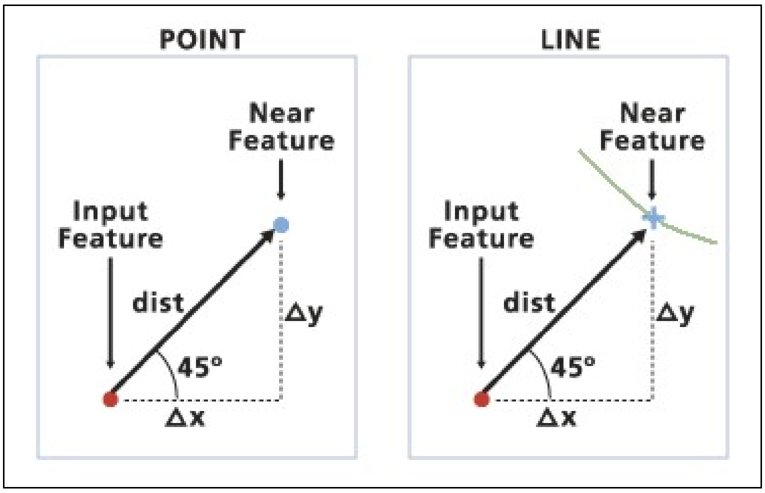


Figure 7.44. Distance and azimuthal angle generated by the NEAR command.

Figure 7.45 shows an example of syncline closure where bedding symbols would be erroneously generalized by the system.

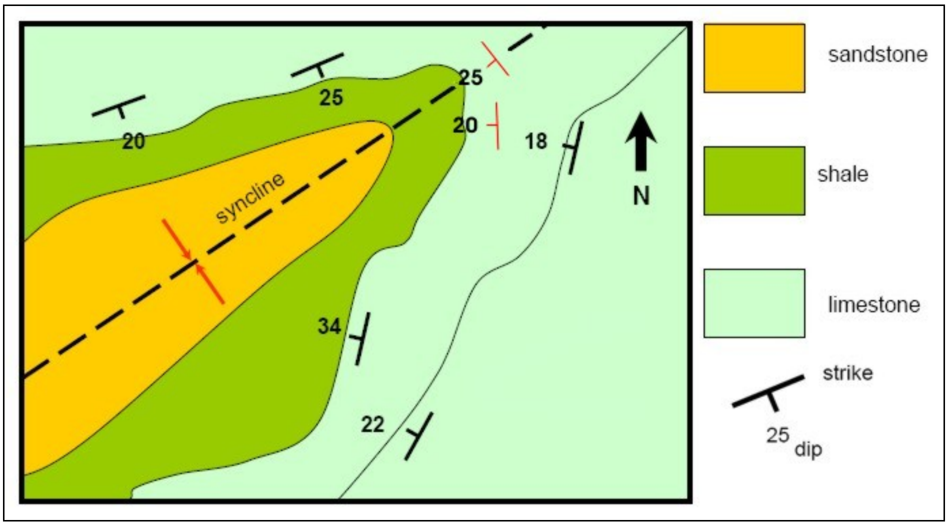


Figure 7.45. An example of syncline closure where bedding symbols highlighted in red would be erroneously generalized by the system (Modified after Boyce, 2006).

The generalization of a geological map is still a subjective process in which the cartographer wants to maintain the logical relationships between the geological objects, representing them with the appropriated symbology and removing unnecessary detail. Therefore, reducing the scale of a geological map implies emphasizing essential geological information and the repression of redundant and duplicated data. Aesthetic rules seem to have guided and still guide the whole generalization process, which is therefore subjective and sensitive to the habits and skills of the cartographer.

The concept of aesthetics is not yet feasible to implement in an automatic generalization system of geological symbols and map features. Although it could be done under convenient assumptions, aesthetic rules are likely to lose their meaning in a dynamic digital geological map visualized on the screen of a computer. In fact, any GIS software allows the display of symbols and geographic features at predefined values of scale within specified ranges of scale. ArcGIS® Maplex extension is the advanced label placement and conflict detection product for high-end cartographic production. It simplifies the labour-intensive placement of map text incorporating a rule-base placement engine. Furthermore, the *Label Priority Ranking* dialog box allows the user to specify the relative importance of the symbols in a map. It is therefore possible to arrange the priority ranking order to place symbols from more important classes on the geological map before other symbol classes. Placing a symbol class earlier in the symbolization process means that more of the symbols from that class will be placed in the available space. The *Label Weight Ranking* dialog box allows the specification of how important it is to avoid covering features with symbols. For instance, for polygon features it is possible to specify different weights for the interior and the boundary of the features. Symbol weights with higher values indicating more important features that should have a lower chance of being hidden by a symbol. This functionality of the ArcGIS® software, although not fully exploited to date, is sufficient to avoid cartographic symbol conflicts and overlapping between symbol classes or symbols belonging to different layers of geological information. A specific generalization procedure like the one that has been proposed is still necessary for the generalization of the geological information.

7.7 Conclusions

The research has demonstrated how a number of existing generalization operations can be applied using standard GIS tools, and can be combined into a rule-based procedure in order to automatically derive a 1:50,000 geological map for printing from a 1:25,000 geological database.

The resulting tool has the potential to provide the geologists and cartographer with a simple yet flexible method for generating alternative representations of the geology of an area. The algorithm needs to be tested against a more complete set of geological symbols and over a larger geographic extent in order to establish more generic sets of rules that will give satisfactory generalization results for different geological maps. Though limited in the choice of only bedding symbols, the initial results are encouraging.

For reasons of quality control and meaningful comparison between different geological maps, there are good reasons to adopt automated solutions that are predictable and consistent. The generalization tool has the merit of introducing standardization and traceability into a procedure that is acknowledged as being subjective and in need of quality control and management. To this end, the Italian Geological Survey has expressed an interest in taking this research further, suggesting that in the first instance it has potential as an interactive generalization tool.

Chapter Eight

8 Conclusions and future work

The design of a Geographical Information System for the management of Earth Sciences data has to deal with the very nature of geology, which being historical in character differs substantially from other fields of geographic applications. Geology is basically concerned with the analysis, classification, and description of complex structures whose presence and extension is affected by uncertainty and by gaps. Geological structures and formations although continuous, only outcrop at spotty discontinuous locations on the surface and their extension and depth has to be interpreted from sparse observations at the surface. Many geological data types such as lithostratigraphic units, rock types, and time scales are commonly categorised and organized into hierarchical arrangements. Computer-based techniques must be capable of effectively manipulating such hierarchies. Moreover, geological information is often gathered in the field with a density of observations corresponding to a scale larger than that of the final representation. This implies a generalization process to maintain readability and to avoid symbol overcrowding.

This research is focussed on the solution of one of the main complex problems in geological map production, the transfer from the 1:25,000 geological database, whose resolution is related with the density of field observations, to the printing of 1:50,000 geological maps. The problems relate mainly with the greater detail of information contained in the database and the smaller printing scale. Such problems can be classified into the design of a geological database scheme, that allows the generalization process based on the rules relating the geological objects to one another, and symbol overcrowding and overlapping. The challenge was to specify and implement a digital version of the decision rules used by geologists and cartographers to generate the final map. Unfortunately, often in practice these rules tend to be highly ambiguous, subjective, and inadequate in view of the modern need of automated generalization of geological information for land-use planning and development.

The proposed system has been based on the application of conventional manual techniques and artificial intelligence computer techniques to the production of digital geological cartography, from the gathering of geological data in the field to some printed product of wide usability.

The objectives satisfied by this research can be summarised as follows:

- The development of a decision support system for the identification and characterization of geological objects based on an *ad hoc* geological and stratigraphic dictionary;
- A GIS system for gathering geological data directly in the field using a hand-held digital device;
- The implementation of a hierarchical geological database scheme for the automated reclassification or generalization of a geological database for both multiple representations and/or for the production of *maps on demand* at different scales;
- The proposal of a system for avoiding symbol overcrowding and overlapping during the production of a geological map, which employs the above mentioned hierarchical geological database scheme and identifies the geological rules that interact between the geological objects represented in a map.

8.1 Results

This research has focused on how reality is abstracted into maps, and how the same reality is abstracted differently in different maps, even though the categories in the different maps are part of the same geological database.

The ideas presented concern mainly the levels of conceptual and logical data modelling. The main focus is on how geographic reality can be abstracted into an object-oriented data model. The approach is based on the cognitive aspect of how humans reason about geological information. The following assumptions form the basis on which the object-oriented model has been constructed:

- Several categories used in geological information are rather fuzzy. Examples that illustrate this were discussed. Owing to the fact that the categories are usually transformed into object classes in a GIS, there is a need to handle fuzzy as well as crisp categories in a process;
- The categories have different meaning in different contexts. The context is set by the application discipline and the application within the GIS;
- The human pattern recognition ability has impacts on the meaning that a particular category in a map acquires. It is the pattern that the category forms in the map that influences the meaning given the category;
- A map that is a view into a database should have the possibility to contain object classes suitable for analytical queries as well as object classes that are only used to visualise information in the map;

- Categories with the same name displayed in different maps are defined within different contexts and thus have more or less different meaning. The categories are most likely overlapping, but whether associations between individual members of two (or more) categories can be explicitly defined has to be decided in each individual case.
- The map presents a view of reality for a particular application. The meaning of the categories included in the map and the design of the map is an optimal compromise to convey the information required by the user.

8.1.1 A system for collecting data in the field

Though there is some resistance among older geologists toward the new way of collecting data in digital form directly in the field, computerized mapping is finally gaining popularity for field use. An example is the free FieldLog software tool developed by Boyan Brodaric with the Geological Survey of Canada. The software is downloadable from the FieldLog Web site http://gis.nrcan.gc.ca/fieldlog/Fieldlog.html. FieldLog aids geologists in the digital management of geological field data providing a means to digitally record, retrieve, display and analyze field observations, and to supplement cartographic map preparation and geological interpretation. The existence of the software has influenced this approach.

PDA electronic data gathering devices have proved themselves as reasonably low-cost mobile systems providing sets of tools in the field. These devices have the ability of loading collected information directly into a database structure that mimics the data structure found at the corporate level. This database structure concept can greatly facilitate the transfer of information to a corporate data holding and reduce the data manipulation needed to facilitate the transfer. Moreover, this methodology can also facilitate the sharing of accurate, up to date information between different groups and disciplines, whose demands continue to grow dramatically.

Capturing geological data directly in the field on a station-to-station basis is considered an effective way of streamlining the information process, while at the same time capturing vital geological information, thus maintaining corporate or official standards and requirements. The tool that was selected to capture geological data is ArcPad® mobile GIS software for field mapping applications by ESRI. The proposed system has been tested in an area in the Liguria region, selecting a portion of the *Sestri Levante* topographic sheet at scale 1:25,000 for the field survey.

An ArcPad® application has been installed on a Compaq iPAQ® handheld device connected to a Garmin eTrex Vista® GPS unit and has provided field-based personnel with the ability to capture, analyze, and display geographic information. Enabling geologists with ArcPad® has allowed for more productive and accurate geological data collection through data capture forms and input from a GPS device. Immediate access to the collected data and GIS tools has also enhanced the geologist's ability to make critical decisions in the field, to interpret observations during the mapping process and to modify the interpretation as more information was acquired. By incorporating visualization and analysis into the mapping workflow, digital methods can also aid and improve the interpretation process.

As a mobile component of ArcGIS®, ArcPad® integrates with ArcGIS® Desktop software to allow field edits to be incorporated into the geodatabase through disconnected editing. ArcPad® is therefore fully integrated with the hierarchical system for the generalization of geological databases presented in Chapter 6 and the rule-based systems for the generalization of geological symbology described in Chapter 7.

8.1.2 A hierarchical system for the generalization of geological databases

As we have seen, the design of a Geographical Information System for the management of Earth Sciences data has to deal with the very nature of geology, which is based on spatial spotty observation of features partly destroyed during geological evolution.

The hierarchical rule-based expert system is proposed for the generalization of the geological database, for both the multiple thematic and the multi-scale representations of the information generated and archived. The set-theoretic method has proved to conform to the relational data model and is advantageous in managing geological hierarchies. The method was applied to several case studies, using standard SQL queries, where the methodology and the geological-object model proposed in this research have been successfully validated. The system has proved to be an effective means for organizing and storing hierarchical geological, lithostratigraphic, and lithologic information, facilitating the generalization at a defined hierarchical level.

The result of this research work is considered important in the process of developing multi-representations of geological databases as it frees database developers from the tedious task of manually comparing geological databases that are represented at different scales, and finding discrepancies among the different representations. It also enables database designers to test whether the implementations of new generalization operations perform as desired. Moreover, in geology classification criteria and schemes are not everlasting. The introduction of new encoding rules may modify a geological classification scheme. The proposed system can accommodate any change in the classification scheme in a simple and logical fashion.

8.1.3 A rule-based system for the generalization of geological symbology

The human ability to learn how to automatically recognise different patterns has been discussed. The difficulties in transforming this *visual* knowledge into a propositional or procedural form, needs to be somehow resolved within an automated system for generalization. It seems reasonable to assume that cartographers and experienced map readers have developed such *visual* knowledge and that this is used when interpreting different maps. The meaning that a map category, such as a geological unit, acquires in a particular map context is influenced by this visual knowledge, and the visual knowledge gives the category a more narrow definition. The definition of the constraints, which rule the generalization process performed by the geologist-cartographer is therefore of paramount importance. This constraints have been applied to the rule-based system proposed, which is representative, although tentatively so, of graphic generalizations for the simplification of cluttered symbols, where the generalization operation is performed at the printing scale to preserve legibility.

The research has demonstrated how a number of existing generalization operations can be applied using standard GIS tools, and thus can be combined into a rule-based procedure to automatically derive a 1:50000 geological map for printing derived from a 1:25000 geological database.

The resulting tool has the potential to provide the geologists and cartographer with a simple yet flexible method for generating alternative representations of the geology of an area. The algorithm needs to be tested extensively against a more complete set of geological symbols and over a larger geographical extent in order to establish a more generic rule-base that will give satisfactory generalization results for different geological maps.

For reasons of quality control and meaningful comparison between different geological maps, there are good reasons to adopt automated solutions that are predictable and consistent. The generalization tool has the merit of introducing standardization, traceability and transparency into a procedure that is acknowledged as being subjective and in need of quality control and management. To this end, the Italian Geological Survey has expressed an interest in taking this research further ahead, suggesting that in the first instance it has potential as in interactive generalization tool.

8.2 Future research

The hierarchical generalization methodology presented in this research deals only with polygon generalization. Geological information is extracted from the geodatabase, manipulated and represented according to the hierarchical generalization system proposed. However, in order to derive a smaller scale geological map from a larger scale geological database there is a requirement for contextual sensitivity. To achieve an appropriate result the interaction between *all* the geological feature and object classes represented on the map *must* be considered and should reflect the interaction of the geological objects in the real world. The system to avoid cluttered symbology concentrates on bedding symbols, but it is acknowledged that generalization should also include the *whole set* of geological symbols and features and the relationships and overlapping conflicts between the different type of symbols shown in a geological map, e.g., the cartographic symbols conflicts and overlapping between symbol classes in a single layer or symbols belonging to different layers of geological information.

To this end, the Italian Geological Survey has expressed an interest in taking this research further. They would like to completely automate the digital production of the geological sheets included in the CARG Project (*CARtografia Geologica* or Geological Cartography) that have not been published yet. In fact, most of geological survey agencies are now developing methods for geological mapping in the *post-paper* map era. In Italy, manually prepared maps take more than one year (sometimes two or more!) to prepare and to be ready for printing. In other national geological agencies, e.g., at the Geological Survey of Canada or at the U.S. Geological Survey, today fully digital geological maps can take as little as one month to prepare, and this with a much reduced cost for production.

In a geological database, not only bedding symbols have a direction (strike) and inclination (dip) attribute. Structural symbols, such as lineations, foliations, schistosity, and gneissosity, for instance, are also represented on a geological map using two vector symbols showing a direction angle and an inclination value. The proposed methodology used to generalize bedding symbols can be therefore applied to these additional classes of geological symbols. The generalization system proposed can be therefore further developed and applied with the same efficiency to any geological or structural symbol plotted on a geological map, supporting the cartographer and the geologist in the decisional phase of the generalization procedure.

With further research, higher levels of completely automated generalization and more accurate geological map production can be obtained. The use of advanced Artificial Intelligence techniques, such as neural networks, fuzzy logic or genetic algorithms, would eventually provide the mapmaker, in a more complex holistic decisional framework, with more intelligent tools for map production. Incorporating the proposed generalization system within such a framework, would allow the geologist and the cartographer to deal more easily with the geological information that is by nature affected by uncertainty and by gaps.

The aim for the future is to construct a systematic procedure of generalization of geological geodatabases and geological symbols for broader use. The present research concentrated only on bedding symbols, and a worthwhile target would be the development of a complete and general solution for the generalization of the entire set of geological features contained in a geological map. This would facilitate and speed up the production of the maps and would aid also the cartographer to guarantee that a standardized, traceable procedure for generalization has been used.

The present work has been just a first attempt to implement a generalization system using the commands, tools, and functions of a standard commercial GIS software, and much more can be done next using the future expanded capabilities of the new forthcoming versions. For this to happen, however, the geological cartographers must arrive at and accept a more logical structuring of the information for map representation within digital databases.

References

Aronoff, S.
Geographic Information Systems: A Management Perspective
WDL Publications, Ottawa, 1989.

Beard, K.
How to Survive on a Single Detailed Database
AutoCarto 8, Baltimore, MD, pp. 211-220, 1988.

Beard, K.
Theory of the Cartographic Line Revisited/Implications for Automated Generalization
Cartographica, 28(4), pp. 32-58, 1991.

Beard, K., and Mackaness, W. A.
Generalization Operations and Supporting Structures
Auto Carto 10, Baltimore, MD, pp. 29-45, 1991.

Bernhardsen, T.
Geographic Information Systems
John Wiley & Sons, Toronto, pp. 318, 1996.

Berry, J.K.
A Brief History and Probable Future of GIS in Natural Resources
GIS '93, Vancouver, British Columbia, 1993.
Web reference accessed 27 January 2006:
http://www.innovativegis.com/basis/Papers/Other/FORS_History/FORS_History.htm

Blaha, M. R., Premerlani, W. J., Bender A. R, Salemme, R. M, Kornfein, M. M., and Harkins, C. K.
Bill-of-Material Configuration Generation
Proceedings of the Sixth International Conference on Data Engineering, Los Angeles, pp. 237-244, 1990.

Boisvert, E., and Lauzier, K.
Database Structure for Geological Data using relational model
Geological Survey of Canada, Internal publication, pp. 59, 1996.

Boyce, J.I.
Lectures of the course Geo 3Z03 - Structural Geology
McMaster University, School of geography and earth Sciences, Hamilton, Canada, 2006.
Web reference accessed 27 January 2006:
http://www.science.mcmaster.ca/geo/undergraduate/courses/thirdyear/geo3z03/index.html

Booch, G.
Object-Oriented Analysis and Design with Applications
Benjamin & Cummings, Inc., Reading, MA, 1994.

Booch, G., Jacobson, I., and Rumbaugh, J.
The Unified Modelling Language for Object-Oriented Development
Document Set Version 0.91 Addendum UML Update, Rational Software Corporation, 1996.

Brassel, K., and Weibel, R.
A Review and Conceptual Framework of Automated Map Generalization
International Journal of Geographic Information Systems 2(3), pp. 229-244, 1988.

Brodaric, B.
The Geological Object Model
Geological Survey of Canada, Ottawa, Unpublished manuscript, pp. 7, 1996.

Brodaric, B.
The design of GSC FieldLog: ontology-based software for computer aided geological field mapping
Computers and Geosciences, 30(1), pp. 5-20, 2004.

Brodaric, B., Boisvert, E., and Patera, A.
A set-theoretic technique and software for managing multiple-classification in geological hierarchies
Proceedings of the IAMG - International Association for Mathematical Geology, 8th Annual Conference, Berlin, p. 1, 2002.

Brodaric, B., and Patera, A.
A set-theoretic approach to managing hierarchies with relational databases
Proceedings of the Joint Annual Meeting: Geological Association of Canada and Mineralogical Association of Canada, Ottawa, Canada, p. A18, 1997.

Brodaric, B., and Patera, A.
New tools to aid regional geological map compilation: geological map generalization using classification hierarchies in the relational data model
Proceedings of the International conference on GIS for Earth science applications, Ljubljana, Slovenia, p. 1, 1998 (Abstract).

Brodaric, B., and Patera, A.
Generalizing geological map units using GIS and tabular data
Proceedings of the IAMG - International Association for Mathematical Geology, 7th Annual Conference, Cancun, Mexico, p. 1, 2001 (Abstract).

Brodaric, B., Patera, A., and Boisvert, E.
Representing geological hierarchies in the relational data model
Unpublished manuscript, pp. 21, 2000.

Brodie, M.
On the Development of Data Models
M. Brodie, J. Mylopoulos, and J. Schmidt (Eds.), *On Conceptual Modelling: Perspectives, from Artificial Intelligence, Databases and Programming Languages,* Springer Verlag, New York, NY. pp. 19-48, 1984.

Brophy, D.M.
Automated Linear Generalization in Thematic Cartography
Master's Thesis, Department of Geography, University of Wisconsin, 1972.

Bruegger, B. P., and Frank, A. U.
Hierarchies over Topological Data Structures
ASPRS/ACSM Annual Convention, Baltimore, MD, pp. 137-145, 1989.

Buller, G.
Ganfield: data integrity from field to final product
Proceedings of the Capturing Digital Data in the Field Workshop, British geological Survey, Nottingham, 2002.
Web reference accessed 27 January 2006: http://www.bgs.ac.uk/dfdc/gbuller.html

Buller, G.
GanFeld: Geological Field Data Capture
Proceedings of the Digital Mapping Techniques 2004 Workshop, U.S. Geological Survey Open-File Report 2004-1451, 2004.
Web reference accessed 27 January 2006: http://pubs.usgs.gov/of/2004/1451/buller

Burrough, P. A.
Principles of Geographical *Information Systems for Land Resources Assessment*
Clarendon Press, Oxford, 1986.

Burrough, P.A., and McDonnell, R.A.
Principles of Geographical Information Systems
Oxford University Press, Oxford, pp. 356, 1998.

Buttenfield, B. P.
Multiple Representations: Initiative 3 Specialist Meeting Report
National Center for Geographic Information and Analysis, Technical Report 89-3, NCGIA, UCSB Santa Barbara, CA, 1989 (a).

Buttenfield, B. P.
Scale-Dependence and Self-Similarity in Cartographic Lines
Cartographica 26(1), pp. 79-100, 1989 (b).

Buttenfield, B. P.
A Rule for Describing Line Feature Geometry
B. P. Buttenfield and R. McMaster (Eds.), *Map Generalization: Making Rules for Knowledge Representation*, John Wiley & Sons, New York, pp. 150-171, 1991.

Buttenfield, B. P.
Multiple Representations – Closing Report
National Center for Geographic Information and Analysis - NCGIA, UCSB Santa Barbara, CA, Technical report, pp. 26, 1993.

Buttenfield, B. P., and Mark, D. M.
Expert Systems in Cartographic Design
Chapter VII in Geographic Information Systems: The Computer and Contemporary Cartography, (D. R. F. Taylor, Editor), Pergammon Press., Oxford, pp. 129-150, 1991.

Chaiken, G.M.
Short Note: An Algorithm for High-Speed Curve Generation
Computer Graphics & Image Processing, 3, pp. 346-349, 1974.

Chou, Y.H.
Exploring Spatial Analysis in GIS
OnWord Press, U.S., pp. 500, 1997.

Codd, E. F.
A Relational Model of Data for Large Shared Data Banks
CACM 13, no. 6., 1970

Codd, E. F.
Data Models in Database Management:
Proceedings Workshop on Data Abstraction, Databases, and Conceptual Modelling, Pingree Park, Colorado, 1980.

Cowen, D. J.
GIS versus CAD versus DBMS: What are the differences?
Photogrammetric Engineering and Remote Sensing, 54(11), pp. 1551-1555, 1988.

Cromley, R. G.
Hierarchical Methods to Line Simplification
Cartography and Geographic Information Systems 18(2), pp. 125-131, 1991.

Date, C. J.
An introduction to Database Systems
Addison-Wesley, Reading, MA, 1995.

de Carvalho Paiva, J. A.
Topological Equivalence And Similarity In Multi-Representation Geographic Databases
PhD thesis, The Graduate School, University of Maine, pp. 165, 1998.

Dettori, J., and Puppo, E.
How Generalization Interacts with the Topological and Metric Structure of Maps
M. J. Kraak and M. Molenaar (Eds.), *7th InternationalSymposium on Spatial Data Handling*, Delft, The Netherlands, Taylor & Francis, pp. 9A.27-9A.38, 1996.

DeMers, M.N.
Fundamentals of Geographic Information Systems
John Wiley & Sons, pp. 448, 1996.

Douglas, D., and Peucker, T.
Algorithms for the Reduction of the Number of Points Required to Represent a Digitized Line or its Caricature
Canadian Cartographer 10(2), pp. 112-122, 1973.

Downs, T. C., and Mackaness, W. A.
An Integrated Approach to the Generalization of Geological Maps
The Cartographic Journal 39(2), pp. 137-152, 2002

Doytsher, Y., and Shmutter, B.
Intersecting layers of information: A computerized solution
Auto-Carto London, pp. 136-145, 1986.

Dunkars, M.
Automatic generation of a view to a geographic database
Licentiate Thesis, Royal Institute of Technology (KTH), Division of Geodesy and Geoinformatics, Stockholm, pp. 103, 2001.

Egenhofer, M., and Frank, A.
Object-Oriented Modelling in GIS: Inheritance and Propagation
Autocarto 9, Baltimore, MA, pp. 588-598, 1989.

ESRI White Paper Series
Automation of Map Generalization - The Cutting-Edge Technology
Environmental System Research Institute, Redlands, 1996.
Web reference accessed 30 January 2004:
http://downloads.esri.com/support/whitepapers/ao_/mapgen.pdf

Fabbri, A. G.
Image Processing of Geologocal Data
Van Nostrand Reinhold, New York, pp. 244, 1984.

Fabbri, A. G., Napolitano, P., Patera, A., Brodaric, B., and Baeza, C.
Managing field data for geological mapping and environmental modelling
Proceedings of the International Association of Mathematical Geologists Congress, Barcelona, Spain, p. 1, 1997 (Abstract).

Fotheringham, S., and Rogerson P.
Spatial Analysis and GIS
Taylor & Francis, London, pp. 296, 1994.

Frank A. U.
Overlay processing in spatial information systems
Auto-Carto 8, pp. 12-31, 1987.

Franklin, W. R., and Peter Y. F. Wu
A polygon overlay system in PROLOG
Auto-Carto 8, pp. 97-106, 1987.

Goodchild, M. F.
A spatial analytical perspective on Geographical Information Systems
International Journal of Geographical Information Systems, 1(4), pp. 327-334, 1987.

Goodchild, M.F, Parks, B.O., and Steyaert, T.L.
Environmental Modeling with GIS
Oxford University Press, New York, pp. 512, 1994.

Hughes, J. G.
Object-Oriented Databases
Prentice Hall Englewood Cliffs, NJ, pp. 280, 1991.

Hull, R., and King, R.
Semantic Database Modelling: Survey, Applications and Research Issues
Acm Computing Surveys, Vol. 19, pp. 201-260, 1987.

International Union of Geological Sciences
Subcommission on Stratigraphic Classification
Report: IUGS Subcommission, 1961

Jacobson, I.
Object-Oriented Software Engineering: A Use Case Driven Approach
Addison-Wesley, Reading, MA, 1992.

Jones, C. B., Kidner, D. B., Luo, Q., Bundy, G. L., and Ware, J. M.
Database Design for a Multi-Scale Spatial Information System
International Journal Geographical Information Systems 10(8), pp. 901-920, 1996.

Kessler, H. and Mathers, S.
Maps to Models
Geoscientist, 14(10), pp. 4-6, 2004.

Kilpeläinen, T.
Multiple Representation and Generalization of Geo-Databases for Topographic Maps
Doctorate thesis, Publications of the Finnish Geodetic Institute, No. 124, pp. 43, 1997.

Koch, G., and Loney, K.
ORACLE: The Complete Reference - *Third Edition*
Osborne MacGraw-Hill, Berkeley, CA, pp. 1066, 1995.

Lakoff, G.
Woman, Fire and Dangerous Things: What Categories Reveal about the Mind
University of Chicago Press, Chicago, 1987.

Lang, T.
Rules for the Robot Draughtsmen
The Geographical Magazine, 42(1), pp. 50-51, 1969.

Longley, P. A., Goodchild, M. F., Maguire, D. J., and. Rhind, D. W
Geographic Information Systems and Science
John Wiley & Sons, Chichester, 2001.

MacEachren, A. M.
How Maps Work
The Guilfoord Press, New York, 1995.

Maguire, D. J., Goodchild, M.F., and Rhind, D.W.
Geographical Information Systems, Principles, Techniques, Applications and Management
Longman, Harlow, Essex, pp. 1096, 1991.

Mark, D. M.
Object Modelling and Phenomenon-Based Generalization
B. Buttenfield and R. McMaster (Eds.), *Map Generalization: Making Rules for Knowledge Representation*, John Wiley & Sons, New York, NY., pp. 103-118, 1991.

McBride, E.
Lectures of the course: Geo420k - Introduction to Field & Stratigraphic Methods
University of Texas, Department of geological Sciences, Austin, 2006.
Web reference accessed 27 January 2006:
http://www.geo.utexas.edu/courses/420k/lectures/Cooke_06/Brunton_Compass_small.ppt).

McCaffrey, K.J.W., Holdsworth, R.E., Clegg, P., Jones, R.R. and Wilson, R.
Using digital mapping tools and 3D visualization to improve undergraduate fieldwork
Planet, Special Edition, 5, pp. 34-36, 2003

McCaffrey, K.J.W., Jones, R.R., Holdsworth, R.E., Wilson, R., Clegg, P., Imber, J., Holliman, N. and Trinks, I.
Unlocking the spatial dimension: digital technologies and the future of geoscience fieldwork
Journal of the Geological Society, 11, 2005.
Web reference accessed 27 January 2006:
epswww.unm.edu/facstaff/tfw/ IMAGES/pdfs/KM_JGS_2005-17-revised.pdf

McMaster, R. B., and Shea, K. S.
Cartographic Generalization in a Digital Environment: A Framework for Implementation in a Geographic Information System
GIS/LIS, San Antonio, TX, pp. 240-249, 1988.

McMaster, R. B., and Shea, K. S.
Generalization in Digital Cartography
American Association of Geographers, Washington, 1992.

McMaster, R. B., and Veregin, H.
Multiple Representations of Spatial Data
Report, 1996.
Web reference accessed 30 January 2002:
http://www.geog.umn.edu/umucgis/nomination4.html

Molenaar, M.
Object hierarchies or uncertainty in GIS or why is standardisation so difficult
GeoInformations-Systeme, 6 (3 1993), pp. 22-28, 1993.

Molenaar, M.
An Introduction to the Theory of Spatial Object Modelling for GIS
Taylor & Francis, London, 1998.

Muller, J.-C.
The Removal of Spatial Conflicts in Line Generalization
Cartography and Geographic Information Systems 17(2), pp. 141-149, 1990.

Muller, J.-C., Lagrange, L.-P., and Weibel, R.
GIS and Generalization:Methodology and Practice
Taylor & Francis, London, 1995.

Muller, J.-C., and Zeshen, W.
Area-Patch Generalization: a Competitive Approach.
The Cartographic Journal 29(2), pp. 137-144, 1992.

Nickerson, B.G., and Freeman, H.
Development of a Rule-Based System for Automatic Map Generalization
Proceedings of the Second International Symposium on Spatial Data Handling, pp. 537-556, 1986.

North American Commission on Stratigraphic Nomenclature
North American stratigraphic code
American Association of Petroleum Geologists Bulletin, Vol. 67, Number 5, 1983, pp. 841-875, 1983.

Oracle Corporation
Oracle7 Server SQL Language Reference Manual
Oracle Corporation, 1992.

Ormsby, T., Napoleon, E., Burke, R., Feaster, L., and Groessl, C.
Getting to Know ArcGIS Desktop
2nd ed., ESRI Press, Redlands, 2004.

Patera, A., and Brodaric, B.
Un sistema esperto gerarchico per la gestione della cartografia geologica
MondoGIS, Roma, pp. 10, 2006 (Forthcoming in 2007).

Puppo, E., and Dettori, G.
Towards a Formal Model for Multiresolution Spatial Maps
Max J. Egenhofer and John Herring (Eds.), *Advances in Spatial Databases, 4th International Symposium, SSD95*, Portland, ME, Springer, pp. 152-169, 1995.

Raper, J.
Three-Dimensional Applications in GIS
Taylor & Francis, London, pp. 320, 1990.

Rigaux, P., and Scholl, M.
Multiple Representation Modelling and Querying
J. Nievergelt, T. Roos, H. Scheck and P. Widmayer (Eds.), *International Workshop on Advanced Research in Geographic Information Systems*, pp. 59-69, 1994.

Robinson, H. A., Morrison, J. L., Muehrcke, P. C., Kimerling, A. J., and Guptil, S. C.
Elements of Cartography
6th ed., John Wiley & Sons, New York, pp. 690, 1995.

Rosch, E. H.
Natural categories
Cognitive Psychology, 4, pp. 328-350, 1973.

Rumbaugh, J., Blaha, M., Premerlani, W., Eddy, F., and Lorenson, W.
Object oriented modelling and design
Prentice Hall, London, 1991.

Schetselaar, E., Deby, R., Sun, Y, Niewenhuis, W., Wolday, T., and Brodaric, B.
Spatial modelling and mobile computing for geo acquisition
Report, 2004.
Web reference accessed 27 January 2006:
http://www.itc.nl/personal/kraak/tgdi/schetselaar.htm

Schetselaar, E.M., Harrap, R., Brodaric, B.
Digital capture of geological field data: bridging the gap between a mapping heritage and the integrated dissemination of geoscience information
Geological Association of Canada Special Volume on GIS Methods in Geological Sciences, in press.

Servizio Geologico d'Italia
Carta geologica d'Italia - Guida alla rappresentazione cartografica
Servizio Geologico d'Italia, Quaderni serie III, 2, Roma, 1996.
Web reference accessed 30 May 2005:
http://www.apat.gov.it/site/it-IT/APAT/Pubblicazioni/Quaderni/

Servizio Gelogico d'Italia
Carta geologica d'Italia 1:50.000 - Banca dati geologici. Linee guida per l'informatizzazione e per l'allestimento per la stampa dalla banca dati
Istituto poligrafico e zecca dello Stato, Quaderni serie III, 6, Roma, 1997.

Shea, K. S., and McMaster, R. B.
Cartographic Generalization in a Digital Environment: When and How to Generalize
Auto Carto 9, Baltimore, MD, pp. 56-67, 1991.

Smith, T. R., Menon, S., Star, J. L., and Estes, J. E.
Requirements and principles for the implementation and construction of large-scale Geographic Information Systems
International Journal of Geographical Information Systems, 1(1), pp. 13-31, 1987.

Star, J., and Estes J.
Geographic Information Systems: An Introduction
Prentice Hall, Englewood Cliffs, N.J., pp. 665, 1990.

The National Center for Geographic Information and Analysis (NCGIA)
A prospectus
Technical report, National Science Foundation, Santa Barbara, 1987.

Timpf, S.
Hierarchical structures in map series
PhD thesis, Department of Geoinformation, Technical University Vienna, Vienna, 1998.
Web reference accessed 30 January 2002:
http://www.geoinfo.tuwien.ac.at/publications/fromerPersonnel/timpf/

Timpf, S., and Devogele, T.
Multi-scale representations - why do we need them and what tools exist in GIS?
ICC'97, Stockholm, 1997.

Timpf, S., Volta, G., Pollock, D., and Egenhofer, M.
A Conceptual Model of Wayfinding Using Multiple Levels of Abstraction
A. U. Frank, I. Campari, and U. Formentini (Eds.), *Theory and Methods of Spatial Temporal Reasoning in Geographic Space*, Pisa, Italy, Springer-Verlag, New York, NY, pp. 348-367, 1992.

Tomlin, C.D.
Geographic Information Systems and Cartographic Modeling
Prentice Hall, Englewood Cliffs, N.J., pp. 572, 1990.

Tomlinson, R. F.
Geographical Data Handling
International Geographical Union Commission on Geographical Data Sensing and Processing, Ottawa, 1972.

Tomlinson, R.F.
Current and Potential Uses of Geographical Information System : The North American Experience
International Journal of Geographical Information Systems, 1, pp. 203-218, 1987.

Tomlinson, R.F.
An overview: The Future of GIS
ArcNews online, 2000.
Web reference accessed 27 January 2006:
http://www.esri.com/news/arcnews/winter9900articles/gis2000/03-tomlinson.html

Topfer, F., and Pillewizer, W.
The principles of selection
The Cartographic Journal, 3(1), pp. 10-16, 1966.

Tryfona, N., and Egenhofer, M.
Consistency Among Parts and Aggregates: A Computational Model
Transactions in GIS 1(3), pp. 189-206, 1997.

Ullman, J. D.
Principles of Database and Knowledge-Base Systems, Volume 1
Computer Science Press, Rockville, MD, pp. 631, 1988.

van Oosterom, P. H. M.
Reactive data structure for Geographic Information Systems
PhD thesis, Rijksuniversiteit, Leiden, pp. 210, 1990.

Visvalingam, M., and Whyatt, J.D.
The Douglas-Peucker Algorithm for Line Simplification: Re-evaluation through Visualization
Computer Graphics Forum 9, pp. 213-228, 1990.

Weibel, R.
An adaptive methodology for automated relief generalization
Auto Carto 8, Baltimore, MD, pp. 42-49, 1987.

Weibel, R.
Three Essential Building Blocks for Automated Generalization
J.-C. Muller, J.-P. Lagrange, and R. Weibel (Eds.), *GIS and Generalization Methodology and Practice*, pp. 56-69, Taylor & Francis, Bristol, 1995.

Weibel, R.
A Typology of constraints to Line Simplification
M. J. Kraak, M. Molenaar (Eds.), 7th International Symposium on Spatial Data Handling, Delft, The Netherlands, Taylor & Francis, pp. 9A.1-9A.14, 1996.

Wittgenstein, L.
Philosophical Investigations
Macmillan, New York, 1953.

Wolfe, C.
Geological data analysis
Lecture notes, 2001.
Web reference accessed 15 December 2006:
http://www.higp.hawaii.edu/~cecily/course/gg313/DA_book/node111.html

Worboys, M.F.
GIS: A Computing Perspective
Taylor & Francis, London, 1995.

Zadeh, L.
Fuzzy sets
Information and Control 8, pp. 338-53, 1965.

Zoraster, S., Davis, D., and Hugus, M.
Manual and Automated Line Generalization and Feature Displacement
U. S. Army Engineer Topographic Laboratories report number ETL-0359, pp. 21, 1984.